A New Paradigm for Developing and Delivering Ubiquitous Positioning Capabilities

Allison KEALY, Australia, Charles TOTH, Dorota BRZEZINSKA, USA, Gethin ROBERTS, China, Guenther RETSCHER, Austria and Vassilis GIKAS, Greece

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SUMMARY

Theoretical and practical approaches to developing ubiquitous positioning systems have traditionally been based around the fusion of all available signals to deliver a positioning solution that overcomes the limitations of Global Navigation Satellite Systems (GNSS). Whilst still valid, the technical and operational landscape across which this paradigm has existed has changed dramatically over the past five years. The most significant of these changes is the rapid growth of location based applications that have performance requirements that no longer centre on demands for high accuracy solutions, but where position availability and integrity are more significant. In addition, increasing volumes of potentially useful measurement data is available from developments in low-cost, low profile traditional augmentation sensors which have merged with the availability of new non-traditional signals and sensors that can be used for positioning. Operational platforms with limited processing capabilities, the availability of application specific information sources and the increasing utility and ubiquity of qualitative information across these application domains are also emerging as important considerations in the design and development of ubiquitous positioning systems. This paper discusses the challenges associated with developing and delivering truly ubiquitous positioning capabilities. It attempts to redefine the classic definition of ubiquitous positioning with the overall aim of delivering an intelligent, responsive positioning solution that offers ubiquitous positioning capabilities whilst balancing performance and cost. It will also present preliminary results generated from a robust, open source platform developed to aid in the performance evaluation of individual sensors and measurements.

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1. INTRODUCTION

In 2010, a collaborative working group across two professional institutions: the International Association of Geodesy (IAG) and the International Federation of Surveyors (FIG) was formed in response to the perceived challenges in designing and developing ubiquitous positioning systems. The challenge of delivering ubiquitous positioning capabilities has raised numerous philosophical, technical and operational questions, many of which are currently under investigation by a vast, multi-disciplinary, international research community. This working group aims to draw together these international efforts under a common umbrella project of ubiquitous positioning.

This paper outlines the current progress of this working group in providing a forum through which the outcomes of these international research initiatives can be aggregated, and used in defining a current and future research agenda towards achieving the common goal of providing a position solution wherever and whenever it is required, which is secure and trustworthy and which has an accuracy fit-for-purpose. It presents a discussion of some of the technical and philosophical issues facing the development of ubiquitous positioning capabilities as well as some of the practical outcomes achieved from two international workshops held by the working group in 2010.

1.1 Ubiquitous Positioning Systems

The definition of ubiquitous positioning has traditionally revolved around the objective "to locate people, objects, or both, anytime, whether they are indoors or outdoors or moving between the two, at predefined location accuracies, with the support of one or more location-sensing devices and associated infrastructure" (Meng et al., 2007). It is based on achieving an idealized positioning performance, modeled on the Global Positioning System (GPS) through the combination of technologies and signals that include, but are not limited to, Global Satellite Navigation Systems (GNSS), cellular and WiFi networks, Radio Frequency Identification (RFID), Ultra Wide Band (UWB), ZigBee, etc (Retscher et al., 2007; Li et al., 2008). At the international level there is no coordinated approach to the development of ubiquitous positioning systems and the associated infrastructure. This situation reflects the complexities involved in developing truly interoperable or compatible geopositioning devices that takes into account all signals of opportunity as well as developing computationally efficient measurement fusion algorithms that can undertake real-time signal processing, interference detection and measurement fusion computations. In addition, discussions surrounding broader issues of delivering a ubiquitous positioning capability are still in their infancy. These issues include: robust procedures for unification of the disparate infrastructure components; definition of best practice guidelines; classification of the different service levels

that can be provided under different operating conditions, etc.
The motivation for establishing a ubiquitous positioning capability has been driven by the increasing number of location based services (LBS) being developed for use across all sectors of society. The majority of these LBS are typically used across operational environments that cannot be serviced by a satellite positioning system only. Fundamentally reliant on a position solution for their operation, the majority of these LBS are more concerned with performance requirements other than positioning accuracy to deliver location related information. For example, an LBS delivering context aware information based on location such as reminder services ("You are in Building C"), safety notifications ("You are leaving a safe area"), emergency situation pictures ("There are five people in the house"), or triggers security applications ("Something is moving here") would be more interested in the availability of a position solution where even though the accuracy characteristics have deteriorated still enables the provision of a certain scale or granularity of information with a known certainty. What has also emerged over time is the need to consider other important positioning performance criteria, i.e. cost and complexity. The cost incurred by a positioning system can result from the sensors themselves, installation of additional infrastructure, increased bandwidth, fault tolerance and reliability etc. The complexity of the signal processing and algorithms used to estimate the location is another issue that needs to be considered, particularly with regards to the processing capacity of typical mobile positioning devices e.g. Personal Digital Assistants (PDAs). What is interesting and significant, is the trade-offs between complexity and accuracy and the overall cost of the system.

This working group aims to review the underlying philosophy of ubiquitous positioning and to address some of the known challenges to positioning in challenging environments. Some of these tasks include;

1. Redefinition of the concept of ubiquitous positioning through mapping of the relationship between users and application performance requirements
2. Development of a practical operational framework for measurement fusion based on signal availability, user performance requirements and available hardware, i.e. the signals and processing algorithms used can be selected and designed 'on-the-fly' to fit the application requirements.
3. Provision of performance and benchmarking data for use in characterizing signals from some of the alternative sensors available for positioning in challenging environments.

2.0 POSITIONING REQUIREMENTS OF LOCATION BASED SERVICES

To build context aware LBS it is necessary to understand the relationships that exist between the characteristics of the location expressions generated or required by LBS and those of the technologies and tools used to generate the coordinates that underpin them. A study has been initiated to develop a taxonomy that facilitates an understanding of these relationships.

Table 1 shows a listing of sample responses (location expressions) that users of LBS can expect to receive from typical queries. All of these expressions refer to the same position.

LOCATION EXPRESSIONS
• 20 Grattan Street, Parkville, Vic, 3010
• Near the Royal Women's Hospital
• In my office
• In the Engineering building
• In Melbourne
• 320438E 5814397S
• ~ 500m from the Melbourne shopping precinct
• North of the CBD
• Entering a parking restricted area
• In an allowed area

Table 1. LBS location expressions

The expressions in Table 1 can be classified according to the characteristics of the expression itself and those of the mechanisms used to generate that information. Figure 1 shows the taxonomy developed and used in this study which is based around this classification. Whilst it is accepted in this study that there are obvious relationships that exist between attributes of the location information and the characteristics of how it was generated (e.g., the accuracy of the location sensor directly affects the accuracy of the location expression), this study aims to determine whether any other relationships can be established across the taxonomy.

2.1 Characteristics of Location Information: Definitions

1. *Spatial referencing*. An absolute spatial reference as one in which objects have specific coordinates, e.g., x,y,z or are positioned as a metric offset from a fixed reference system. Absolute reference systems may be local or global and typically describe the unique location of an object. Relative location can be described as the position of an object relative to an arbitrary location mark using orientation, distance or topological relationships. For LBS, this location mark may be a land mark ('in front of the church') or the mobile users themselves ('after three hundred meters turn left'). For example, the location expression 320438E 5814397S is absolute, however the same point expressed as 'in the Engineering building' is relative.
2. *Granularity*. Granularity refers to the spatial scale of a location expression. Montello (1993) provides definitions of four classes of location granularity based on the projective size of the space relative to the user. "*Figural* space is projectively smaller than the body; its properties may be directly perceived from one place without appreciable locomotion. *Vista* space is projectively as large or larger than the body but can be visually apprehended from a single place without appreciable locomotion. *Environmental* space is projectively larger than the body and surrounds it. It is in fact too large and otherwise obscured to apprehend directly without considerable locomotion. *Geographical* space is projectively much larger than the body and cannot be apprehended directly through locomotion; rather, it must be learned via symbolic representations such as maps or models that essentially reduce the geographical space to figural space." For example, location expressions such as 'in my office' can be classed as vista and 'in Melbourne' can be classed as environmental.
3. *Accuracy*. Accuracy is defined as a measure of how close the location expression is to

the true location of the object. This may be a quantitative value determined from a numerical analysis or it may be qualitative based on its fitness for use in the application or on the qualitative aspects of non-spatial data sets used in generating the location expression. For example, the accuracy required for an in-car navigation system can be described as ±5m representing the quantitative accuracy of a GPS position, this can also be described as 'low' representing the qualitative accuracy requirements for in-car navigation systems.

4. *Useability*. Three classes of usability are described that can apply to LBS:
   Understandability. The capability of LBS to enable the user to understand how it can be used for particular tasks and conditions of use.
   Learnability. The capability of LBS to enable the user to learn its application.
   Operability. The capability of LBS to enable the user to operate and control it.

2.2 Characteristics of Location Information Generation: Definitions

1. *Availability*. Availability can be defined both spatially and temporally. Temporally it is defined as the percentage of time that a position solution can be computed by the positioning sensor or technology. Depending on the application, availability is also a function of the positioning accuracy and can be defined as the percentage of time that a positioning solution can be computed to the specified accuracy required for the application. Spatially it refers to the coverage provided in terms of point locations or regions. For example, a GPS receiver can provide continuous positioning at a specified accuracy across a region when sufficient satellites are available over a region. GPS positioning becomes unavailable when operating in an indoor environment.
2. *Activation*. Two activation modes exist for LBS and are typically based on the level of user interaction. An explicit activation requires the user to provide some input to retrieve information, e.g., requesting route directions to a specific location from an in-car navigation system. An implicit activation is one in which the user provides no input but information specific to their location is provided, e.g., 'you were caught speeding here'.
3. *Source*. Source refers to the methods for capturing or deriving location information. The information can be sensed directly, e.g., a user provides address details to emergency services or a GPS receiver measures the user's position. Alternatively, position information can be derived from a fusion of measurements or technologies including other sensors, user knowledge, logical constraints or existing data. For example LBS that require high availability of location information could integrate GPS/WiFi/Cell ID to position seamlessly in indoor/outdoor environments.

Within this study, the relationship between the source of information generation and the attributes of the location information is of particular interest and a number of practical experiments are under investigation to further study this relationship.

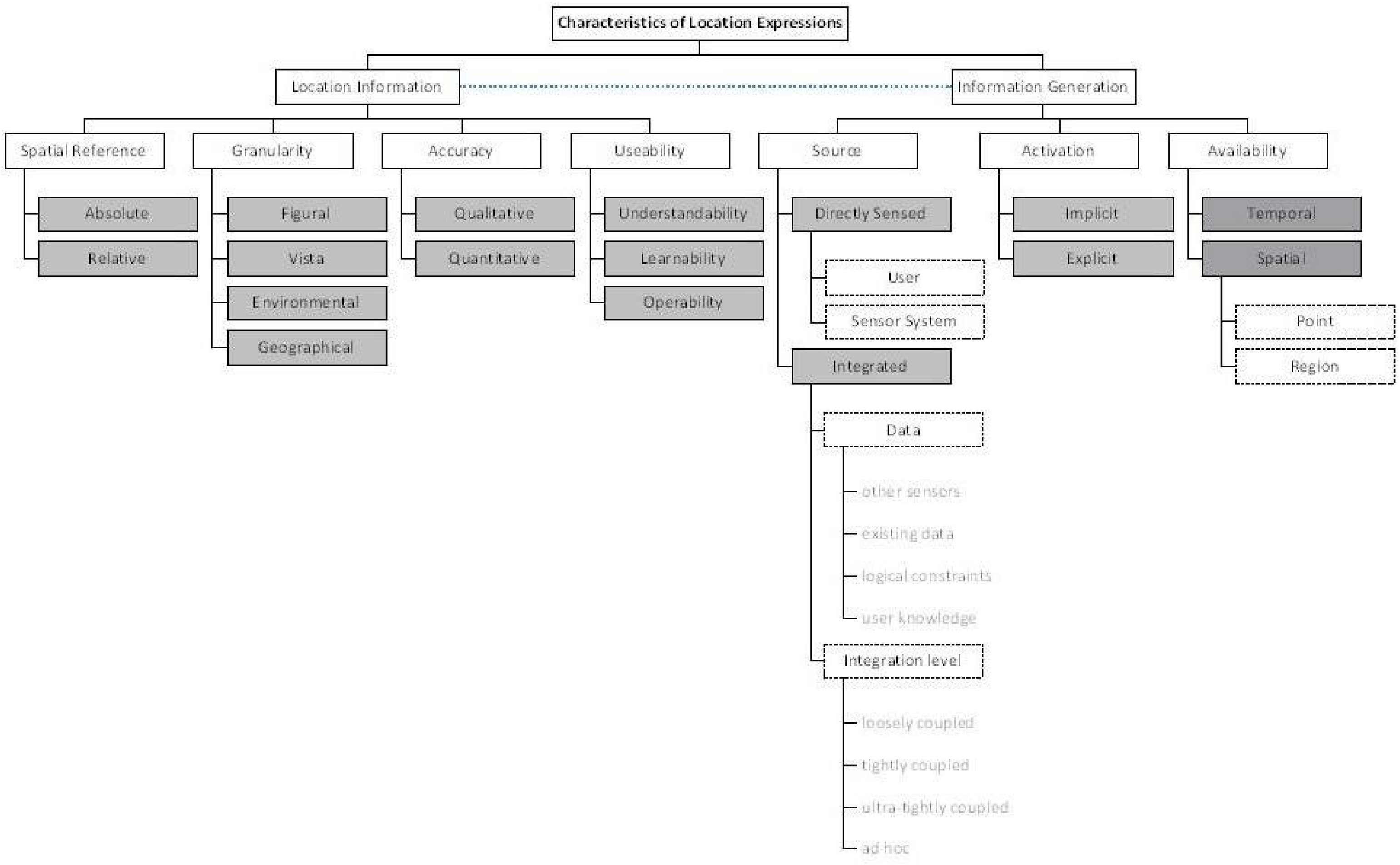


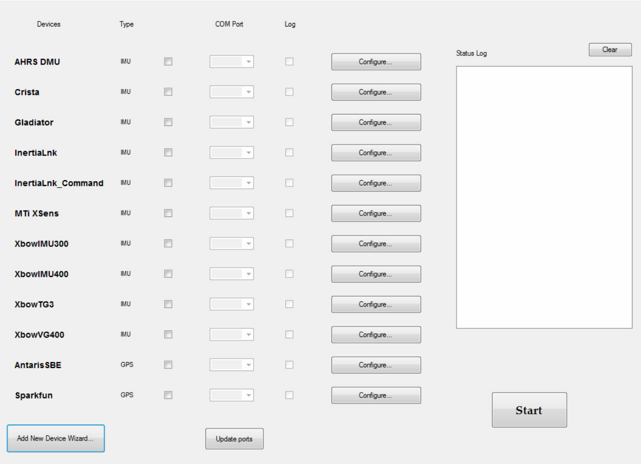
Figure 1. Taxonomy describing the characteristics of location expressions

3.0 WORKING GROUP ACTIVITIES IN SUPPORT OF UBIQUITOUS POSITIONING

In 2010, the FIG working group WG5.5 collaborative with IAG working group 4.2.5 – Ubiquitous Positioning - held two international workshops. These workshops kicked off a longer term practical study into understanding the signals used in ubiquitous positioning systems. Low-cost MEMS inertial navigation sensors (INS) were the focus of these tests. With the overall aim of characterizing the operational environment for mobile users (using a range of low-cost MEMS INS) the first workshop was held at the University of Nottingham. The second workshop was held at the Ohio State University with the aim of acquiring benchmarking datasets for GNSS/INS systems that could be used by the broader research community. This section presents the outcomes of these two workshops.

3.1 Time Synchronization of GNSS and MEMS Inertial Navigation Sensors

To evaluate the performance of low-cost MEMS INS within the context of bridging GPS outages and maintaining the availability of a position solution, a time synchronisation software package has been developed as a generic data capture platform for ubiquitous positioning, and allows for the addition of new sensors by simply configuring a few parameters describing the communications interface, data output format, field descriptions and data conversion factors. The program uses the GPS pulse per second (PPS) when it is available to synchronize the incoming data while native kernel32 is used between GPS time updates. Fig. 1 shows a screen shot of the data capture software developed and used to synchronize the MEMS INS data with the GPS 1PPS output from the GPS receiver.



Devices	Type		COM Port	Log	
AHRS DMU	IMU	☐		☐	Configure...
Crista	IMU	☐		☐	Configure...
Gladiator	IMU	☐		☐	Configure...
InertiaLnk	IMU	☐		☐	Configure...
InertiaLnk_Command	IMU	☐		☐	Configure...
MTi XSens	IMU	☐		☐	Configure...
XbowIMU300	IMU	☐		☐	Configure...
XbowIMU400	IMU	☐		☐	Configure...
XbowTG3	IMU	☐		☐	Configure...
XbowVG400	IMU	☐		☐	Configure...
AntarisSBE	GPS	☐		☐	Configure...
Sparkfun	GPS	☐		☐	Configure...

Figure 1. GNSS/INS time synchronization software interface

3.2 Qualitative Information Derived from MEMS Sensors

To demonstrate the potential for extracting useful, qualitative information from the measurements made by MEMS INS, a field study was conducted on the University of Nottingham campus to simulate a typical mobile operational environment. A mobile platform was fitted with an array of four commercially available MEMS INS, one high performance navigation grade INS integrated with a high performance, dual frequency GNSS receiver and an additional high sensitivity, single frequency GPS receiver. The MEMS sensors represent current state of the art in low-cost, low profile INS and the high performance integrated GNSS/INS was used to provide the ‘truth’ against which the MEMS solutions could be evaluated. The route navigated covered an indoor/outdoor trajectory, covering a distance of ~0.3km over a ten minute time period.

In Figure 2 some of the qualitative information describing the GNSS positions (obtained from the high accuracy Applanix GPS/INS system) comes from evaluating the satellite availability information as well as the horizontal dilution of precision (HDOP) figures.

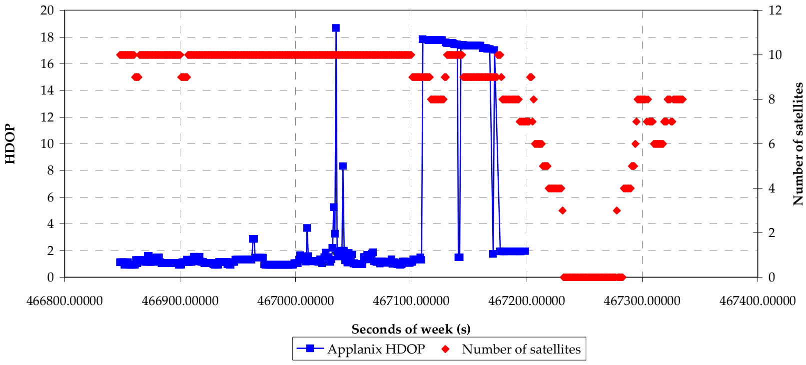


Figure 2. GNSS satellite availability and HDOP

At approximately time 467100, the GNSS receiver experiences very poor HDOP, recovers at around time 467180 for a short time and then 20 time instances later loses its position altogether for the rest of the test. What should be noted is that although this receiver appeared to continue to output valid position solutions, it is during these times that the largest trajectory outliers are experienced. This situation in shown in Figure 3 where, as the platform enters the building at point *A*, the blue trajectory drifts linearly away from the building. We propose to use this deterioration in satellite geometry as an indicator of a change in the platform state, that is, when correlated with the map base indicates that the user has entered a building. When this indicator is received, the positioning algorithm automatically changes its weighting to favor the measurements of the inertial sensors and more specifically the qualitative information derived from the inertial measurements.

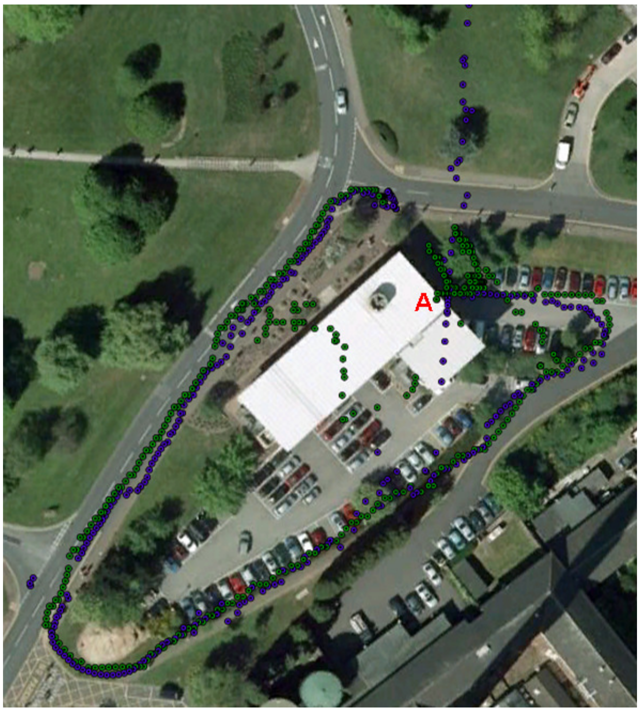


Figure 3. GNSS position solutions

Figure 4 shows the raw accelerations and angular rates measured by one of the MEMS INS used in these tests, the Crista^{TM} INS along the *x*-, *y*- and *z*-axes. Whilst the absolute measurements themselves deviate significantly from the 'true' navigation grade INS values (shown in Figure 5), patterns of movement can still be detected, for example when the platform is moving or stopped. To assist the measurement fusion process a set of qualitative rules have been established based on identified navigation patterns in the data. Table 2 presents a sample of the kinds of rules that can be generated from this data.

Further work will investigate the benefits to positioning that can be derived from integrating these qualitative 'measurements' into the measurement fusion process.

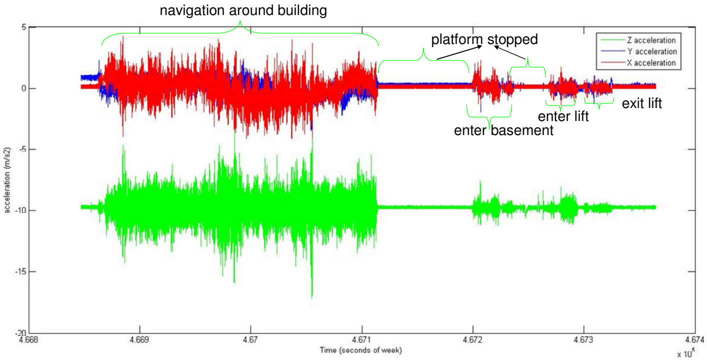


Figure 4. Crista MEMS INS measurements

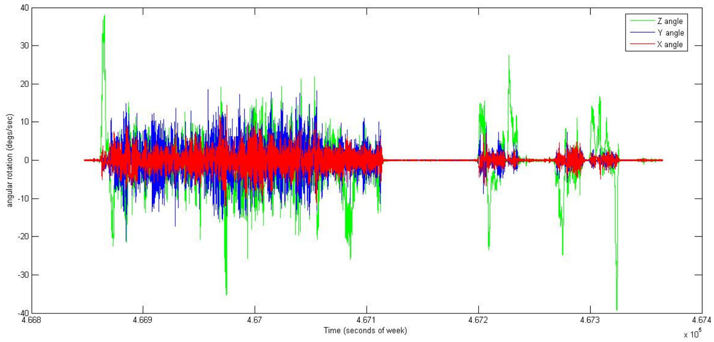


Figure 5. ‘True’ measurement information from navigation grade INS

Time	Qualitative information detected	Information provided to user
467110	Poor GPS HDOP/change in satellite visibility. INS detects no motion	You have stopped outside the Institute of Engineering Science and Space Geodesy (IESSG)
467220	No satellites available and building in close proximity	You are in the basement of the IESSG building
467300	Only Z acceleration detected and lift close by	You are in the lift of the IESSG building
467305	Sharp heading change	Exiting lift on second floor of IESSG building

Table 2. Derived qualitative information from MEMS INS measurements

3.3 Generating MEMS INS Benchmarking datasets

The aim of this workshop was to generate representative datasets that could be used in benchmarking the performance of MEMS INS as well as providing a data resource for the research community involved in the development of GPS/INS sensor fusion algorithms. Figure 6 shows the schematics of the equipment used in the data collection tests at the Ohio State University. A range of MEMS INS with small variations in the manufacturer performance specifications and a navigation grade INS were used in these tests. The axes of these INS were aligned with the vehicle's body axis. All of the INS x axes were aligned with the vehicle's body forward axis, y axes to the right axis and z axes to the down axis, with the exception of the Crista, where its y axis was aligned to the vehicle's body left axis. This was later corrected during data processing.

Lever arm offsets were measured during data collection, where all of the INS positions were referenced to the main GPS antenna. For these tests, the inertial sensors were mounted on a test vehicle and their relative positions accurately surveyed. To provide comprehensive datasets to support further research in this area the trajectories navigated were designed to have both low and medium dynamics in terms of velocity and turning rate profiles, depicting typical land based vehicle dynamics. A sample of these datasets in presented in Figure 6. This trajectory covered approximately 7.4 kilometres in approximately 22 minutes. The trajectory was designed with a static phase in the first 2 minutes followed by a dynamic phase lasting 15 minutes with a short 2 minutes static phase in the middle. Another static phase was introduced at the end of the trajectory, lasting another 2 minutes. Velocities along the trajectory varied from 0 to 84 km/h.

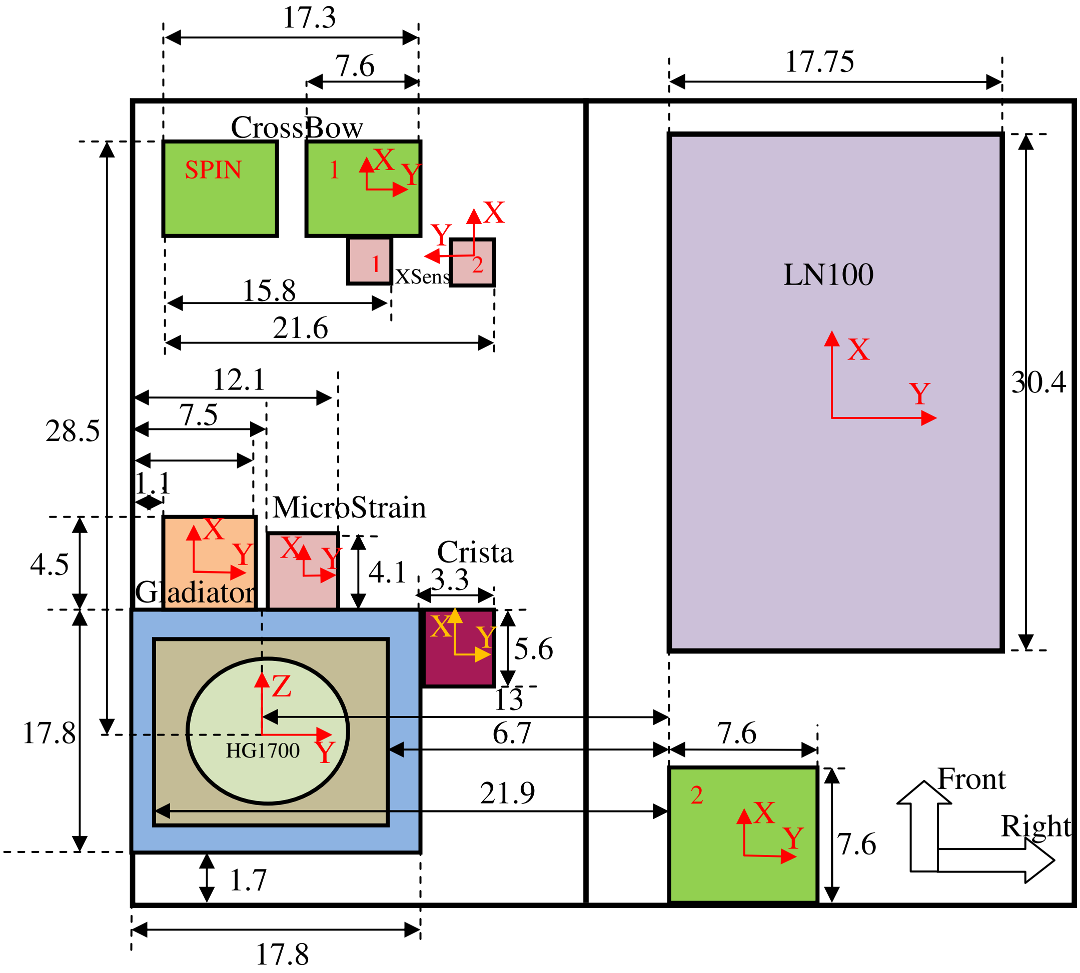


Figure 6. Sensor schematics for data benchmarking tests

Further work will focus on analyzing each of these datasets to characterize the performance characteristics of each of the MEMS sensors under different navigation conditions. In the first instance this would be to simply compare the measurements from the MEMS sensors to the high accuracy navigation grade INS as shown in Figure 8. More detailed signal characterization tests will form part of the working group's study into the development of robust sensor fusion algorithms. In addition, these datasets will form part of an advanced study into the design of more accurate and representative models of land vehicle dynamics which will again form part of the measurement fusion process. The datasets collected and all associated information are freely available to the broader FIG/IAG research community.

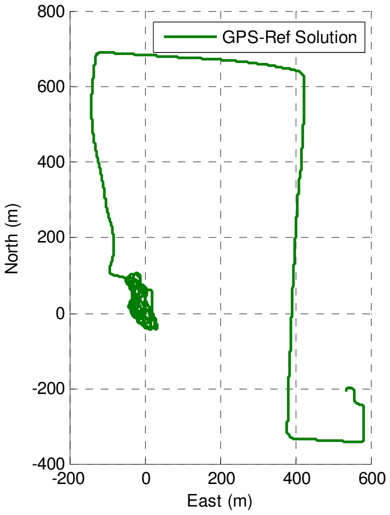


Figure 7. Sample navigation trajectory

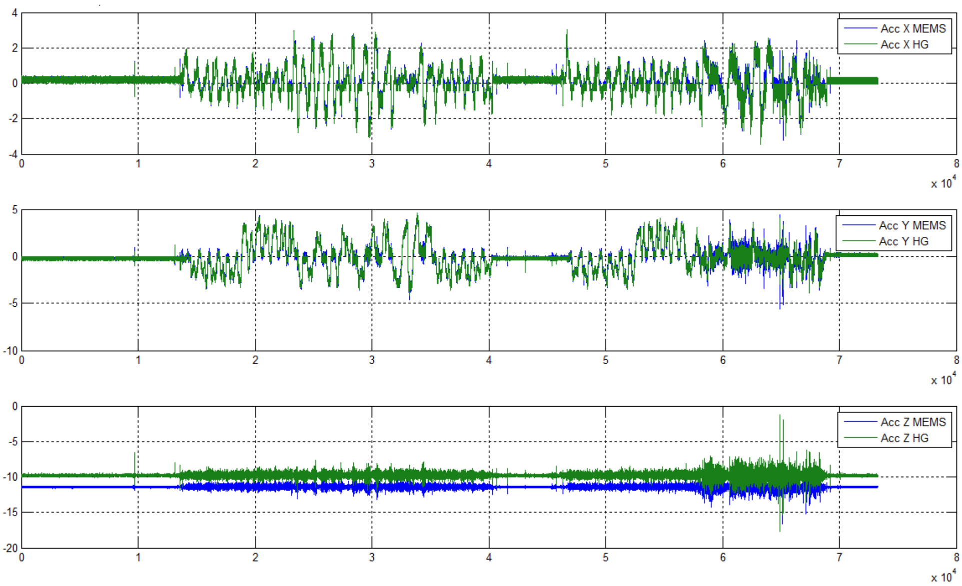


Figure 8. Sample measurement comparison of the MEMS Crista INS with the navigation grade INS.

4.0 CONCLUSION & FUTURE DEVELOPMENTS

A collaborative FIG/IAG working group has been established with the goal of addressing the challenges to establishing a ubiquitous positioning capability. The focus to date has been on redefining the concept of ubiquitous positioning in the evolving landscape of competing performance requirements for current and next generation LBS. Current activities have centered on the development of datasets for use by the broader research community for benchmarking and algorithm development activities. Future work will focus on a broader assessment of alternative positioning signals as well as an analysis of the infrastructure components required for ubiquitous positioning and procedures for its unification and management.

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BIOGRAPHICAL NOTES

Dr Allison Kealy is a senior lecturer in The Department of Infrastructure Engineering at The University of Melbourne Australia. She holds an undergraduate degree in Land Surveying from The University of the West Indies, Trinidad, and a PhD in GPS and Geodesy from the University of Newcastle upon Tyne, UK. Allison’s research interests include sensor fusion, Kalman filtering, high precision satellite positioning, GNSS quality control, wireless sensor networks and location based services. Allison is currently the co-chair of FIG Working Group 5.5 entitled Ubiquitous Positioning which is coordinated collaboratively with IAG Working Group 4.2.5.

Charles K. Toth is a Senior Research Scientist at the Ohio State University Center for Mapping. He received an M.S. in Electrical Engineering and a Ph.D. in Electrical Engineering and Geo-Information Sciences from the Technical University of Budapest, Hungary. His research expertise covers broad areas of 2D/3D signal processing, spatial information systems, high-resolution imaging, surface extraction, modeling, integrating and calibrating of multi-sensor systems, multi-sensor geospatial data acquisition systems, and mobile mapping technology. He is Chairing ISPRS WG I/2 on LiDAR and InSAR Systems and serves as the Director for the Photogrammetric Application Division of ASPRS.

Dorota A. Grejner-Brzezinska is a Professor in Geodetic Science, and director of the Satellite Positioning and Inertial Navigation (SPIN) Laboratory at The Ohio State University. Her research interests cover GPS/GNSS algorithms, in particular, high precision positioning and navigation, such as DGPS and RTK, GPS/inertial and other sensor integration for navigation in challenged environments, sensors and algorithms for indoor and personal navigation, Kalman filter and non-linear filtering. She published over 180 peer reviewed journal and proceedings papers, numerous technical reports and five book chapters on GPS and navigation, and led over 20 sponsored research projects. She is ION Fellow, and the recipient of the 2005 ION Thomas Thurlow Award, the 2005 United States Geospatial Information Foundation (USGIF) Academic Research Award, and ESRI Award for Best Scientific Paper in Geographic Information Systems published in 2004.

Vassilis Gikas received the Diploma degree in Surveying Engineering from the National Technical University of Athens, Greece and the Ph.D. degree in Kalman filtering and Geodesy from the University of Newcastle upon Tyne, UK in 1992 and 1996, respectively. He is currently an Assistant Professor with the School of Rural and Surveying Engineering at the National Technical University of Athens, Greece. In the past (1996-2001) he served the offshore and land seismic industry in the UK and the USA and more recently (2001-2005) the private sector in a series of surveying and transportation engineering projects. His principal areas of research include engineering surveying for structural deformation monitoring and analysis and sensor fusion and Kalman filtering for mobile mapping applications.

Guenther Retscher is Associate Professor at the Institute of Geodesy and Geophysics of the Vienna University of Technology, Austria. He received his Venia Docendi in the field of ‘Applied Geodesy’ from the same university in 2009 and his Ph.D. in 1995. His main research and teaching interests are in the fields of engineering geodesy, satellite positioning and navigation, indoor and pedestrian positioning as well as application of multi-sensor systems in geodesy and navigation. Guenther chairs the IAG Sub-Commission 4.2 ‘Applications of Geodesy in Engineering’ and the working group WG 4.1.2 on ‘Indoor Navigation Systems’ under Sub-Commission 4.1. He is also co-chair of the collaborative FIG WG 5.5 ‘Ubiquitous Positioning Technologies and Techniques’ with IAG. He has published more than 100 journal and conference papers.

Gethin Wyn Roberts is Professor of Geospatial Engineering and Dean of the Faculty of Science and Engineering at the University of Nottingham Ningbo, China. He is the Chair of FIG’s Commission 6 “Engineering Surveys”, a Fellow of the Chartered Institution of Civil Engineering Surveyors.

CONTACTS

Dr. Allison Kealy
Department of Infrastructure Engineering
University of Melbourne
Melbourne, AUSTRALIA
Email: a.kealy@unimelb.edu.au

Dr. Charles Toth
Center for Mapping
The Ohio State University
Columbus, OH, USA
E-mail: toth@cfm.ohio-state.edu

Professor Dorota Grejner-Brzezinska
Center for Mapping
The Ohio State University
Columbus, OH, USA
E-mail: dbrzezinska@osu.edu

Dr Guenther Retscher
Vienna University of Technology
Institute of Geodesy and Geophysics
Engineering Geodesy
Vienna, Austria
Email: gretsch@pop.tuwien.ac.at

Vassilis Gikas
School of Rural and Surveying Engineering
National Technical University
Athens, Greece
Email: vgikas@central.ntua.gr

Gethin Roberts
The University of Nottingham,
Ningbo, China
Email: gethin.roberts@nottingham.edu.cn