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Emerging MEMS IMU and Its Impact on Mapping Applications

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ABSTRACT

Cost and space constraints are currently driving manufacturers of Mobile Mapping Systems (MMS) and location based services to investigate and develop next generation of low cost and small size navigation systems to meet the fast growing mobile mapping and location services market demands. Advances in Micro-Electro-Mechanical Systems (MEMS) technology have shown promising light towards the development of such systems. MEMS are integrated micro devices or systems combining electrical and mechanical components whose size ranges from micrometers to millimeters. MEMS is an enabling technology and the MEMS industry has a projected 10-20% annual growth rate to reach 200 billion US$ market by 2009. Advances in MEMS technology combined with the miniaturization of electronics, have made it possible to produce chip-based inertial sensor for use in measuring angular velocity and acceleration. These chips are small, lightweight, consumes very little power, and extremely reliable. It has therefore found a wide spectrum of applications in the automotive and other industrial applications. MEMS technology, therefore, can be used to develop next generation Direct Georeferencing (DG) systems that are inexpensive, small, and consume low power (microwatt). However, due to the lightweight and fabrication process, MEMS sensors have large bias instability and noise, which consequently affect the obtained accuracy from MEMS-based IMUs. For land MMS, introducing auxiliary velocity update in the body frame, (e.g. non-holonomic constraint and odometer signal) is an option to solve the problem. This paper describes the development of a MEMS IMU/GPS navigation system by the Mobile Multi-Sensor Systems (MMSS) Research Group at the University of Calgary. The development objective was to develop a fully integrated system with price range of US $100 – 200 using low-end (surface micromachined) MEMS inertial sensors. The system's accuracy performance will be investigated by land and airborne vehicles tests.

1. INTRODUCTION

Virtually all MMS systems include, but are not limited to, a GPS receiver, an inertial measurement unit (IMU), and CCD cameras. Some land MMS also include additional navigation aids like distance measurements units (DMI) or digital compasses. The mapping sensors can be extended to include 3-D laser scanners, IFSAR, and ground penetrating RADAR. The navigation data streams arising from the GNSS and IMU sensors are first processed by a Kalman filter that combines the information in an optimal way. The output of this processing step is a trajectory description file, including the position and attitude of the IMU, with frequency at the IMU output frequency or less; usually, better than 100Hz. Based on event mark pulses of the camera the captured images are time-tagged. The position and attitudes of each camera are then determined using the navigation trajectory, the time tags, and the inter-sensor calibration parameters. The mapping process becomes a straightforward step by doing space intersection of the conjugate light rays to obtain the 3-D object space coordinate of the point under consideration. Symbols can be attached to the captured point features to describe their attributes. This symbol assignment process facilitates the integration with GIS software databases.
Unfortunately, the INS/GPS systems used for direct georeferencing of the MMS have near-universally used navigation-grade or tactical-grade Inertial Measuring Units (IMUs). The high cost of such IMUs ($15,000-$100,000), their considerable size and their restricted handling regulations have limited their use, particularly in developing countries. Recently, new types of INS/GNSS systems have been developed that use low-cost inertial sensors based on Micro-Electro-Mechanical Systems (MEMS) technology. They are chip-based sensors that are small in size (micrometers to millimeters), lightweight (milligrams), extremely inexpensive ($5-$30), and consume very little power (microwatts). Unfortunately, due to their fabrication process MEMS inertial sensors have large bias instabilities and high noise. Hence, when they are integrated with GPS, the resulting

systems provide poor navigation accuracy when the GPS signals are blocked for even short periods of time. Thus, special considerations have to be taken into account for MEMS INS/GPS integration to meet the requirement for georeferencing of the MMS.

2. DEVELOPMENT OF GEOREFERENCING TECHNOLOGY

DG is the determination of time-variable position and orientation parameters for a mobile digital imagery. The most common technologies used for this purpose today are satellite positioning by GPS and inertial navigation using an Inertial Measuring Unit (IMU). Although each technology can in principle determine both position and orientation, they are usually integrated in such a way that the GPS receiver is the main position sensor, while the IMU is the main orientation sensor. The orientation accuracy of an IMU is largely determined by the gyro drift rates, typically described by a bias (constant drift rate), the short term bias stability, and the angle random walk. Typically, four classes of gyros are distinguished according to their constant drift rate, namely (Schwarz and El-Sheimy, 2007):

- Strategic gyros (0.0005-0.0010 deg/h or about 1 degree per month)
- Navigation-grade gyros (0.002-0.015 deg/h or about 1degree per week)
- Tactical gyros (0.1-10 deg/h or about 1degree per hour)
- Consumer grade gyros (100-10 000 deg/h or about 1degree per second)

Operational testing of direct geo-referencing started in the early nineties, see for instance Cannon and Schwarz (1990) for airborne applications, and Lapucha et al (1990) for land-vehicle applications. These early experiments were done by integrating differential GPS with a navigation-grade IMU (accelerometer bias: 2-3 10-4ms-2, gyro bias: 0.003 deg/h) and by including the derived coordinates and attitude (pitch, roll, and azimuth) into a photogrammetric block adjustment. Although GPS was not fully operational at that time, results obtained by using GPS in differential kinematic mode were promising enough to pursue this development. As GPS became fully operational the INS/DGPS geo-referencing system was integrated with a number of different imaging sensors. Among them were the Casi sensor manufactured by Itres Research Ltd., see Cosandier et al (1993); and a set of CCD cameras, see El-Sheimy and Schwarz (1993). Thus, by the end of 1993 experimental systems for DG of mobile mapping existed for both airborne and land-vehicle mode. The evolution of the georeferencing technology during the past decade was due to the ongoing refinement and miniaturization of GPS-receiver hardware and the use of low and medium cost IMU's that became available in the mid-nineties. Only the latter development will be briefly discussed here.

The inertial systems used in INS/GPS integration in the early nineties were predominantly navigation-grade systems, typically strapdown systems of the ring-laser type. When integrated with DGPS, they provided position and attitude accuracies sufficient for all accuracy classes envisaged at that time. These systems came, however, with a considerable price tag (about US $ 130 000 at that time). With the rapidly falling cost of GPS-receiver technology, the INS became the most expensive component of the georeferencing system. Since navigation-grade accuracy was not required for the bulk of the low and medium accuracy applications, the emergence of low-cost IMU in the mid-nineties provided a solution to this problem. These systems came as an assembly of solid state inertial sensors with analog read-outs and a post-compensation accuracy of about 10 deg/h for gyro drifts and about 10-2 ms-2 for accelerometer biases. Prices ranged between US$ 10 000 and 20 000 and the user had to add the A/D portion and the navigation software. Systems of this kind were obviously not suited as stand-alone navigation systems because of their rapid position error accumulation. However, when provided with high-rate position and velocity updates from differential GPS (1s pseudo-range solutions), the error growth could be kept in bounds and the position and attitude results from the integrated solution were suitable for low and medium accuracy applications.; for details on system design and performance, see Bäumker and Matissek (1992), Lipman (1992), Bader (1993), and Knight et al (1993) among others.

With the rapid improvement of fibre optic gyro performance, the sensor accuracy of a number of these systems has improved by about an order of magnitude (1 deg/h and 10-1ms-2) in the past five years. Typical cost are about US$ 30 000. Beside the increased accuracy, these systems are more user friendly and offer a number of interesting options. When integrated with a DGPS phase solution the resulting position and attitude are close to what is required for the high-accuracy class of applications. When aiming at highest possible accuracy these systems are usually equipped with a dual-antenna GPS, aligned with the forward direction of the vehicle. This arrangement provides regular azimuth updates to the integrated solution and bounds the azimuth drift. This is of particular importance for flights flown at constant velocity along straight lines, as is the case for photogrammetric blocks. Commercialization of the mobile mapping system concept for all application areas has been done by the Applanix Corporation (www.applanix.com), NovAtel Inc (www.novatel.com), and IGI (www.igi-systems.de) In general, the position and orientation accuracy achieved with these systems is sufficient for all but the most stringent accuracy requirements.

3. A LOW END EXAMPLE OF MEMS IMU

The rapid development of Micro-electromechanical (MEMS) inertial sensors in the last decade has clearly been driven by certain factors. These include technological advances in miniaturization, new materials and large scale funding for commercial and military applications. . Current prices per sensor range from US$ 10 – 150, depending on accuracy, but predictions are that they will get into the range of dimes rather than dollars. The inertial sensors produced until recently by MEMS were for the mass market and were of poor quality when compared to navigation-grade inertial sensors. Gyros had constant drift rates of thousands of degrees per hour.

There are different grades of MEMS inertial sensors in the market. Normally they are divided into surface-machined and bulk-machined based on the fabrication processes [Yazdi 1998]. Surface-micromachined sensors offer the opportunity to integrate the sensing structure and interface circuitry on a single chip, but have relatively thin proof mass and hence high mechanical noise. While bulk-micromachined sensors can attain higher resolution due to their thick proof mass, but the sensing structure is process-incompatible with the interface circuitry and therefore difficult to be mass produced. Surface-micromachined inertial sensors are relatively cheaper more compact but have lower performance than the bulk-micromachined sensors.

Figure 1 shows a picture of the MEMS IMU developed by the MMSS Research Group at the University of Calgary. The outputs are analog voltage signals from the MEMS sensors with signal conditioning. Strictly speaking, the unit is an inertial sensors assembly (ISA). The analog outputs are sampled by a 16-bit data acquisition card, NI DAQCard-6036E [http://www.ni.com] at 100Hz sampling rate; then the sampled voltage signals are converted to angular rate and specific force in the computer. The synchronization of the two systems is achieved via the Pulse-Per-Second (PPS) signal from GPS. This unit was developed under a research project with the overall objective is to develop a navigation system that costs $100-200 while achieving the accuracy requirements for land vehicle applications. Therefore the surface-micromachined inertial sensor chips from Analog Devices Inc. (ADI), whose prices are as low as $10 per gyro [ADI 2002] and $2.5 per accelerometer

[ADI 2004], were selected. The gyro module is the ADXRS150EB [ADI 2003a; ADI 2003b] and the accelerometer chip is the ADXL105AQC [ADI 1999].

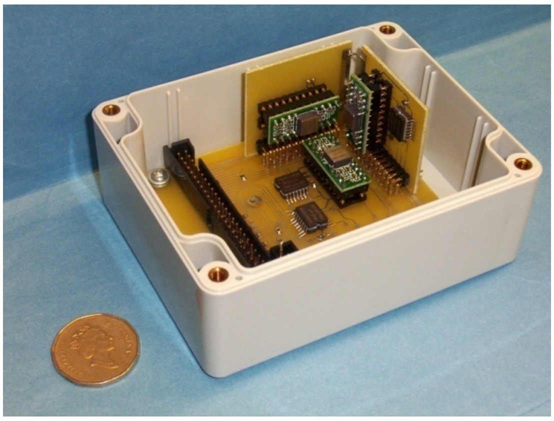


Fig. 1: MEMS IMU using sensors from ADI.

4. UNDERSTANDING THE PERFORMANCE CHARACTERISTIC OF MEMS INERTIAL SENSORS

For the conventional inertial navigation systems (INS), gyros take the most important role in terms of navigation accuracy. Among the errors of gyros, the long term bias instability (include the run-to-run bias) is the dominate error because the inertial systems often work alone. This is why the inertial systems are cataloged by the gyro bias error.
However, MEMS sensors have much larger bias instability and noise level. Therefore, MEMS IMUs are rarely used as stand-alone navigation systems, but integrated with other complementary system like GPS. Because of such integration, the slow bias drifts of the sensors (i.e. long-term bias instability) can be estimated by the integration algorithm (i.e. Kalman Filter, KF) and then compensated online. Therefore the residual short-term bias instability becomes the major concern that affect the navigation accuracy, especially when there are GPS outages.

MEMS INS integrated with GPS normally has good position performance, which is actually dominated by the GPS accuracy. The inertial part doesn't contribute much when GPS signals are well available, except offering the attitude information. The MEMS inertial system play important role when the satellite signals are blocked. In that case, the MEMS INS works in standalone to bridge the GPS signal gaps. Such stand-alone solution normally drifts quickly with time. This drift depends on not only the stability of the inertial sensors, but also the state estimation accuracy at the moment of losing GPS signals. The latter rely on the appropriate design of the navigation algorithm and the fine tuning of the KF, which is a major challenge for MEMS inertial system implementation. Therefore, the position drifts after certain period of GPS blockage is often used as an indicator of the quality of MEMS navigation systems.

Table 1 lists the specifications of the MEMS gyro and accelerometer, from ADI, used in the MEMS IMU presented in the previous section. They have various types of errors, but the short-term bias instability of gyro is the major concern, as mentioned above. The most popular method of measuring the bias instability is the Allan Variance analysis [IEEE 1997]. Fig. 2 is an example Allan Variances plot of ADI gyros. (Actually it is Allan standard deviations, i.e. square root of Allan variances.). Bias instability is normally picked from the bottom of the curve, which can be somehow regard as the best bias stability the sensor can offer. In Fig. 2, this value is about 0.01 deg/s.

Table 1: Example specification of MEMS IMU after lab calibration.

	GYROS	ACCELEROMETERS
Range	± 150 deg/s	± 5 g
Scale factor	12.5 mV/(deg/s)	250 mV/g
Non-linearity	0.1 % of FS	0.2 % of FS
Axis-misalignment	± 0.2 deg	± 0.2 deg
Bias error	± 0.5 deg/s	± 6 mg
Bias instability (100 sec)	0.01 deg/s	0.2 mg
Scale factor error	± 0.1%	± 0.1%
Noise	0.05 deg/s/√Hz	0.225 mg/√Hz

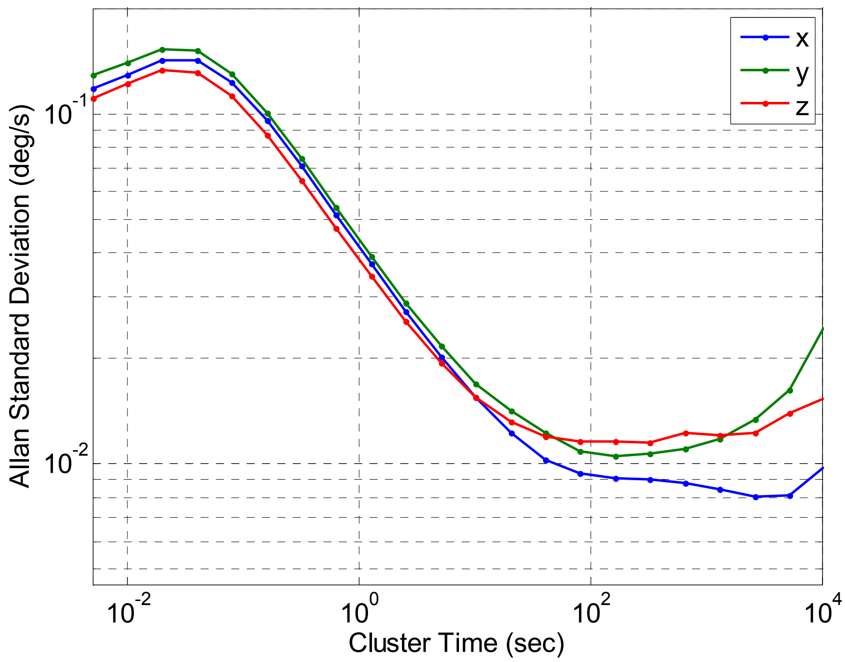


Fig. 2: Allan Variance plot of ADI gyros.

Then how will this gyro bias instability affect the navigation performance. The following is a simple analysis which can provide rough estimate of how much position drift will gyro bias instability cause after losing GPS signals. The following assumptions need to be made (El-Sheimy and Niu, 2007):

- Assume the vehicle is static, to screen the effects of other kinematic errors (i.e. scale factor error);
- Assume the system has no navigation errors (include position, velocity, and attitude) at the moment of losing GPS;
- Assume the best gyro bias estimation by the navigation KF can be only as good as the short-term bias instability given by Allan Variance curve; and this gyro bias error is constant during the GPS outage.

Because of the static assumption, the heading error caused by the gyro drift won't generate position error. So we can focus on the errors along pitch and roll, i.e. the tilt angles. The constant gyro bias will cause linear increase tilt error; then make the wrong projection of the gravity on to the horizontal plane as acceleration error; and be integrated twice to become to position drift. The derivation is as follow:

$$\Delta\theta = \int_0^t \Delta\omega \cdot d\tau = \Delta\omega \cdot t$$

$$\Delta v = \int_0^t \left(g \cdot \Delta\theta\right) \cdot d\tau = \int_0^t \left(g \cdot \Delta\omega \cdot \tau\right) \cdot d\tau = \frac{1}{2} \cdot g \cdot \Delta\omega \cdot t^2$$

$$\Delta r = \int_0^t \Delta v \cdot d\tau = \int_0^t \left(\frac{1}{2} \cdot g \cdot \Delta\omega \cdot \tau^2\right) \cdot d\tau = \frac{1}{6} \cdot g \cdot \Delta\omega \cdot t^3$$

where, t is the time after losing GPS;

- $\Delta\omega$ is the assumed constant gyro bias;
- $\Delta\theta$ is the tilt error;
- Δv is the velocity error;
- Δr is the position error.

Assume a GPS signal outage of half minute, i.e. $t = 30s$; substitute the gyro bias error of 0.01 deg/s (according to Fig. 2) into the equation, the derived position drift is

$$\Delta r = \frac{1}{6} \cdot 9.81 \cdot \left(0.01 \times \frac{\pi}{180^o}\right) \cdot 30^3 = 7.7m$$

This is only the drift along one direction (north or east). Consider the 2D error, the total position drift should be

$$\sqrt{2} \cdot \Delta r = \sqrt{2} \times 7.7m = 10.9m$$

Please note that such quick evaluation is based on highly simplified analysis (the above three assumptions). It doesn't consider the effects of other errors (include the navigation errors and other sensor errors) and the coupling of these errors. Therefore the results will be definitely optimistic. But the starting point of the analysis, i.e. short-term gyro bias instability is the major error source of MEMS navigation systems during GPS outages, is a firm assumption.

5. FIELD TEST

The MEMS-based navigation system was tested in a set of land-vehicle field tests. Fig. 3: Trajectory of the field test shows the trajectory of a typical field test in an urban area with relatively good GPS signal availability. Double-difference carrier phase derived GPS positions and velocities were used as the GNSS update, because they are available for post processing in the mobile mapping system without much additional cost.

To investigate the accuracy and error behavior of the MEMS system, a navigation grade IMU, the CIMU from Honeywell (0.005 deg/h bias drift), was included in the test to generate a reference trajectory. The optimal solution of GPS/CIMU (smoothing) was used as the true values (position and attitude) for MEMS system. This "true" solution will also be used for the mapping simulation in the next section.

In this section, navigation results of the MEMS system will be presented and analyzed. Results based on different processing strategies will be compared:

- Forward filtering
- Backward smoothing
- Backward smoothing with non-holonomic constraint.

The effect of the vehicle dynamics and GPS signal quality to the navigation results (position and attitude) will be discussed. At the end of this section, the best possible performance of the MEMS-based navigation system will be summarized.

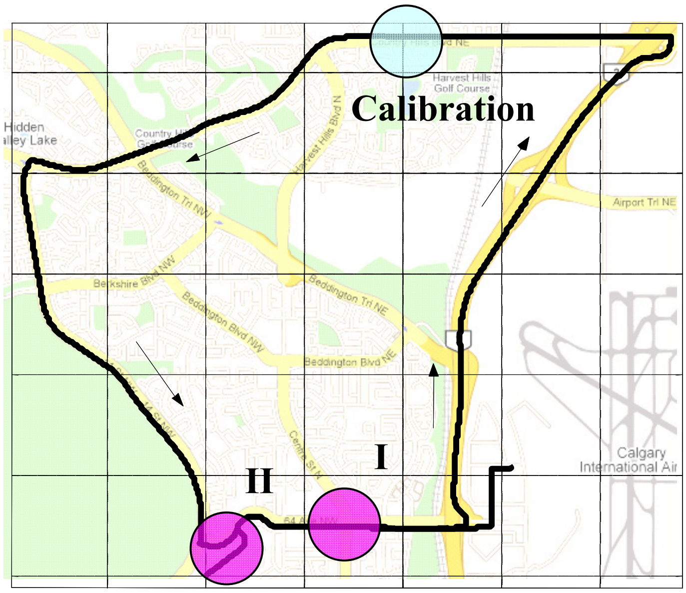


Fig. 3: Trajectory of the field test.

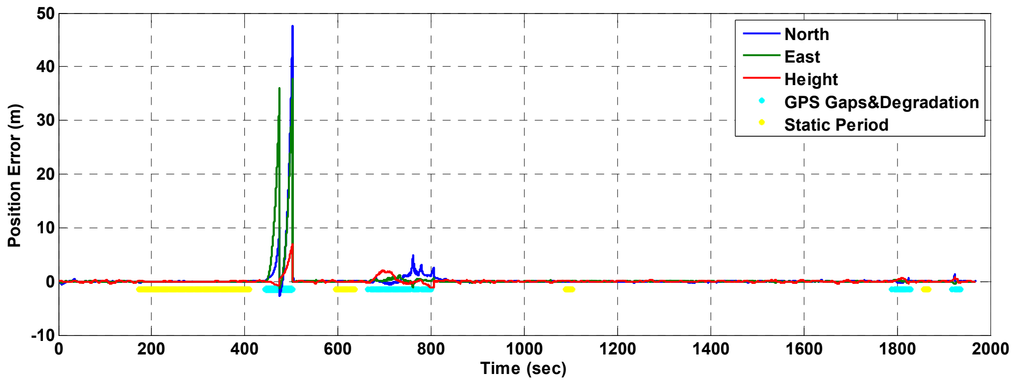
5.1.1. Forward filtering

MEMS IMU data was first processed by the forward filter (EKF). Figure 4 shows the errors of the navigation results. Here the cyan color highlights the time periods that GPS signal was blocked or degraded, while the yellow color highlights the time periods where the vehicle was stationary. In Figure 4a, it can be seen that when GPS signal was under normal condition the position error was small, with an RMS of about 0.1m. When there was GPS signal outage or degradation, however, position error increases dramatically. For example, the two adjacent 30s outages between 443s and 503s caused position drift of almost 50m, and the GPS signal degradation between 665s and 804s generated 5m position error.

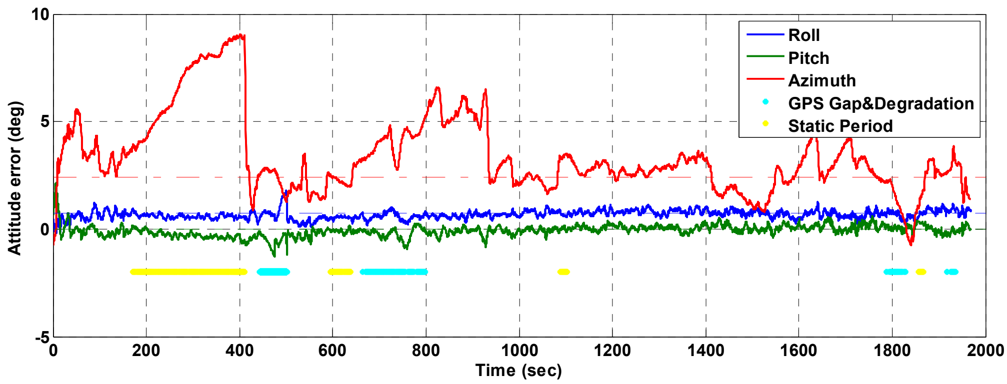
In Figure 4b, the roll and pitch angles are accurate and stable, but the azimuth was in error by as much as 6.5 deg. Detailed investigation has shown that the azimuth error is strongly related to the vehicle dynamics. When there is little dynamics, the observability of the azimuth by the GPS update is almost zero, causing the azimuth to diverge (Niu and El-Sheimy 2005). A typical example is the 4 minute stationary period from 172s to 410s (zero kinematics). The azimuth drifted to 6.5 deg until the vehicle started moving again. Therefore, it is recommended to intentionally make some maneuvers (speed up/down, turns, etc.) regularly to keep the accuracy of the MEMS systems during the mobile mapping survey.

Here please note there are some biases in the attitude errors, i.e. +0.75 deg for roll, 0.0 deg for pitch, and +2.4 deg for azimuth. These biases come from the mounting misalignment between the MEMS IMU and the reference system (CIMU). They are physically existed and do not belong to the estimation error. Later it will appear in the boresight calibration of the camera in the next section.

The results shown in Figure 4a are typical for MEMS navigation systems. Obviously they are far from the requirements of mobile mapping. The navigation performance has to be improved significantly.



a) Position error



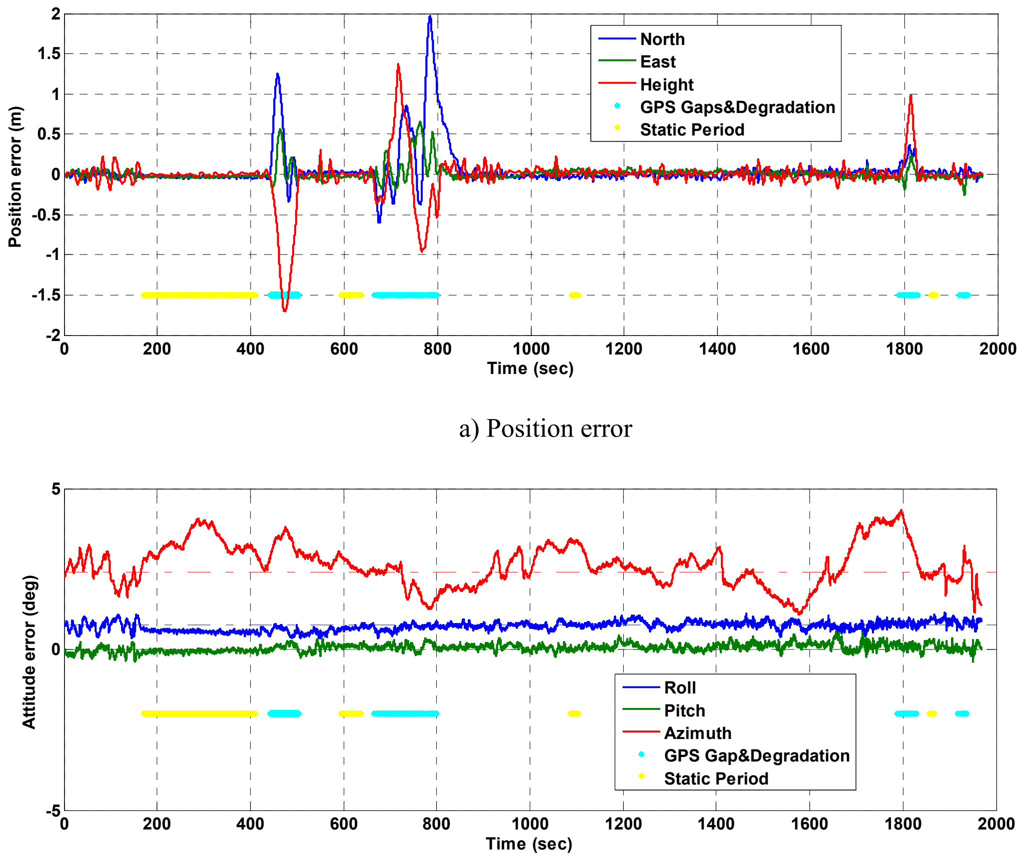
b) Attitude error

Fig. 4: Navigation error of the forward filtering.

5.1.2. Backward smoothing

As mentioned at the beginning of this section, backward smoothing can improve the navigation performance significantly, since it makes full use of the information during the whole test. Figure 5 shows the results when backward smoothing is applied. When compared to the results in Figure 4 it is obvious that both position errors (especially during GPS signal outages) and attitude errors (especially the azimuth) are dramatically reduced. The maximum position error in GPS outages and degradations is reduced from 50m to 2m. The RMS azimuth error is reduced from 1.5 deg to 0.6 deg (after removing the misalignment angles to the reference CIMU), while the maximum azimuth error is reduced from 6.5 deg to 1.6 deg (in the static period from 172s to 410s).

Although the system performance is significantly improved by backward smoothing, the azimuth error still wandered around in a range of +/- 1.6 deg, affecting by the vehicle kinematics. This is still too large as from mobile-mapping georeferencing.



a) Position error

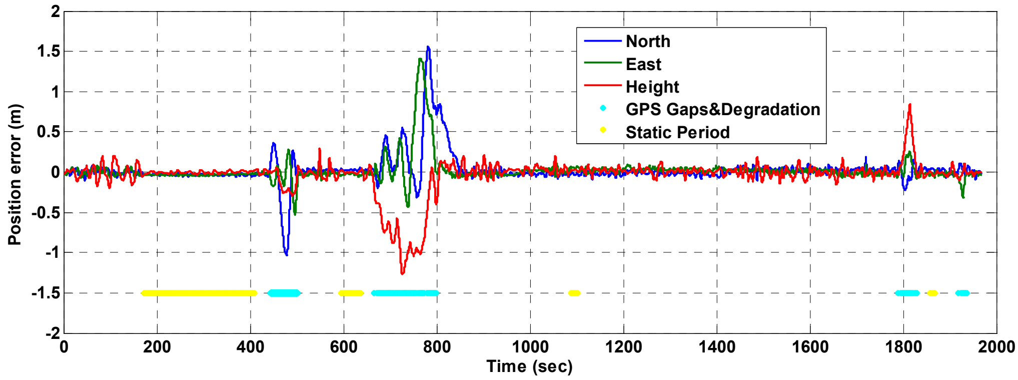
b) Attitude error

Fig. 5: Navigation error of the backward smoothing.

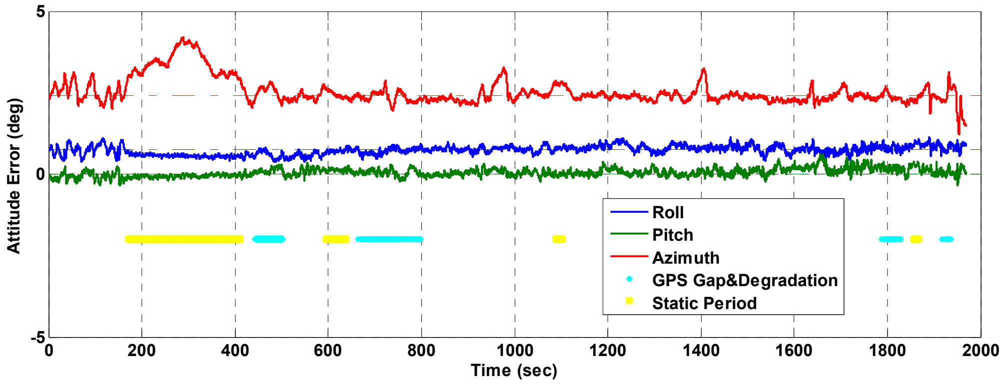
5.1.3. Backward smoothing with non-holonomic constraints

Non-holonomic constraints are stochastic constraints that limit the velocity of the vehicle in the plane perpendicular to the forward direction (Sukkarieh 2000; Shin 2001). In a land vehicle traveling on smooth roads, this velocity should be almost zero. Analysis and results have shown that such constraints suppress both the position drift along lateral direction of the vehicle in GPS outages and degradations, and the azimuth error by improving the observability of the azimuth (Niu and El-Sheimy 2005).

Figure 6 shows the smoothing results after applying non-holonomic constraints. Compared with the azimuth error to Figure 5, the RMS error is reduced from 0.6 deg to 0.35 deg. The position drift during GPS signal outages also reduced. Such accuracy is suitable for georeferencing of mobile-mapping systems.



a) Position error



b) Attitude error

Fig. 6: Navigation error of the backward smoothing (applying non-holonomic constraint).

Table 2 summarizes the processing results of the MEMS-based INS/GPS navigation system. Obviously, the backward smoothing with non-holonomic constraints offers the best position and attitude estimation. Therefore, this processing strategy will be used for the georeferencing in the simulations in the following sections. Under the good testing conditions, i.e. with stable GNSS update and regular vehicle kinematics, the MEMS navigation system can offer the georeferencing information with RMS position accuracy of 0.05m and attitude accuracy of 0.35 deg.

Table 2: Navigation performances of MEMS system using different processing strategies.

	Forward filtering	Smoothing	Smoothing with non-holonomic constraints
Position accuracy (RMS) with stable GPS update	0.1 m	0.05 m	0.05 m
Maximum position drift in GPS gaps and degradations	50 m	2.0 m	1.5 m
Attitude error in general (RMS)	1.5 deg	0.6 deg	0.35 deg
Maximum attitude drift with absence of kinematics	6.5 deg	1.6 deg	1.6 deg

Another airborne test was conducted on April 2009, Fig. 5 show the test trajectory and system setup.. The test equipments include the MEMS IMU presented in section 3, the LN200 tactical grade IMU as a reference and NovAtel OEM4 dual frequency receiver. The collected data has been processed to evaluate the performance of the prototype system.

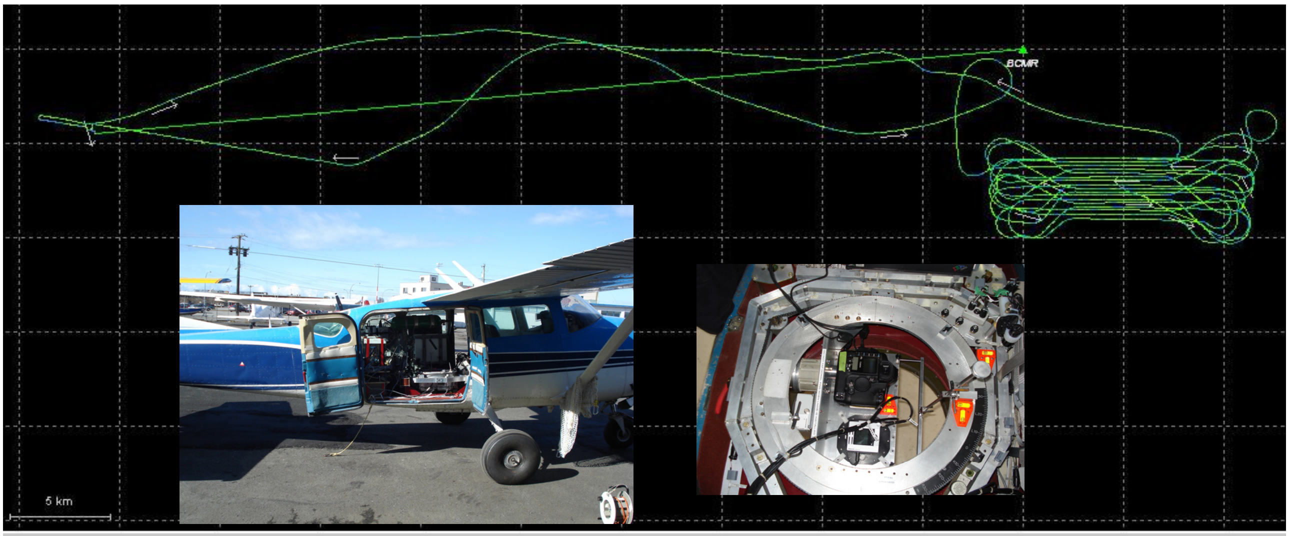


Fig. 5: Trajectory and system setup for April 2009 airborne test.

The low-cost MEMS INS data was processed using all possible processing instances in KF (concerning alignment). For instance, using the option of Levelling & LN200 Heading, Static Coarse/Fine, In-Motion, Transfer alignment etc. The best results obtained using the Levelling & LN200 Heading option (which is consistent with the land-vehicle MEMS common results). The Static Coarse/Fine alignment option was found to give exactly the same results as the Levelling & LN200 Heading option results (during all flight lines), which means that the system could recover the heading after take-off and having an "artificial" in-motion alignment before performing the flight lines trajectory. Table 3 provides a summary of the integrated MEMS IMU and DGPS attitude performance when compared to the integrated LN200 and DGPS solution. The results clearly show that the high potential for MEMS IMU for many mapping applications such as Right of Way (ROW) of highways and Oil&Gas pipelines.

Table 3: Summery of attitude performance.

Including all 16 Flight lines	Error Statistics (deg)			
	Mean	Min	Max	RMS
Roll	0.0	-0.75	1.21	0.28
Pitch	0.0	-1.15	1.07	0.44
Heading	0.2	-2.5	3.8	1.8

6. CONCLUSIONS AND OUTLOOK

MEMS inertial technology has reached the ridge of its development. The fact that MEMS-based systems are lightweight will translate to decreases in deployment payloads (important aspect for military applications) and increases in mobility for personnel and platforms (important aspect for cell phone and car navigation applications). Similarly, their small size means that many of these devices can be integrated to increase the level of system intelligence (important aspect for reliability). The work presented in this paper has shown the promising potentiality of using low-end MEMS (surface micromachined) inertial sensors for land and airborne mapping application. The low cost of the sensors makes it feasible to build an integrated navigation system at $100-200 cost level. In summary, the developed MEMS IMU/GPS navigation system presented in this paper offer a promising low-cost navigation system for many mapping applications. The auxiliary velocity updates in the body frame, i.e. the non-holonomic constraint and the odometer signal, can efficiently reduce the position drift during GPS signal outages. The non-holonomic constraint can also improve the estimation accuracy of the heading significantly. The developed MEMS IMU/GPS navigation system can reach an average position accuracy of 3.3m after 30 sec of GPS signal outages and attitude accuracy of 0.2 deg (RMS) for land MMS and attitude accuracy of 0.2-0.4 for roll and Pitch and 1.4 degrees for azimuth for airborne mapping applications...

7. ACKNOWLEDEGEMENTS

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