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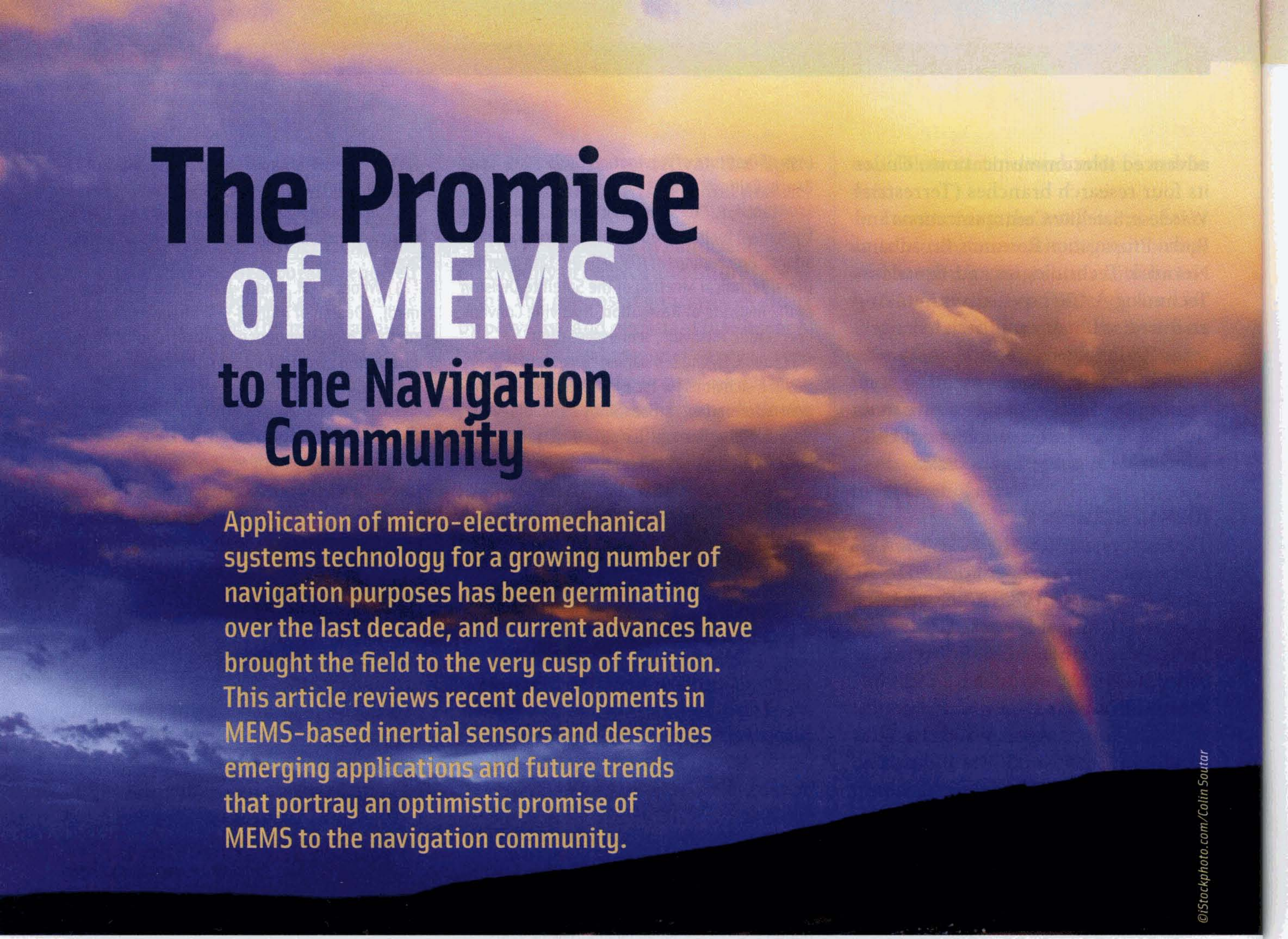

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The Promise of MEMS to the Navigation Community

Application of micro-electromechanical systems technology for a growing number of navigation purposes has been germinating over the last decade, and current advances have brought the field to the very cusp of fruition. This article reviews recent developments in MEMS-based inertial sensors and describes emerging applications and future trends that portray an optimistic promise of MEMS to the navigation community.

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GPS clearly dominates the current market in positioning and navigation (POS/NAV). Besides being globally available, it provides the whole range of navigation accuracies at very low cost. GPS is also highly portable, has low power consumption, and is well suited for integration with other sensors, communication links, and databases.

At this point in the development of navigation technology, the need for alternative positioning systems only arises because GPS does not work in all environments. Current GPS receiver chips are reaching a unit price of about $5, and the predictions are that this figure will drop to about $1 when, most likely, it will level off.

Module cost is not equivalent to system cost, but the recent development of receivers at a price of $100 shows clearly that module costs are an important factor, not only in consumer mass markets but also for high-volume commercial products, such as for asset and container tracking.

Even more important is the fact that with unit cost that low, GPS is becoming a commodity, comparable to a Sony Walkman, pocket calculators, or a digital wristwatch. Thus, personal GPS devices will drive the module market and provide navigation receivers of high versatility at even lower cost.

Considering these price trends, can any POS/NAV technology be competitive with GPS?

At this point the answer is clearly in the negative. Therefore, other navigation technologies would typically be developed for "non-GPS" environments, that is, for environments in which GPS does not function at all (underground, underwater, in buildings) or where it performs poorly (forested areas, urban environments). Although a substantial navigation market for operating in "non-GPS" environments exists, it is much smaller than the one predicted for GPS.

In the portion of the market where GPS is only available for part of the time, the question will be, "How much is the user willing to pay for a continuous navigation solution?" This obviously will depend on the specific application, and it might be possible that niche markets will develop around such applications.

In such applications, integrated solutions will be of high interest and may involve sensor integration as well as data base integration for techniques such as map matching. In those applications where GPS does not work at all, the search for cost-effective alternatives will continue.

One promising development is the emergence of micro-electromechanical systems (MEMS) technology (also known as micromachined technology). MEMS is an enabling technology with a massive global market volume worth $12 billion in 2004 and is expected to reach $25 billion in 2009 (Source: "NEXUS Market Analysis for MEMS and Microsystems III, 2005-2009"). This means that, overall, MEMS technology will be much larger than the market size of GPS at that time.

A small portion of this MEMS market will support inertial sensor technology. Yole Development estimated that the world markets for MEMS-based inertial sensors have reached almost $0.7 billion in 2004 and will exceed $1 billion in 2008. The major growth opportunities will come from automotive and consumer application markets, with a steady growth of the industrial and defense business, too. (Source: *World MEMS Inertial Sensor Markets, Research Report # YD4264,* Yole Development, April 2005).

Since INS technology is capable of working in all environments where GPS has difficulties, MEMS inertial technology is seen as both a possible complement of GPS technology and a potential alternative to GPS if market volumes develop in the way anticipated. The idea of an "inertial measurement unit (IMU) on a chip" and unit cost as low as GPS modules are anticipated in the very near future.

MEMS Inertial Sensor Development

MEMS is not a product per se but rather a way of making things. As the full name might imply, those things are small and have both mechanical and electronic components. MEMS have been used to describe microminiature systems that are constructed with both fabrication techniques based on integrated circuits (ICs) and other mechanical fabrication techniques.

Microminiature systems have physically been around since the late 1960's when the first MEMS device was a gold resonating MOS gate structure. (See the article by H.C. Nathanson, et al cited in the "Additional Resources" section at the end of this article.) MEMS product developments are driven by miniaturization, multiplicity, and microelectronics.

Having miniature sensors and systems offers many advantages. From a practical sense, smaller often implies easier to carry or to supply with power: features that may be crucial in the case of a personal navigation system. In a physical sense, smaller and lighter can mean higher resonant frequencies (and, in turn, higher operating frequencies and bandwidths) along with shorter thermal time constants, to name a few examples.

Multiplicity is attractive because it makes production easier and cheaper. Significantly, the multiplicity concept also implies that systems that run in parallel might be more easily produced, for example, arrays of sensors. With recent advances in microelectronics, intelligent electronics can be combined on the same chip as the sensors, resulting in relatively complex and advanced systems.

Category	Sensing Element	Advantages	Disadvantages
Polysilicon Micromachining	Thin silicon structure located on the surface of a die	Well-suited for integration with other sensors	Relatively low accuracy and small bandwidth
Bulk Micromachining	Single crystal inside a block sandwiched between two layers	Better accuracy than polysilicon micromachining	Larger size, more expensive & not good for integration

TABLE 1. Classification of MEMS sensors according to fabrication processes

As we will see, examples of this are closed loop accelerometers and complete single chip IMU designs. Among the many applications of MEMS in the field of positioning and navigation are miniature power supplies, processors, data storage devices, and, of course, inertial sensors. Just the idea of miniaturizing any one of these is immediately attractive in many ways.

Several factors have clearly driven the rapid development of MEMS inertial sensors during the last decade. These include technological advances in miniaturization, new materials, and large-scale funding for commercial and military applications. Accelerometer development appears more mature than gyro development, due primarily to the push for reliable crash detectors in the automobile market.

As far as MEMS IMU development, gyro development is therefore the limiting factor in achievable accuracy. The next section lists the principles that are used for MEMS sensors, classifies them according to fabrication process and design, outlines their current accuracy, and mentions the physical properties that limit their accuracy.

Classification of MEMS Inertial Sensors

MEMS inertial sensors can be classified according to the fabrication process, method of detecting the position of the mass (if based on that principle), and mode of operation.

MEMS inertial sensors are divided into surface-machined and bulk-machined based on the fabrication processes. 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.

In comparison, 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 as a result they are difficult to be mass produced. From the customer's perspective, the surface-micromachined inertial sensors are relatively cheaper and more compact but have lower performance than the bulk-micromachined sensors.

Table 1 compares the two main methods of the fabrication process of MEMS-based inertial sensors.

MEMS sensors in general can also be classified in terms of the mass position detection criterion as piezoresistive signal pick-off, capacitive, and piezoelectric. **Table 2** summarizes the motion sensing technique as well as the advantages and the disadvantages of each category.

Mode of operation is another means of classifying MEMS inertial sensors. They can be either closed loop (with feedback) or open loop. The former implies increased complexity.

Top-down vs. Bottom-up

According to the two foregoing manufacturing processes, the development of MEMS inertial sensors also follows two tracks: top-down and bottom-up. Manufacturers following top-down strategy normally use the bulk-micromachining process. In this case, they guarantee the performance of the MEMS sensors as high as possible at the beginning and then try to reduce the cost and increase the productivity.

A typical example of this case can reportedly reach the performance of a tactical grade (medium-quality) IMU and is going to decrease the price to one tenth of the same grade traditional products.

On the contrary, bottom-up strategy normally uses surface-micromachining process. It keeps the inherent feature of low-cost for MEMS and tries to improve the performance step by step. An example of this approach can be seen in a company that has announced the price of its gyro is $10 per axis and its accelerometer, less than $1 for three axis. **Table 3** summarized the feature of these two strategies of MEMS inertial sensors development.

From the point of view of price, commercial applications of MEMS inertial sensors currently focus on the bottom-up products. However, the developments for military applications are mainly driven by the top-down strategy to guarantee the performance.

To date, the bottom-up and top-down trends cannot meet each other to come up with a satisfactory solution for all users. So, some doubt exists about whether MEMS inertial technology, especially gyroscopes, can be accepted by the navigation market before the technology push gets exhausted.

Fortunately, technique breakthroughs have kept coming in the past three years. The top-down products are dropping in price, and the bottom-up products are boosting their performance rapidly. Even sensors following the bottom-up track have already been used for navigation purposes.

Forces Driving MEMS POS/NAV

The market for MEMS inertial sensors (accelerometers and gyroscopes) is set to grow from $835 million in 2004 to over $1360 million in 2009 (Source: NEXUS). Currently, the main applications are in the automotive industry. These markets are well established and growth rates range from a stagnant one percent for airbag acceleration sensors up to eight percent for gyroscopes used in electronic stability program (ESP) units and navigation assistance systems.

Much more exciting for MEMS inertial sensors is the market opportunity for mobile applications and consumer electronics. Over the next few years, NEXUS report predicts annual growth rates exceeding 30 percent for accelerometers. Mobile phones in particular will provide multi-axis accelerometers with interesting opportunities in menu navigation, gaming, image rotation, pedometers, GPS navigation, and the like. Gyroscopes are largely servicing markets for image stabilization and hard disk drive protection in camcorders.

Accelerometers Development. MEMS inertial accelerometers, when produced in large quantities, will be extremely inexpensive. Current prices per sensor range from US$ 2–10, depending on accuracy, but predictions are that they will get into the range of dimes rather than dollars. At least 10 companies are working on tri-axis MEMS accelerometers, some of which were initially developed for the automotive industry.

With few exceptions, accelerometers work by measuring the motion of a proof mass versus a fixed frame or reference. The main sensing approaches are capacitive (an approach followed by companies such as Bosch, Freescale, Kionix, oki Electric, STMicroelectronics and Analog Devices), piezoresistive (for example, Hitachi Metals, Matsushita, Fujitsu, and Hokuriku) or the less common thermal accelerometers from sole proponent MEMSIC (with two-axis and three-axis in development).

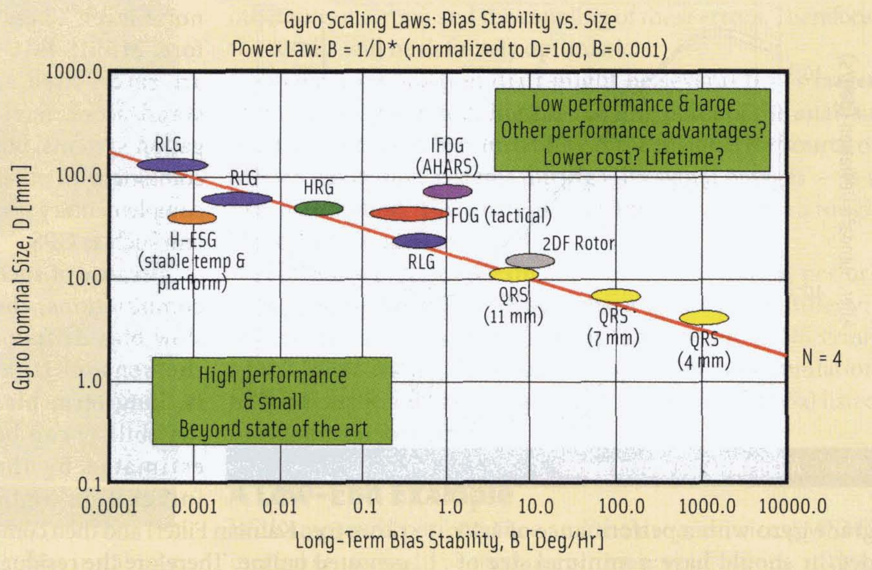
Each design has its advantages, but price is the bottom line. The lowest cost three-axis sensors are currently $2 per unit in volume. The lowest cost solution for two-axis sensors is now under $1, and a $0.50 price point is expected to be reached this year. Meanwhile, power

Category	Motion sensing Technique	Advantages	Disadvantages
Piezoresistive signal pick-off.	Deflection of the piezoresistive material	Low-cost, simple interface and wide range	Low precision and high sensitivity to temperature
Capacitive Sensors	The change in capacitance of two electrodes	More accurate, excellent linearity & low temperature sensitivity	Great complexity, electromagnetic interference & small dynamic range
Piezoelectric Sensors	Produces an electric charge due to change in motion	Relatively wide dynamic range	Low sensitivity

TABLE 2. Classification of MEMS sensors according to mass position detection

MEMS Category	Top-down	Bottom-up
Performance	High	Low
Processing	Bulk-machining	Surface-machining
Quantity	Small-scale	Large-scale
Cost	High	Low
Trend	Merge the two approaches	

TABLE 3. Comparison of top-down and bottom-up developments



Courtesy: Honeywell

FIGURE 1 **Bias Stability vs. Nominal Size for Mature Gyro Technology.**

consumption has gone well under one milliwatt.

Gyros Development. Most commercial gyros are vibratory and use the transfer of energy between two vibration modes caused by Coriolis force. They are challenging to manufacture, hence, their higher cost compared to accelerometers.

Compared to automotive applications, gyro packages in consumer electronics are about 1/10th the size (targeting 25 cubic millimeters). The resolution requirements are lower — 5–10 degree per second compared to 0.1–1 degree per second in cars. Current MEMS gyros are larger devices than MEMS accelerometers, and can require as much as 10 times more power due to the higher drive requirements (5V).

Manufacturers employ many different sensing approaches and materials to make MEMS gyroscopes. Silicon micromachined capacitive gyros, piezoceramic devices, thin-film resonators deposited with lead zirconate titanate (PZT), and quartz gyros. These are all single axis solutions.

Currently, one piezoceramic single-axis solution costs in the range of $7–8. Other companies have two-axis solutions estimated to cost under $10. Today, the smallest packaged device is 21 mm^3 — a single axis quartz piezoelectric gyroscope. At 6 mW, this latter unit is also the lowest power solution, in part due to a lower drive voltage compared to 5V drive capacitive gyroscopes.

Cell phones could represent the largest future market for gyroscopes, but they are still too expensive for this application. Acceptable gyro prices for cell phone manufacturers could be around $5 for an application such as GPS navigation, according to a recent article by R. Dixon, R. and J. Bouchaud (See Additional Resources).

Is MEMS Navigation for Real?

Results presented at many recent conferences indicate that companies are actively working on MEMS-based tactical gyros. (See, for instance, the articles by J. Hanse and J. Geen cited in Addition Resources.) Considering that the production processes for MEMS inertial sensors are relatively new and that the potential for improvement is considerable, can we expect at some point in the future that the accuracy and affordability of these sensors will be sufficient to support navigation-type applications?

At this point we cannot answer this question in an unequivocal way. However, two arguments will be given here — one in favor, the other against — that may be helpful for forming an opinion.

The argument against is based on some interesting empirical results that the authors received courtesy of Dr. Robert J. Smith at the Honeywell Technology Center. They have been partly reproduced in **Figure 1**. Gyro performance (measured by long-term bias stability) is plotted versus the nominal size of the gyro on a log-log scale. (Note that the figure is not based on a comprehensive market analysis, but derives from an in-house study conducted by Dr. Smith. This is the reason why only Honeywell gyros are shown.)

The gyros represented in this figure vary in terms of size (between 120 mm and 4 mm) and principle used (ring laser gyro [RLG], electrostatic gyro [ESG], hemispherical resonator gyro [HRG], fiber-optic gyro [FOG], two degrees of freedom rotor [2DF rotor], quartz rate sensor [QRS]). Each gyro is represented by an ellipse showing the performance range in the horizontal direction and the variability in size in the vertical.

It is remarkable that the line N=4 gives such a close fit to most gyros presented in the chart. This indicates that gyro accuracy, independent of the principle used, is determined by the size of the sensor. The gyros above the line fit are typically not pressing the state of the art, because of other considerations (cost, lifetime).

For the one gyro below the line, the H-ESG, which seems to outperform the general trend, only bias stability values in a benign temperature environment were available. That unit might, therefore, not be directly comparable to the other performance values, which cover a wide range of production environments.

Excluding these special cases, the N=4 line can be considered as an empirical law for gyro performance that is independent of the principle used to build the gyro. This means that it can be used as a predictor for gyro performance in cases where the size of the gyro is given by other considerations.

When applying this principle to the MEMS gyro environment, it would mean that a gyro with a nominal size of two millimeters would perform at the 10,000 deg/hr level, while a tactical

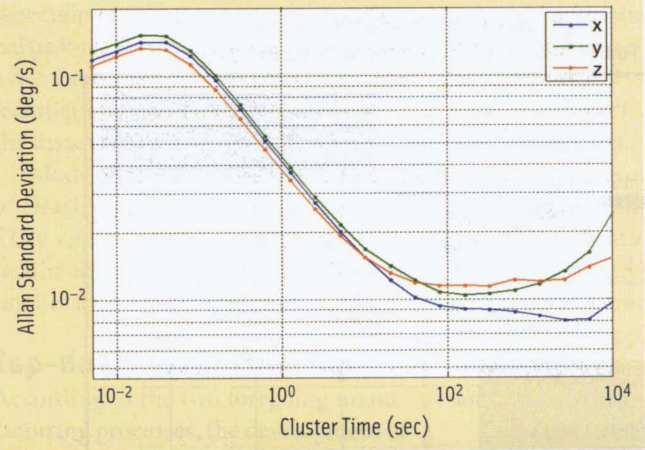


FIGURE 2 Allan Variance plot of gyros

grade gyro with a performance of 1-10 deg/hr should have a minimal size of about 20 millimeters.

Chip size thus will essentially limit the accuracy of the IMU-on-a-chip. Similarly, the likelihood that MEMS-based gyroscopes will reach navigation-grade performance is tied to the nominal size of the gyro, which needs to be about six centimeters in diameter to meet the requirements.

The argument in favor of MEMS gyro usage for navigation-type applications is based on publications recently presented at the IEEE PLANS 2004 conference and results obtained by the Mobile Multi-Sensor Research Group at the University of Calgary, Canada. The latter were obtained in a land-vehicle test using a MEMS-based IMU developed by employing off-the-shelve MEMS sensors with an average cost $5–20 per sensor. More details about the performance of this system will be given later in the section entitled, "A Low-End Example."

MEMS Inertial Performance

For conventional inertial navigation systems, gyros play the most important role in terms of navigation accuracy. Among the errors of gyros, long-term bias instability (include the run-to-run bias) is the dominant error because the inertial systems often work alone. This is why the inertial systems are cataloged in terms of the gyro bias error.

However, MEMS sensors, especially products on the bottom-up track, have much larger bias instability and noise level. Therefore, MEMS IMUs are rarely used as stand-alone navigation systems, but combine with other complementary system such as GPS.

Because of such combinations, the slow bias drifts of the sensors (that is, long-term bias instability) can be estimated by the integration algorithm (i.e., Kalman Filter) and then compensated online. Therefore the residual short-term bias instability becomes the major concern that affect the navigation accuracy, especially when GPS outages occur.

MEMS INS combined with GPS normally has good positioning performance, which is actually dominated by the GPS accuracy. The inertial part doesn't contribute much when plenty of GPS signals are available, except offering the 3D attitude information. The MEMS inertial system plays an important role when the satellite signals are blocked. In that case, the MEMS INS works alone to bridge the GPS gaps.

Such stand-alone solutions normally drift 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. The latter rely on the appropriate design of the navigation algorithm and the fine-tuning of the Kalman filter, which is a major challenge for MEMS inertial system implementation. Therefore, the position drifts after a certain period of GPS blockage is often used as an indicator of the quality of MEMS navigation systems.

Table 4 lists the specifications of the MEMS gyro and accelerometer from one manufacturer. They have various types of errors, but the short-term bias instability of the gyro is our major concern, as mentioned previously.

The most popular method of measuring the bias instability is the Allan Variance analysis. (For more details see the citation "(IEEE 1997 in Additional Resources.). **Figure 2** presents an Allan Variances plot of these gyros. (Actually, the figure uses 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 regarded as the best bias stability the sensor can offer. In Figure 2, this value is about 0.01 degrees per second.

How, then, will this gyro bias instability affect the navigation performance? In other words, how much position drift will it cause after losing GPS signals? This is really a tough question to answer. To simplify the analysis, the following assumptions need to be made:

- assume that the vehicle is static, to screen the effects of other kinematic errors (i.e., scale factor error)
- assume that the system has no navigation errors (including position, velocity, and attitude) at the moment of losing GPS
- assume that the best gyro bias estimation by the navigation Kalman

	Gyros	Accelerometers
Range	± 150 deg/s	± 5 g
Scale factor	12.5 mV/(deg/s)	250 mV/g
Non-linearity	0.1 % of Full Scale	0.2 % of Full Scale
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

TABLE 4. Example specification of MEMS IMU after lab calibration *based on Allan Variance Analysis*

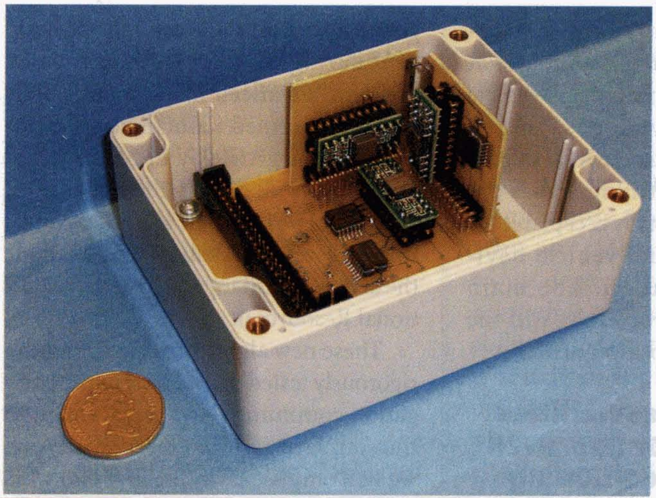


FIGURE 3 System using MEMS IMU sensors

filter can be only as good as the short-term bias instability given by the Allan Variance curve and that this gyro bias error is constant during the GPS outage.

Because of our assumption that the vehicle is not moving, the heading error caused by the gyro drift won't generate a position error. So, we can focus on the errors along pitch and roll, that is, the tilt angles. The constant gyro bias will cause a 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 follows:

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

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

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

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.

Assuming a GPS signal outage of half minute and substituting the gyro bias error of 0.01 deg/s (according to Figure 2) into the equation, the derived position drift is

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

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

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

Similarly, assuming a GPS signal outage of one minute (t = 60s), the corresponding position drift will be 87.1 meters. Please note that this quick evaluation is based on a highly simplified analysis (the three stated assumptions). It doesn't consider the effects of other errors (including the navigation errors and other sensor errors) and the coupling of these errors. Therefore, the results will be definitely optimistic.

The actual position drift might be several times larger than the analysis result. But the starting point of the analysis — short-term gyro bias instability is the major error source of MEMS navigation systems during GPS signal outages — is a firm assumption. This analysis is a handy way to have a rough idea of the navigation accuracy.

For more precise investigation of the navigation performance of MEMS GPS/INS systems, a summary of different levels of comprehensive methods as "Lab testing," "INS simulator," "Field testing," and also a proposed hybrid emulation method can be found in the article by X. Niu et al (2006a) listed in Additional Resources.

A Low-End Example

With improved performance and the drop in prices, MEMS inertial sensors will be used in ever more applications, such as 3D input devices, robotics, platform stability, camcorder stabilization, virtual reality, vehicle stability control, navigation assist, roll over detection, and so forth.

One of the most challenging applications is using MEMS inertial sensors for car navigation. Due to price competition, commercial vehicles must use low-end MEMS inertial sensors (from the bottom-up track), which cost only a few dollars per axis. However, land vehicle navigation requires relatively high accuracy from the inertial sensors.

The next sections will demonstrate the capability of MEMS inertial sensors by the performance of a MEMS car navigation system developed by the Mobile Multi-Sensor Systems (MMSS) Research Group at the University of Calgary. This system uses low-end MEMS sensors with the objective of creating a system with a total price of less than $200. We can regard this system as a typical prototype that is close to the consumer market.

Figure 3 shows of the inertial sensor triad, which includes three gyro chips and three accelerometer chips. After lab calibration to remove the constant bias and scale factor errors, the triad is used as an IMU. This MEMS IMU was combined with a GPS receiver to produce an integrated GPS/INS navigation system. Aided Inertial Navigation System (AINS) software developed by the MMSS group was used to process the IMU data and integrate it with other updates, for example, the GPS data.

This MEMS navigation system was subjected to a set of field trials conducted in test vans under different road and driving conditions. **Figure 4** shows the trajectory of one test, which represents typical highway driving with open-sky conditions. To test the performance of the system, a navigation-grade IMU was included in the test, to provide high accuracy DGPS/commercial IMU solution as the reference solution (i.e., true values).

The MEMS IMU signals were processed with integration of single-point GPS (SPGPS). Because so few GPS signal blockages occurred during the test, a number of short-term GPS signal outages (30 seconds and 60 seconds, respectively) were

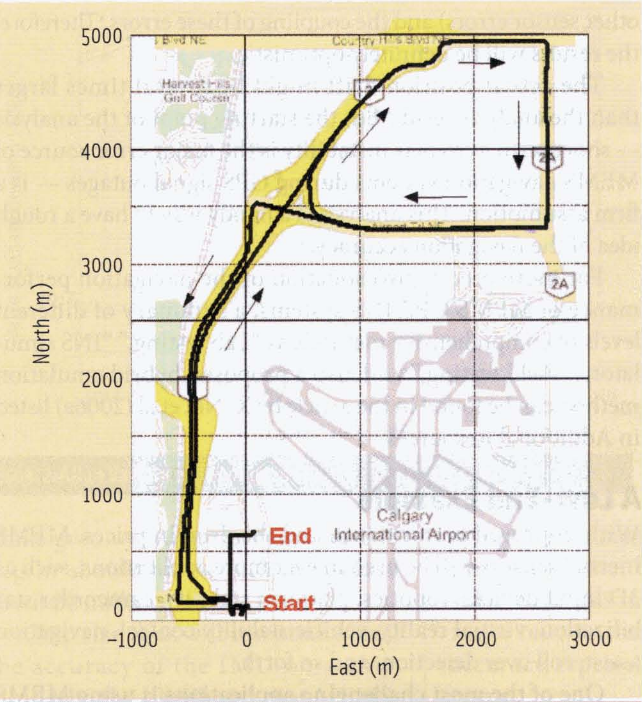


FIGURE 4 Trajectory of the Field Test

simulated to evaluate the quality of the MEMS system in stand-alone mode of operation. Meanwhile, the attitude error is also checked as an additional metric.

Figure 5 shows the result with simulated 30-second GPS signal outages. The upper subplot is the position error, using different colors to identify the three directions. The cyan color on the time axis indicates the GPS signal gaps. The lower subplot shows the attitude error. The position drifts in the 30-second outages are as large as 50 meters, with about 30 meters on average.

Such position drift can scarcely be accepted for land vehicle navigation because it might place the car on the wrong road if used with a digital map. And 30 seconds of GPS signal blockage might often happen in urban areas.

For the attitude error, the effect of GPS signal outages is much less than on the position. Here the roll and pitch errors are less than one degree, but the azimuth error can be as large as a few degrees. This is because the azimuth is poorly observed by the GPS position (and velocity) update in the navigation Kalman filter, especially when the vehicle is exhibiting few dynamics.

The azimuth drift happened not only during GPS signal gaps but also at times of less vehicle dynamics. In any case, several degree attitude errors are totally acceptable for land vehicle navigation. The main problem is still the position drifts.

Possibilities for Improved Positioning

One way to improve positioning accuracy of the integrated GPS/INS system is to make use of aiding information from the vehicle dynamics, for example, non-holonomic constraint (the assumption that the vehicle can only move forward and backward) and the odometer signal. Such aiding signals can be regard as the velocity update in the body frame for the navigation Kalman filter.

Another way to improve accuracy is to use a backward smoothing algorithm, which is appropriate for the applications that allow post-processing. A third way is to develop some new navigation algorithms to reduce the position drift during GPS signal outages, based on some advanced mathematics tools such as unscented Kalman filter (see for example the article by El-Sheimy et al – *Inside GNSS,* March 2006), artificial neural network, or an adaptive neural fuzzy inference system (See for example the article by Chiang et al listed in Additional Resources).

These new algorithms have not been rigorously tested or accepted in the navigation community as a replacement to the standard Kalman filter. Therefore, we will only focus on the first two ways of improvements in the rest of this discussion.

Aiding from the vehicle

Non-holonomic constraints refer to the fact that unless the vehicle jumps off the ground or slides on the ground, the velocity of the vehicle in the plane perpendicular to the forward direction is almost zero. This constraint can be regarded as a velocity update (zero update) along cross-track and vertical axis of the vehicle, i.e., $v_y^b \approx 0$ and $v_z^b \approx 0$, where, v_y^b and v_z^b are the velocity projection in the body frame along cross-track and vertical directions.

Complementary to the non-holonomic constraint, the odometer signal can be regarded as the velocity update along the forward (along-track) direc-

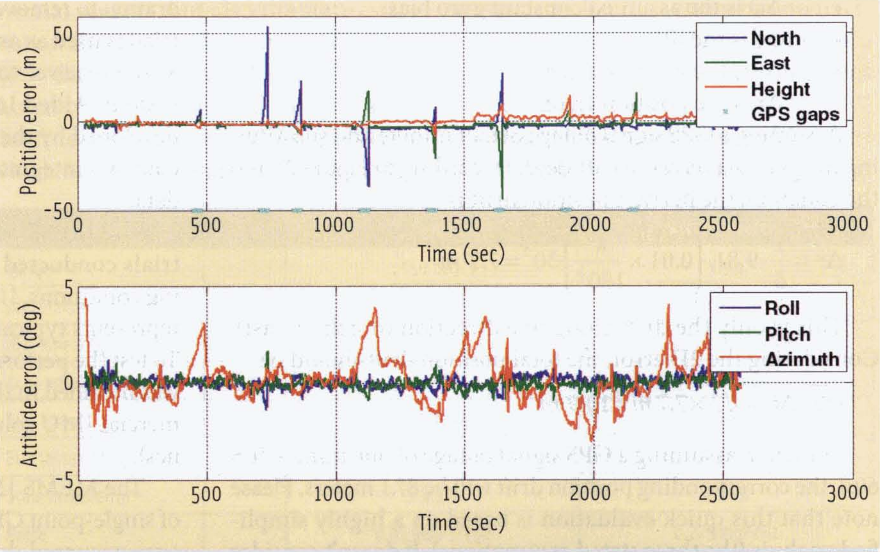


FIGURE 5 Navigation Errors of the MEMS inertial system during 30-second GPS signal outages

tion, i.e., $v_x^b \approx v_{\text{odom}}$ where, v_x^b is velocity projection in the body frame along forward direction; v_{odom} is the derived speed from the odometer signals.

Therefore, the non-holonomic constraint and the odometer signal compose a complete 3-dimensional velocity update in the vehicle (body) frame, i.e.,

$$v^b \approx \begin{bmatrix} v_{\text{odom}} \\ 0 \\ 0 \end{bmatrix}$$

Figure 6 shows the result applying the non-holonomic constraint. Compared to Figure 5, the position drift during most GPS signal outages was decreased significantly. The average position error after 30-second outages was reduced from 30 meters to 17 meters. Furthermore, the azimuth accuracy improves significantly as well. The maximum error was reduced from a few degrees to one degree. This is because the non-holonomic update improved the observability of the azimuth.

Further applying the odometer update with non-holonomic constraint continues reducing the position drift in GPS outages to 6.5 meter, as shown in **Figure 7**. Here the position error of the single-point GPS has became the dominant part of the error rather than the drift from the inertial. **Figure 8** shows the 2D position drifts during a GPS signal outage, which clearly indicates that the non-holonomic constraint (green) reduced the cross-track drift while the odometer update reduced the along-track drift effectively.

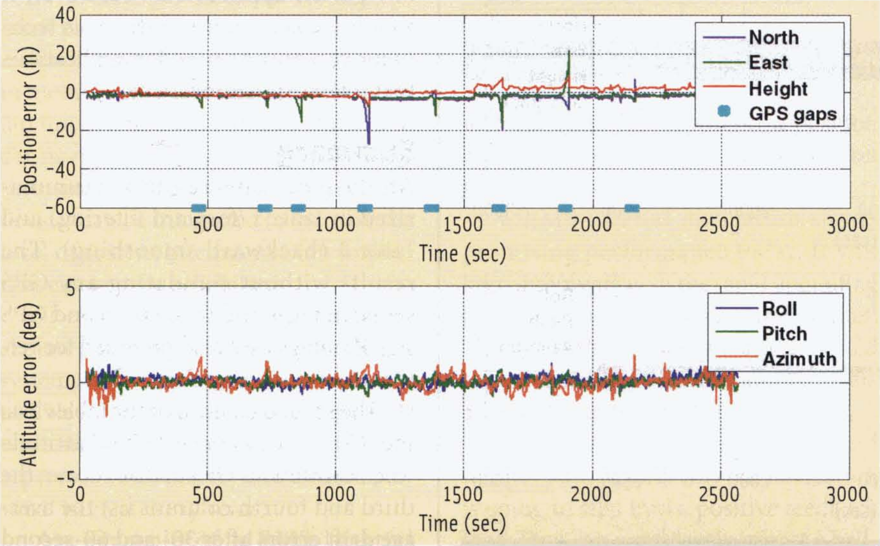


FIGURE 6 Navigation Errors of the MEMS inertial system during 30-second GPS signal outages (with non-holonomic constraint)

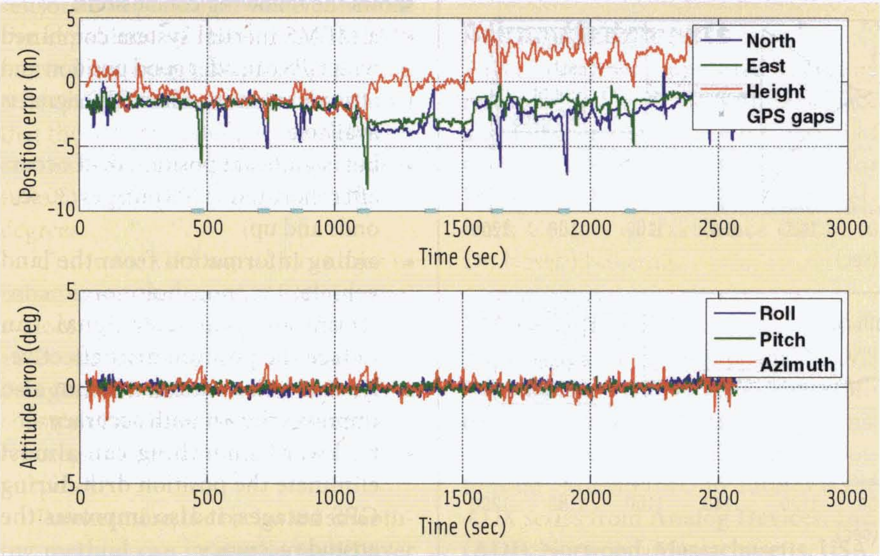


FIGURE 7 Navigation Errors of the MEMS inertial system during 30-second GPS signal outages (with non-holonomic constraint and odometer update)

Obviously, the more aiding information from the vehicle, the better navigation performance we can get. But considering the application scenario, the odometer signal has to be picked either from the transmission or the anti-lock braking system of the vehicle, which would require professional installation and is not quite feasible as a consumer product.

Actually, if the odometer signal is available, then a simple dead-reckoning system composed of the odometer and a heading gyro, plus update from GPS, can do a similar great job for car navigation. The IMU can be omitted to save cost. Relatively speaking, the option of applying non-holonomic constraint is feasible in many cases, and the performance is acceptable, as shown in Figure 6.

Backward Smoothing

Some applications of MEMS inertial system allow postprocessing of the data, e.g., road survey. In that case, backward smoothing can be considered to improve the navigation accuracy. This smoothing can be understood as a kind of weighted average of the forward solution and backward solution.

The processing algorithm that we used, AINS, has a module to run the Rauch-Tung-Striebel (RTS) smoother, which is a well-known fixed-interval smoother for linear filters. The backward smoothing result is shown in **Figure 9**. Compared to Figure 5, the position drift in GPS outages drops tremendously! Actually it is hard to notice the position error caused by the GPS absence. The attitude error is also reduced significantly, especially the azimuth.

Figure 10 is a zoom-in comparison of the position drifts during the fourth

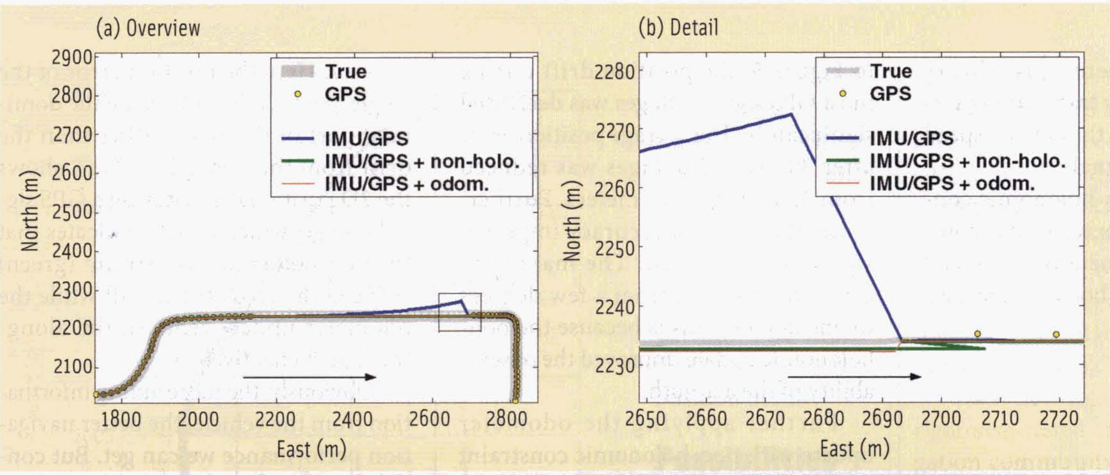


FIGURE 8 A typical case showing the effect of non-holonomic constraint and odometer update during GPS signal outages

GPS outage, which is highlighted by the orange circle in Figure 9. It shows how backward smoothing significantly bridges and smoothes the forward position drift. The figures clearly indicate that backward smoothing can offer excellent accuracy that satisfies many of the navigation applications. However, it should be kept in mind that this technique can only be used for applications that tolerate postprocessing.

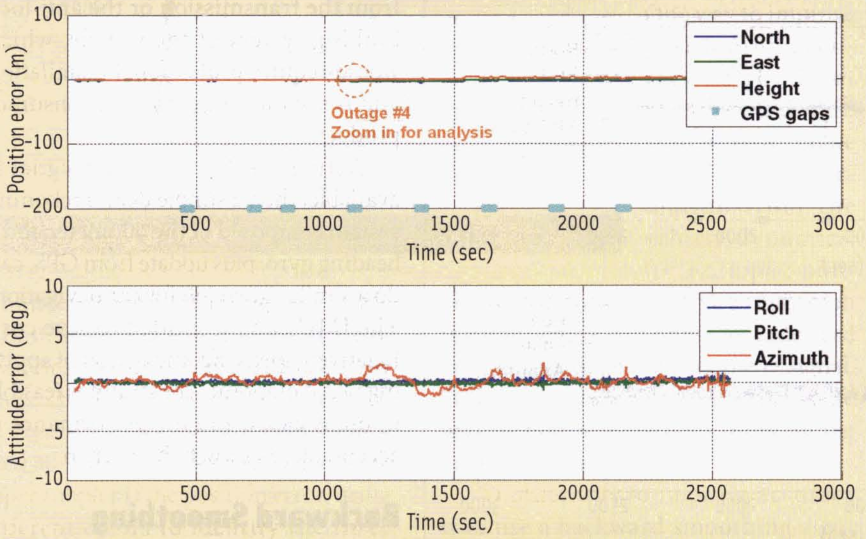


FIGURE 9 Backward smoothing errors of the MEMS inertial system during 30-second GPS signal outages

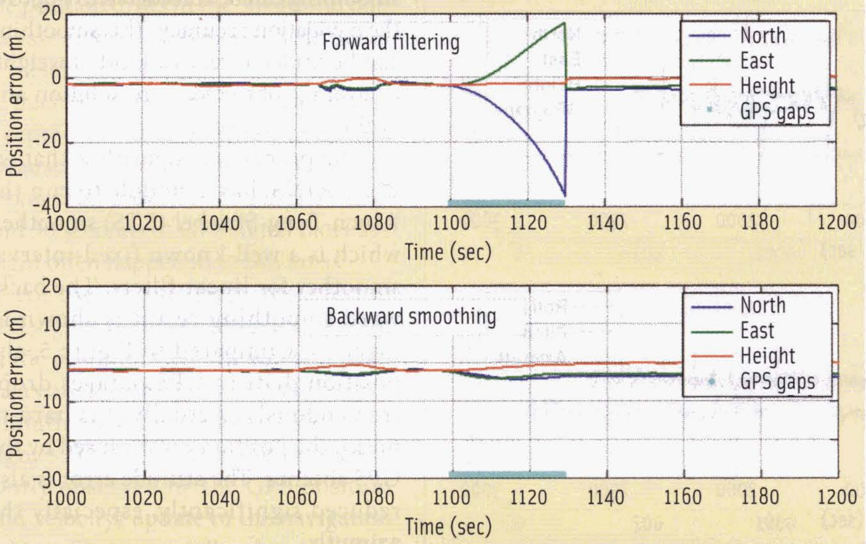


FIGURE 10 Comparison of Forward Filtering and Backward Smoothing Position Drift during a GPS Signal Outage

Summary

All the processing results are summarized in **Table 5** (forward filtering) and **Table 6** (backward smoothing). The results without simulating any GPS signal outages and with 60-second GPS signal outages are also provided for reference.

The second column of the tables lists the RMS error of position and attitude when continuous GPS updates occur; the third and fourth columns list the average drift errors after 30- and 60-second GPS signal outages, respectively.

Comprehensive analysis of the results shows the following conclusions:

- a MEMS inertial system combined with GPS can offer good position and attitude solutions when GPS signal is available
- but significant position drift occurs after short-term GPS outages (30 seconds and up)
- aiding information from the land vehicle, i.e., non-holonomic constraint and odometer signal, can reduce the position drift effectively; non-holonomic constraint also improves the azimuth accuracy
- backward smoothing can almost eliminate the position drift during GPS outages; it also improves the attitude accuracy
- the more other aiding information used in the system, the less sensitive

Filtering	RMS error with GPS update	Drift error in 30S GPS gap	Drift error in 60s GPS gap
GPS/INS	3.53 m 0.93 °	29.8 m 1.88 °	169.2 m 2.79 °
GPS/INS + holo	3.49 m 0.36 °	16.9 m 1.05 °	34.6 m 1.55 °
GPS/INS + holo + odom	3.53 m 0.32 °	6.5 m 0.95 °	11.3 m 1.41 °

TABLE 5. **Summary of MEMS inertial system field test results (forward filtering)**

Smoothing	RMS error with GPS update	Drift error in 30S GPS gap	Drift error in 60s GPS gap
GPS/INS	3.46 m 0.55 °	4.2 m 0.85 °	6.7 m 1.40 °
GPS/INS + holo	3.45 m 0.24 °	4.0 m 0.47 °	5.2 m 0.64 °
GPS/INS + holo + odom	3.45 m 0.20 °	3.9 m 0.40 °	4.3 m 0.51 °

TABLE 6. **Summary of the backward smoothing results**

is the system to the GPS blockage time

- on the other hand, the more additional aiding information used, the less a contribution comes from the inertial part. But the bottom line is that the inertial part can offer 3D attitude information of vehicle dynamics, which is not available from other sensors.

Conclusion

MEMS inertial technology has reached the ridge of its development. The fact that MEMS-based systems are lightweight will translate into decreases in deployment payloads (an important aspect for military applications) and into increases in mobility for personnel and platforms (an 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 (an important element for reliability).

The fact that MEMS-based systems are low power means that personnel and systems incorporating these devices will be able to operate for extended periods without power resupply (an important aspect for both military and civilian personal navigation systems).

An example of MEMS inertial navigation systems based on the commercial off-the-shelf, low-end MEMS sensors was presented to demonstrate the capability of the current MEMS inertial systems. Comprehensive field tests and processing results have shown that the MEMS system works well with continuous GPS updates and offers attitude information as accurate as a few degrees.

Under the GPS signal blockages in urban areas, the tested MEMS inertial system can keep position drift under 10-20 meters with up to half-minute outages, with aiding of non-holonomic constraint of the vehicle. This is certainly acceptable for land vehicle navigation purposes.

Furthermore, the backward smoothing method can be applied whenever data post-processing is allowed. This smoothing can eliminate the position drift efficiently and suppress the position error to the level of the GPS, which is on the order of several meters.

MEMS inertial navigation shows promising performance today. It will keep improving with the rapid upgrading of MEMS sensors entering the market. The cost of these systems is also expected to drop quickly with the blooming, overall MEMS sensor market.

Given the technology push and market pull, MEMS inertial navigation is going to step into a positive feedback loop. One can confidently expect a brilliant future for MEMS POS/NAV. We should be prepared for that day.

Acknowledgments

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Manufacturers

The example of the "top-down" MEMS IMU in Table 3 is an HG1900 from **Honeywell Aerospace Electronic Systems**, Minneapolis, Minnesota, USA; the "bottom-up" MEMS IMU in Table 3 is the ADX series from **Analog Devices, Inc. (ADI)**, Norwood, Massachusetts, USA.

The gyro and accelerometers specifications in Table 4 are based on ADI devices. The sensor triad IMU developed by the University of Calgary Mobile Multi-Sensor Systems Research Group incorporates three ADXRS150 gyro chips and three ADXL105 accelerometer chips from **Analog Devices**.

The MEMS IMU was combined with an OEM4 GPS receiver from **NovAtel, Inc.**, Calgary, Alberta, Canada, to produce the integrated navigation system used in the field trials. A Commercial IMU (C-IMU) from **Honeywell Corporation**, Phoenix, Arizona, USA, was used with differential GPS positioning as the reference system for the field trials.

Silicon micromachined capacitive gyros are produced by Analog Devices and **Kionix, Inc.**, Ithaca, New York, USA. Piezo-ceramic devices are available from **NEC Tokin**, Tokyo, Japan, and **Murata Manufacturing Co., Ltd.**, Kyoto, Japan; thin-film resonators deposited with PZT from **Matsushita Electric Industrial Co., Ltd.**, Tokyo, Japan; quartz from **Seiko Epson Corporation**, Nagano, Japan; and **Microcomponents SA**, Grenchen, Switzerland. These are all single axis solutions.

Currently, Murata manufactures a piezoceramic single-axis solution that costs $7–8. **Sony** and **InvenSense Inc.**, Santa Clara, California, are examples of companies with two-axis solutions estimated to cost under $10. Today, the smallest packaged device is 21 mm^3 — a single axis quartz piezoelectric gyroscope from Seiko Epson. At 6 mW, it is also the lowest power solution, in part due to a lower drive voltage compared to 5V drive capacitive gyroscopes.

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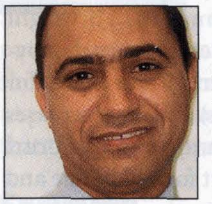

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