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EVALUATING THE PERFORMANCE OF MEMS BASED INERTIAL NAVIGATION SENSORS FOR LAND MOBILE APPLICATIONS

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ABSTRACT: In 2010 a collaborative working group was formed under the professional associations: International Association of Geodesy (IAG WG4.2.5) and International Federation of Surveys (FIG WG5.5). Entitled ubiquitous positioning, this working group aims to harness and develop existing research outputs available internationally in this research domain. Our goal over the next four years is to provide an online resource for academic and industry professionals, who can use these research outputs thereby reducing duplication and facilitating more rapid progress in the development of ubiquitous positioning systems. This paper presents a summary of the research activities and results of the working group to date. In particular, it presents the results of extensive testing to characterise the performance of a range of low-cost MEMS inertial sensors. The test scenarios, data acquisition software, processing tools and results obtained will be fully described and presented. The performance of these sensors in augmenting GNSS positioning is also presented using results obtained from a combination of loosely and tightly coupled Kalman filters. Finally, the future plans for the working group over the next four years and opportunities for wider collaboration will be discussed.

1. INTRODUCTION

The increasing reliance of society on positioning information to support the delivery of critical services such as transportation, banking etc combined with a rapidly growing consumer market for location based products and services have established new drivers for the development of ubiquitous positioning systems. Specifically, the expectation today of a ubiquitous positioning system is that it mirrors the performance capabilities of Global Navigation Satellite System (GNSS) in the most difficult operational environments e.g. in buildings, forests etc.

Many of the approaches to delivering a positioning solution in these difficult environments have in the past revolved around augmenting the core GNSS receiver with a variety of complementary sensors including traditional inertial navigation sensors (INS), and more recently with signals available from a wide variety of non-traditional sensors including wireless local area networks (Wi-Fi), Radio Frequency Identification Tags (RFiD) etc. This approach is broadly applicable for applications where the performance requirements outweigh the cost implications i.e. high accuracy and reliability applications typically use expensive hardware which can support the heavy signal processing and computational overheads required of standard ubiquitous positioning systems. In addition, the use of costly, high performing augmentation sensors can be absorbed in the overall system costs for these applications. The emergence of consumer grade devices that support positioning are now demanding similar levels of performance not necessarily in terms of accuracy but in terms of solution availability and reliability. Unfortunately, the typical consumer grade platform is unable to maintain a balance between performance and cost and consequently the delivery of a ubiquitous positioning capability cannot be delivered using these traditional approaches. Interestingly, perhaps, the traditional definition of ubiquitous positioning i.e. positioning everywhere using all available signals and sensors, can be reconsidered in the face of how these consumer applications work as well making use of the inherent qualitative intelligence captured by individual sensors

In 2010, a collaborative working group was formed under the professional associations: International Association of Geodesy (IAG WG4.2.5) and International Federation of Surveyors (FIG WG5.5). The intention of this group is to develop the foundations – theory, algorithms and tools that support the delivery of a ubiquitous positioning capability. This paper presents a summary of the research activities and results of the working group to date. In particular, the following outputs have been generated through the activities of the working group.

1. An open source time synchronisation platform for sensor integration.
2. Representative datasets for use in characterizing the performance of a range of MEMS, low-cost inertial sensors.
3. Simple sensor fusion algorithms based around Kalman filtering for evaluating the potential of MEMS INS to perform as part of a GPS/INS integrated positioning system

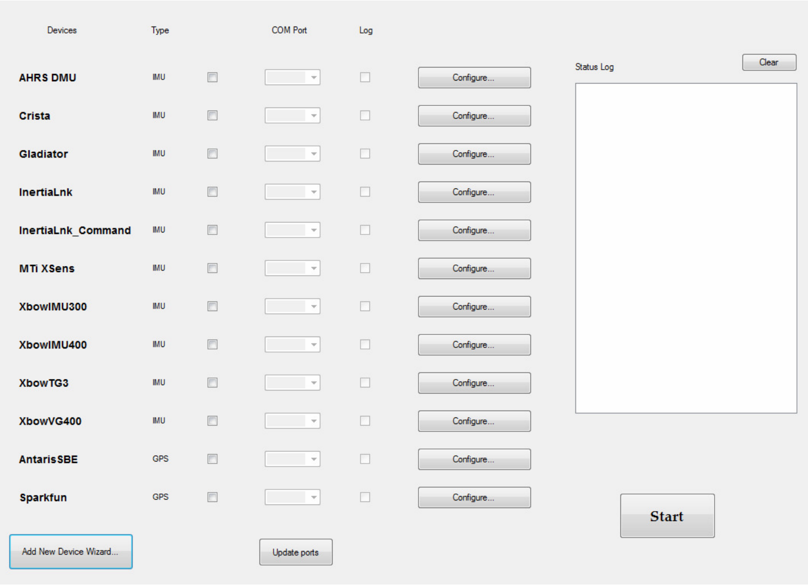
2. DATA ACQUISITION SOFTWARE FOR SENSOR FUSION

An important component of developing algorithms for sensor fusion is the availability of tools that can robustly collect, synchronize and process the disparate measurements made. As part of the working group activities, an open source software package called the ‘Universal Datalogger’ was developed to enable data from a range of sensors to be captured through simple inputs and data characterization.

2.1 Universal Datalogger

In its current form the Universal Datalogger is able collect data from INS, GPS (NMEA format) and fundamentally any sensor with a serial output stream. It can handle both binary and ASCII data formats. When GPS is available, its time and Pulse-Per-Second (PPS) are used to accurately synchronize incoming data, while native kernel32 is used to time-stamp the incoming INS measurements between GPS time updates. The Kernel32 has an accuracy of sub millisecond and resolution of 1 millisecond, making it suitable to accommodate high rate INS updates. To ensure the integrity of incoming data, the checksum function is included where its method is dependent on individual manufacturer's configuration. The Universal datalogger developed here was used to capture the data presented in this paper.

The Universal datalogger was designed to reduce the complexities involved in communicating with different sensors. The future intention of the working group is to develop it as a generic software tool that can capture data from all available signals so that it provides the data resources that can facilitate the development of robust integration algorithms as well as characterisation of the inherent measurement errors and biases.



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...

Fig. 1. Software interface for time synchronisation of inertial sensors

3. MEMS PERFORMANCE DATA

Six MEMS based INS have been evaluated in this research. These INS commercially available and represent the state of the art currently for low-cost, MEMS INS. Table 1 provides some basic information for each of these sensors. These INS consist of tri-axial accelerometers, tri-axial gyroscopes, temperature sensors and on-board processors. In addition, the InertiaLink and MTi contain tri-axial magnetometers. Further information can be found in (Cloud Cap Technology, 2006; Crossbow Technology, 2007, 2005; Xsens Technologies B.V., 2006; MicroStrain Inc., 2007; Gladiator Technology Inc., 2007). The measurements recorded for the analysis are fully calibrated for sensor misalignment, gyro G-sensitivity and gyro scale factor non-linearity and are temperature compensated. This is to ensure the outputs are optimized as recommended by the manufacturers.

Tab. 1. MEMS INS Characteristics

MEMS IMU	Cost		Range	U.R.	Bias Stability	Noise
Size(WxLxH)mm	USD	axis	g, °	Hz	$\frac{m}{s^2}$, $\frac{\circ}{s}$	$\frac{m/s^2/}{\sqrt{Hz}}$, $\frac{\circ/s/}{\sqrt{Hz}}$
InertiaLink 3DM-GX2	$\sim$ 2000	Acc	5	100	0.098	-
41 x 63 x 24		Gyro	300	100	0.200	-
Xsens MTi	$\sim$ 2100	Acc	1.7	100	0.020	0.002
58 x 58 x 22		Gyro	300	100	1.000	0.100
Crista IMU	$\sim$ 2000	Acc	10	100	0.245	0.120
52 x 39 x 25		Gyro	300	100	0.200	0.700
Gladiator LMRK10	$\sim$ 2500	Acc	1.7	200	0.029	0.005
50 x 45 x 30		Gyro	300	200	0.028	0.100
Xbow VG 400 CB	$\sim$ 10000	Acc	4	75	-	0.017
76 x 95 x 81		Gyro	100	75	-	0.0375
Xbow IMU 400 CD	$\sim$ 10000	Acc	4	100	-	0.017
76 x 95 x 81		Gyro	100	100	-	0.0375

3.1 Test Scenarios

Firstly, twelve hours of static data was collected simultaneously from each of the MEMS sensors to determine its stochastic error properties. An Allan Variance analysis was used to evaluate the data. Figure 2 shows the configuration used for these tests. Allan Variance allows for the identification of five stochastic errors that are inherent in inertial sensors, namely quantization noise, random walk, bias instability, rate random walk and rate ramp.

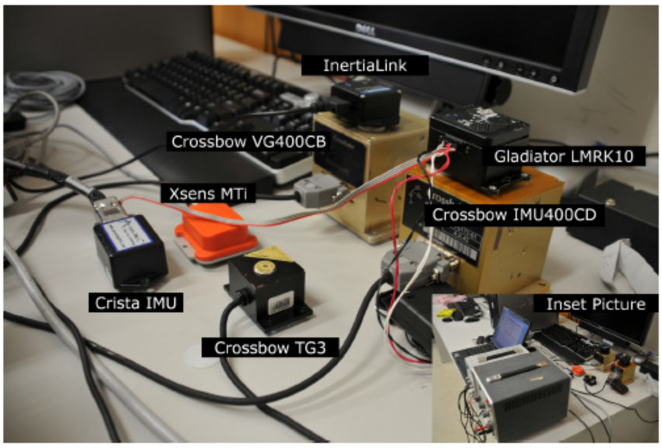


Fig. 2. MEMS Static Testing

Random noise or stochastic error in inertial sensors is caused by a number of sources. One of these is electrical noise which limits the resolution of inertial sensors. It is also caused by mechanical instabilities and vibrations such as in pendulous accelerometers and spinning mass gyros. Random noise, when integrated causes velocity and angle random walk.

Secondly, two datasets were used to analyse the performance of the MEMS sensors when used as part of an integrated INS/GNSS positioning system. The first dataset was collected near the vicinity of The Ohio State University, in Ohio, United States (Test 1) while the second dataset was collected in the Albert Park Drive, in Melbourne, Australia (Test 2).

Figure 3 shows the hardware schematics for Test 1. A similar configuration was used for Test 2. The INS axes were aligned to the vehicle's body axis. All of the INS x axes were aligned to 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 through data processing.

Lever arm offsets were considered during data collection, where all of the INS positions were referenced to the main GPS antenna. For Test 1, the INS were deployed in a test van, where the INS placements were accurately surveyed using total stations. For Test 2 however, INS were rigidly screwed to a wooden board and placed at the back seat of the test car. The separations between INS and main GPS antenna were then surveyed using photogrammetric technique. Both GPS antennas were placed on the vehicle's rooftop for both Test 1 and 2 to ensure direct line of sight with GPS satellites could be achieved.

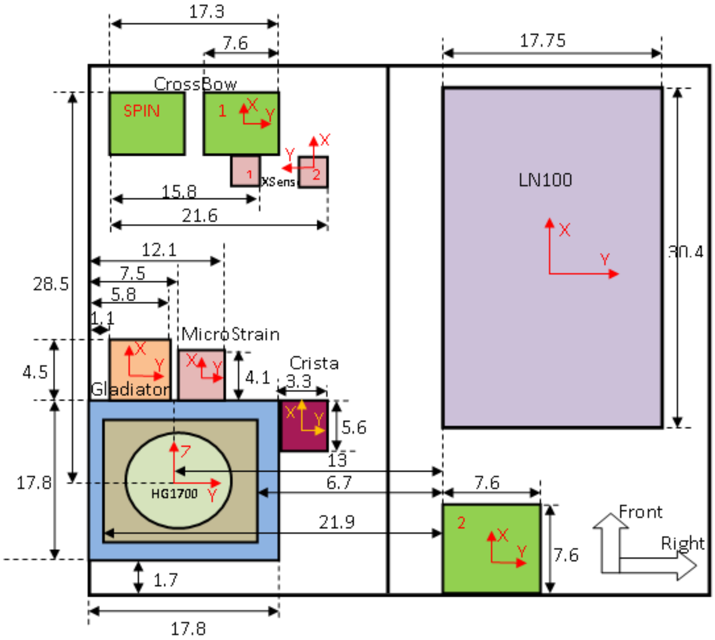


Fig. 3. D1 Hardware Schematics

The total time span for Test 1 (Figure 4) was 22 minutes, covering a distance of approximately 7.4km. The trajectory consisted of a static test conducted in the first 2 minutes followed by a kinematic test lasting 15 minutes with a short 2 minutes static test in between. Another static test was conducted at the end of the trajectory, lasting another 2 minutes. Velocities along the trajectory varied from 0 reaching up to 84 km/h.

The total time span for Test 2 (Figure 5) was 20 minutes, covering approximately 5.4km. Velocities along the trajectory varied from 0 to 54 km/h with an average of 40 km/h. This site was chosen primarily for its road dynamics, where it has a combination of both low and medium speed corners in addition to considerable length of straight path. As this track has been specifically designed for Formula 1 racetrack driving, unlike other major roads, the track on this course is relatively smooth and continuous, thus making it a suitable location for the INS/GPS kinematic test.

Figures 4 and 5 show the trajectories as described by the post processed, dual frequency GPS solution. This solution was used as the 'truth' against which the GPS/INS solutions generated from these tests could be evaluated.

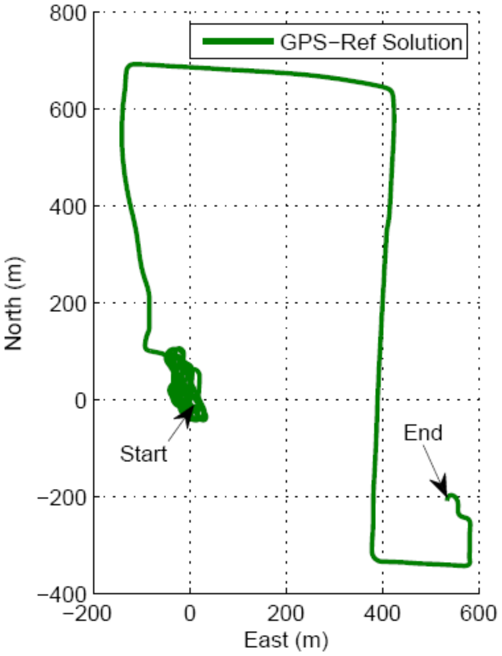


Fig. 4. Test 1Trajectory

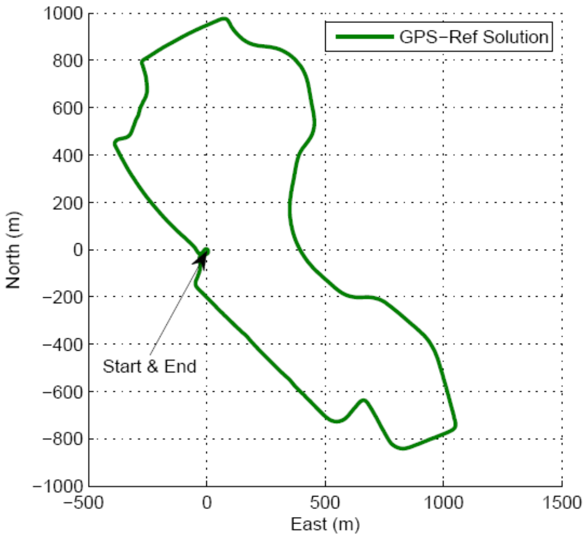


Fig. 5. Test 2 Trajectory

3.2 Results

The results of the Allan Variance analysis shows that the identified random errors for the inertial sensors tested are mostly within the parameters provided by manufacturers. For almost all of the sensors, it can be concluded that the dominating stochastic errors are velocity/angle random walk and bias instability. Rate random walk is only observed in some inertial sensors such as Xbow VG and Crista IMU. None of the inertial sensors exhibit quantization noise and rate ramp characteristics. This is likely due to the angle and velocity random walk noise masking the quantization noise.

Figure 6 shows the overall comparison of the MEMS inertial sensors velocity and angle random walk coefficients derived from the Allan Variance Analysis. Note that the performance of an inertial sensor is better when its noise coefficient is smaller.

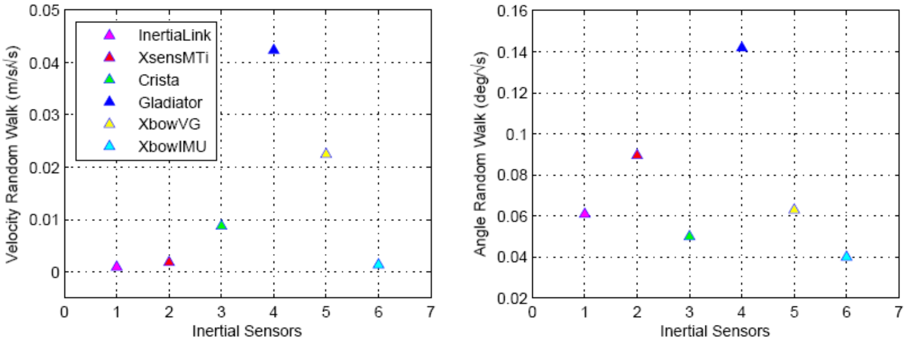


Fig. 6. MEMS INS Noise Characteristics

From Figure 6, it can be seen that the InertiaLink has the best accelerometer performance as its noise coefficient is the lowest, followed by XbowIMU, Xsens MTi, CristaIMU, Xbow VG and lastly, Gladiator LMRK10. In Figure 6, the XbowVG is observed as having the best gyroscope performance followed by Xbow IMU, CristaIMU, InertiaLink, Xsens MTi and finally, Gladiator LMRK10. Based on the analysis performed on the six inertial sensors, it is concluded that the overall best performance among all six sensors is the XbowIMU and the overall worst performance is the Gladiator LMRK10.

A loosely coupled GPS/INS Kalman filter was then used to evaluate the performance of the MEMS INS when used as part of an integrated positioning system. Figure 7 shows a comparison of the RMS errors derived from each of the GPS INS integrations for Test 1 when compared to only the GPS standard point position (SPP) solution. This graph shows the compares the GPS/INS positions and those of the GPS SPP to the dual frequency, carrier phase post processed reference solution. The results show that not all INS/GPS solution provided better accuracy than GPS-SPP. For example, only the XbowIMU and XbowVG provided slightly more accurate results in 2D and 3D while Crista and Xsens have improved accuracies in 3D only over GPS-SPP. In terms of maximum error, none of the 2D INS/GPS maximum error is lower than GPS-SPP maximum error. In 3D however, Crista, XbowIMU and XbowVG managed to produce slightly lower maximum error compared to GPS-SPP, thus a slight accuracy improvement in order of a few centimeters. Similar results were obtained for Test 2 and for conciseness only the results of Test 1 are presented here.

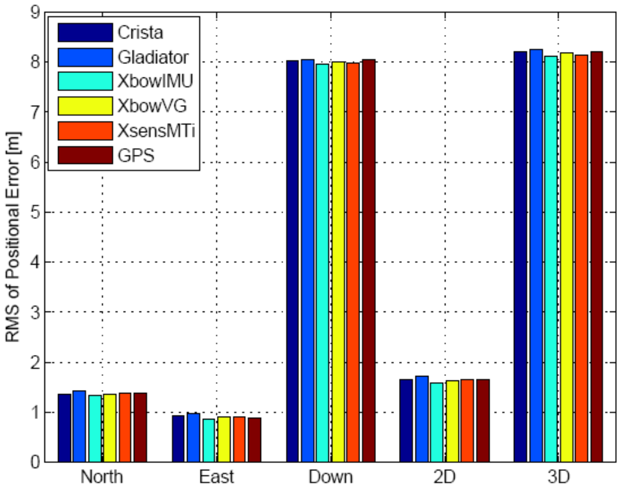


Fig. 7. Results of Loosely Coupled GPS/INS Integration for Test 1

Whilst this performance indicates very little improvement of the GPS SPP solution, it is the performance of the GPS/INS during periods of GPS unavailability that is significant. Three outages were simulated for Test 1, as shown in Figure 8. The partial outages are simulated in order to investigate the capabilities of INS/GPS using a tightly coupled integration architecture which enables GPS aiding even when the number of satellites available is below four. This in turn will result in limiting the error growth, thus providing better positioning solution than the loosely coupled solution.

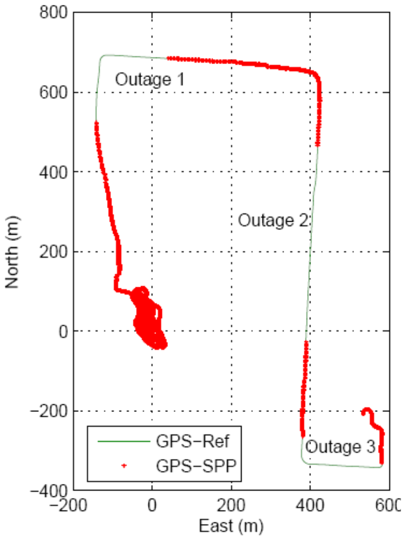


Fig. 8. Simulated Outages for Test 1

Firstly, Figure 9 shows the results obtained for the inertial sensors under full satellite availability but using a tightly coupled integration architecture. In Figure 9, the improvements of the integrated solution in almost all components, proves that INS/GPS integration using the tightly coupled architecture is able to produce superior results than when using loosely architecture. This is mainly attributed to both the INS and GPS being processed in a single KF, as well as better handling of the correlations in the satellite measurements.

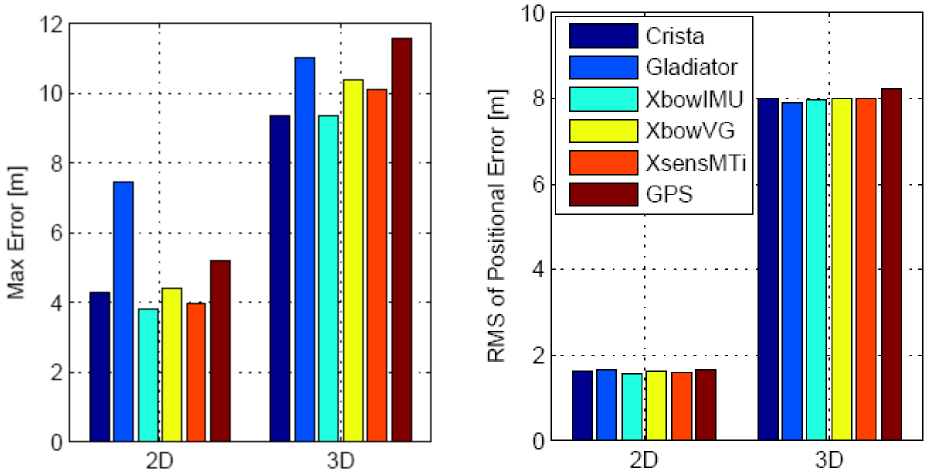


Fig. 9. Results of Tightly Coupled GPS/INS Integration for Test 1

Figure 10 shows the 2D and 3D maximum errors averaged across all three outages when only one satellite was available. It can be seen that almost all of the resulting INS/GPS errors from the tightly coupled integration are reduced when compared to the loosely coupled integration, with the exception of the XsensMTi 2D error. This indicates that when only one satellite is available to aid the INS/GPS, the accuracy no better than the accuracy of INS/GPS with complete GPS outage. However, as illustrated in Figure 10, the averaged errors across all three outages show that their respective errors are reduced by 55m for Gladiator and 10m for XbowIMU. This is consistent for the other INS as illustrated in Figure 10. This is more clearly illustrated in Figure 11 which compares the maximum errors for the integrated XbowIMU/GPS solution using both the loosely and tightly coupled integrations architectures, with 3, 2 and 1 satellite visible. Evidently, this figure shows that there are significant improvements of the tightly coupled integration over the loosely coupled integration architecture.

In summary, the results obtained using the Test 1 and Test 2 datasets were comparable. It is shown that using the loosely coupled integration architecture with full GPS availability, the accuracy in terms of error RMS and maximum error of INS/GPS integrated systems employed are similar to the accuracy of GPS-SPP. Only the high grade low cost INS such as XbowIMU and XbowVG show slight improvements in both 2D and 3D while the other three INS, namely Crista, Gladiator and XsensMTi results are slightly worse than GPS-SPP. On the other hand, the results of the INS/GPS integration using the tightly coupled integration architecture shows better accuracy characteristics under full satellite availability.

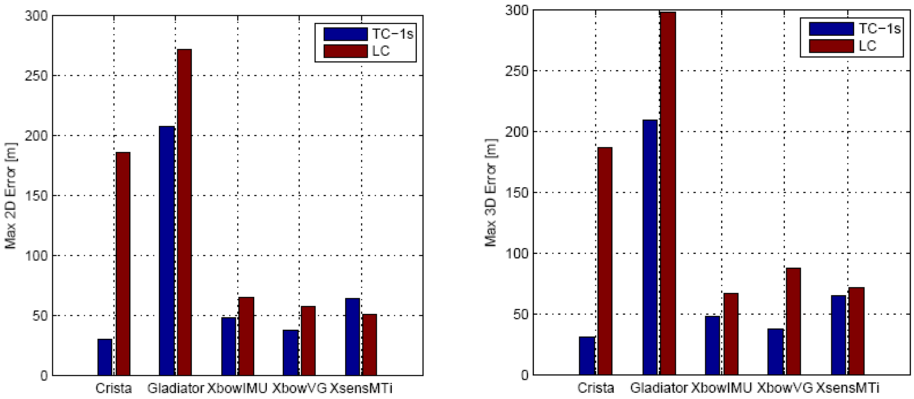


Fig. 10. Maximum Error When 1 Satellite Available

During periods of simulated GPS outages, the INS/GPS results using the tightly coupled integration architecture improved considerably over loosely coupled. Overall, the improvements range from 15m to 50m for better quality INS such as the XbowIMU and improvements range from 20m to 200m for lower grade INS, namely Gladiator. This is expected since the tightly coupled integration architecture enables satellite aiding even when the number of satellites available is below four, thus providing superior INS/GPS results during GPS outages. Based on the results obtained from these tests, it can be concluded that INS/GPS integrated system with a tightly coupled integration architecture does provide a more accurate, thus reliable navigation solution compared to GPS-SPP. In addition, INS/GPS is able to continually provide positioning solutions even in the absence of GPS, which ultimately makes it a more robust navigation system.

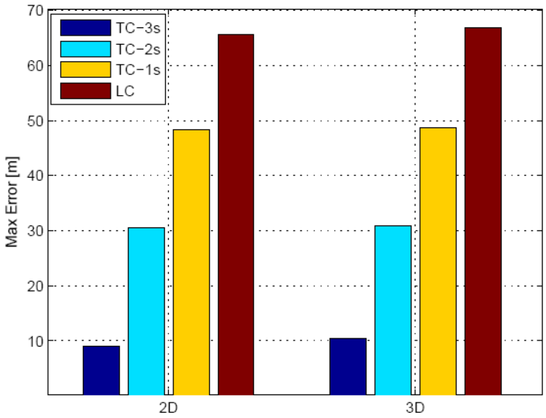


Fig. 11. Maximum Error With Different Numbers of Satellites Available

When comparing the INS/GPS performances to each other, the XbowIMU has shown to consistently have the best performance across all scenarios. This is followed by XbowVG and XsensMTi, where their performances are relatively close. Finally, the Crista and Gladiator are observed to consistently have the poorest performance amongst the INS tested.

4. CONCLUSIONS

A collaborative working group under the auspices of the FIG and IAG has been established to investigate performance issues surrounding alternative positioning technologies. The focus to date has been on generating benchmarking data sets for low cost MEMS sensors as well as evaluating their performance capabilities. A data acquisition tool has been developed which will be made available to the broader research community. In addition, preliminary results and datasets indicating the performance of commercially available MEMS sensors has been demonstrated.

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