The Battle Between MEMS and FOGs for Precision Guidance

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IDEA IN BRIEF

Fiber optic gyroscopes (FOGs), previously the low cost equivalent to other technologies such as ring laser gyroscopes (RLG), have some fresh competition. Microelectromechanical system (MEMS) gyroscopes are beginning to take market share away from traditional FOG applications. Specifically, antenna array stabilization, agricultural machine control, and general vehicle navigation are the battlegrounds where MEMS and FOGs faceoff.

To determine the similarities between the two technologies for use in navigation applications, a comparison of select high-end MEMS gyroscopes to low-end FOG gyroscopes is explored. The navigation software and test cases are controls used in the analysis to determine whether MEMS are truly prepared to function at tactical navigation performance levels.

MEMS FOR PRECISION GUIDANCE

In the last few years, the navigation industry has seen MEMS gaining traction due to improved error characteristics, environmental stability, increased bandwidth, better *g*-sensitivity, and the increasing availability of embedded computational power that can run advanced fusion and sensor error modeling algorithms.

New precision inertial navigation system (INS) markets are materializing and MEMS technology is also entering markets that were previously dominated by FOG technology. An apparent transition from FOG to MEMS technology is in antenna array stabilization applications.

Machine control applications could also benefit from the advancements in MEMS technology. Traditionally, users have gravitated towards FOG or RLG navigation systems costing $30,000+ because the performance has been 20 times more accurate and reliable than a representative $1,000 MEMS navigation system. Precision agriculture and UGV/UAV/USV are two examples of applications that would greatly benefit from improvements of low cost MEMS navigation.

REAL-TIME NAVIGATION HARDWARE

The navigation system used in this work was designed to provide high rate attitude outputs to a motor, which then stabilized an antenna array on the roof of a vehicle. The antenna array's purpose was to maintain communication with a geostationary satellite.

The navigation system was used as a strapped down INS/GNSS navigator, which provided high rate positions and velocities. Inertial measurement unit (IMU) data flowed to the navigation filter at 1000 Hz, and these data packets were used to predict the position, velocity, and attitude solution. GNSS positions, velocities, and headings derived from dual antennas were used as updates to the navigation filter. When GNSS was not available, a magnetometer was used to help initialize the heading. A barometer was also used to aid altitude.

Special calibration routines occurred in parallel to the navigation filter. These routines calibrated the magnetometer, the dual-antenna mounting misalignment, the IMU mounting misalignment, and the level of vehicle vibrations for static period detection.

The system was designed to operate in two hardware configurations. The first configuration consisted of two FOGs (for heading and pitch angles), one MEMS gyroscope (for roll), a triaxial MEMS accelerometer, a triaxial MEMS magnetometer, and a MEMS barometer with a total sensor hardware bill of materials (BOM) cost of about $8,000 for low volumes.

The second configuration contained three MEMS gyroscopes (for all attitude angles), the same triaxial MEMS accelerometer, triaxial MEMS magnetometer, and MEMS barometer as the previous configuration with a total cost of about $1,000 for low volumes. The prices of these systems can fluctuate with market conditions and volume, but generally, FOGs are eight to ten times more expensive than the MEMS.

The MEMS gyroscopes and accelerometers chosen for this design have very good bias stability, orthogonality, *g*-sensitivity, and bandwidth within their price class. The primary constraint of this system is the high bandwidth requirement. Many MEMS accelerometers offer a high bandwidth, but MEMS gyroscopes typically have 100 Hz bandwidth or less. This is fine for typical vehicle navigation, but the application for which this system was designed needed to accommodate high rate control. Moreover, several MEMS gyroscopes that provide good bias stability are available but have reduced bandwidths or high noise. The MEMS gyroscopes chosen for this system balanced bandwidth with performance. The actual specifications of the MEMS chosen are given in Table 1.

Table 1. MEMS IMU Specifications (ADIS16485)

	Measure	Value	Units
Gyroscopes	Bandwidth	330	Hz
	Bias instability	6.25	deg/hr
	Angular random walk	0.3	deg/sqrt(hr)
	g-sensitivity	0.009	deg/s/g
Accelerometers	Bandwidth	330	Hz
	Bias instability	32	µg
	Velocity random walk	0.023	m/s/sqrt(hr)

Adoption rates of inertial MEMS are on the rise. As a result, there has been significant investment towards advancing the technology.

The MEMS gyroscopes used in this system incorporate a multicore architecture which provides an optimized balance of stability, noise, linearity, and linear-*g* performance. Fully differential quad resonators are closely combined with on-chip high performance signal conditioning, resulting in the required response range of the resonator being minimized to a highly linear region, as well as providing a high degree of vibration rejection.

With the MEMS gyroscopes and accelerometers integrated into the multiaxis IMU (see Figure 1), a potentially dominant error source is the x/y/z orthogonality of the sensors. It is common to specify this as either cross-axis sensitivity or misalignment. It is fairly typical to see a specification of ±2% cross-axis sensitivity. The subject IMU of this system has a cross-axis sensitivity of 0.087% (0.05° degree orthogonality). More importantly, this specification holds over temperature, as a result of a device specific calibration done at the factory. For a given rotation rate, for instance on the yaw axis, the orthogonal axes will have rate output equal to CrossAxisSensitivity × YawRate, even when there is zero real rotation on the roll and pitch axes. A 2% cross-axis error will typically result in an order of magnitude greater off-axis noise adder beyond the native gyro noise; whereas, the 0.087% sensitivity of the IMU here is carefully balanced to the native gyro noise level.

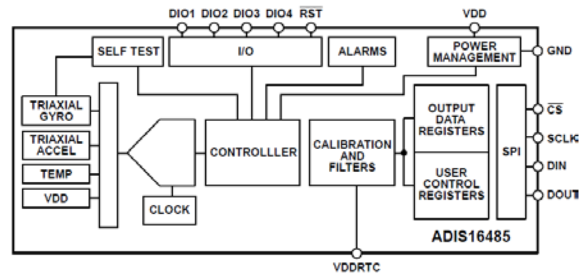

Figure 1. MEMS IMU Configuration (ADIS16485)

Available bandwidth and its associated relevance to the ability to phase match across the axes is also critical to multiaxis designs. Some gyroscope structures have restricted bandwidths associated with total noise reduction, while others have limited bandwidth (typically below 100 Hz) as a result of the sensor processing used in the feedback electronics. This can result in added phase-related errors rippling through the sensor signal path, particularly in the Kalman filter. With 330 Hz of available bandwidth and an embedded and tunable filtering system, the MEMS IMU provides a well balanced approach to minimize the total error sources and allows for system-specific error optimization with the embedded filtering, even in the field.

The core sensors used in this MEMS IMU have inherent strengths in vibration rejection, as well as in linearity, making their performance not only suitable to high dynamic applications, but particularly robust and predictable over environmental extremes as well.

The FOGs used in this design were chosen based on a combination of price, performance, and size. The bandwidth, bias stability, and noise level of the FOGs were a determining factor in the final choice of the sensors. The important performance parameters are given in Table 2. The FOGs have better bias stability and a significant improvement of angular random walk in comparison to the MEMS.

Table 2. FOG Specifications (uFors-6U)

	Measure of Performance	Value	Units
Gyroscopes	Bandwidth	1000	Hz
	Bias stability	3	deg/hr
	Angular random walk	0.1	deg/sqrt(hr)

NAVIGATION SOFTWARE

The real-time navigation software processed the solution at 1000 Hz and used traditional SINS mechanization with measurement updates. The measurement updates came from a variety of sources including:

1. GNSS positions and velocities
2. Dual antenna heading updates
3. Magnetometer heading updates
4. Barometer height updates
5. Optional speed updates from the vehicle OBDII

Each update was used to correct the drift of the INS-only solution, but the updates themselves could be interrupted or inaccurate.

Dual antenna heading updates have good accuracy but are prone to multipath. Therefore, the dual antenna heading updates were only reliable in open sky. The same can be concluded for the position and velocity estimates coming from the GNSS receiver, also benefitting from SBAS.

Heading estimates from the magnetometer could be affected by large inclination angles due to poor vertical observability during calibration. Magnetometers can also be inaccurate around other ferrous materials, such as when driving beside other vehicles. Thus, the magnetometer was used to help initialize the system when GNSS was not available or to help reduce heading drift during very long GNSS outage periods (e.g., 20 minutes).

The barometer was used to aid altitude readings when GNSS was unavailable or inaccurate. The speed updates were used to prevent velocity from drifting without GNSS updates, especially in the along-track direction. These speed updates also aided in reducing the position uncertainty of the solution, which helped to reject poor GNSS position updates. The entire navigation software was designed to provide accurate results in any GNSS condition.

NAVIGATION TESTS

To properly compare both systems, three system-level navigation benchmarking tests were devised:

1. Open sky with good GNSS signals to assess the accuracy of roll, pitch, and heading.
2. GNSS multipath scenarios, such as in urban downtown areas where the GNSS solution could be poor quality due to tall buildings. The intent of this test was to compare the filtered position performances which would also show attitude and velocity errors.
3. INS-only performance to evaluate the INS drift in position, which again also represents velocity and attitude performance.

OPEN SKY ATTITUDE RESULTS

With GPS available and a clear line of sight to several satellites, the positioning and velocity results were comparable between both systems. The attitude angles—roll, pitch, and heading—were the primary navigation parameters being compared because they are largely determined by the gyroscope performance.

Table 3. Open Sky Attitude Results

	FOG	MEMS
Roll RMS Error (deg)	0.08	0.10
Pitch RMS Error (deg)	0.08	0.10
Heading RMS Error (deg)	0.13	0.14

The attitude performance was nearly the same when GNSS was available, with the FOGs having about a 5% advantage.

DEGRADED GNSS POSITIONING RESULTS

The next test was designed to compare the two systems in the presence of GNSS multipath. A trajectory was driven in downtown Calgary that included some very narrow alleyways and slow driving in traffic while surrounded by tall buildings.

The focus on performance can now include positioning results as the gyroscopes can be a large contributor to position performance in the absence of quality GNSS measurements. The results of this test show the two systems are comparable. However, the FOG system was approximately 20% to 30% better.

Figure 2 shows a plot of the GPS-only solution. The high precision GPS receiver used in this test experienced some significant signal reflections while navigating the harsh downtown trajectory. The GPS-only solution had errors up to 100 meters.

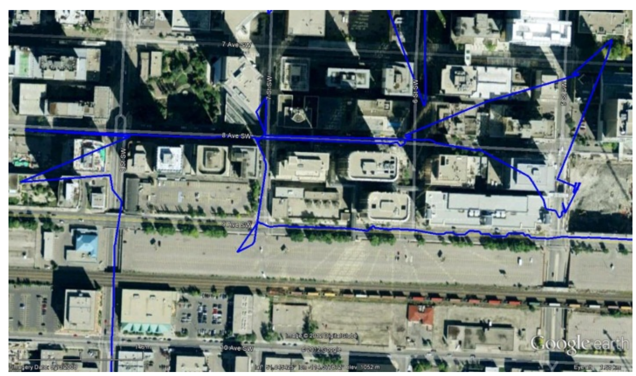

Figure 2. GPS-Only Results with Multipath

The FOG integrated solution in red (Figure 3) clearly shows the path taken by the vehicle and is accurate to 10 meters or better in the downtown area.

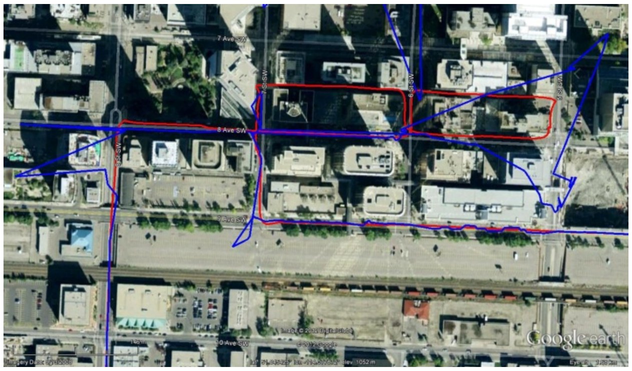

Figure 3. FOG/GPS Integrated Solution (FOG + GPS Red, GPS-Only Blue)

The MEMS solution is shown in Figure 4 in green is within 15 meters at all times. This solution is more prone to "pulls" by bad GNSS position updates because of the weaker weighting of the INS predictions.

Figure 4. MEMS/GPS Integrated Solution (MEMS + GPS Green, GPS-Only Blue)

To help the MEMS solution overcome the inaccurate GPS updates, additional sensors were used. Figure 5 shows the addition of OBDII to the system to obtain vehicle speed.

Figure 5. MEMS/GPS/OBDII Integrated Solution (MEMS + GPS + OBDII Green, GPS-Only Blue)

The MEMS solution is within 10 meters at all times, and may be even slightly better than the FOGs without OBDII, as shown in the zoom-in of Figure 6.

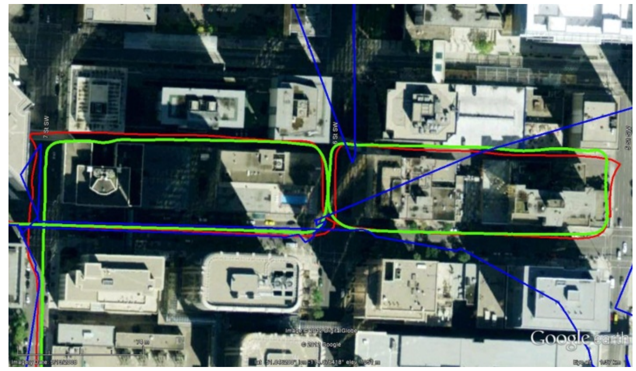

Figure 6. MEMS with OBDII (Green) Compared to FOG without OBDII (Red), GPS-Only in Blue

INS-ONLY RESULTS: EXAMPLE AND BENCHMARKS

The final comparison between the two systems was an INS-only navigation test. The systems were converged using open-sky GNSS updates. The antenna connection was then removed from both systems for 4.5 minutes, and the position drifts were used as indicators of performance. The distance travelled during this time was approximately 5500 meters.

Figure 7 shows an overview of the trajectory. The straight blue line shows where GPS was disconnected at the bottom right to the top left, where it was reconnected.

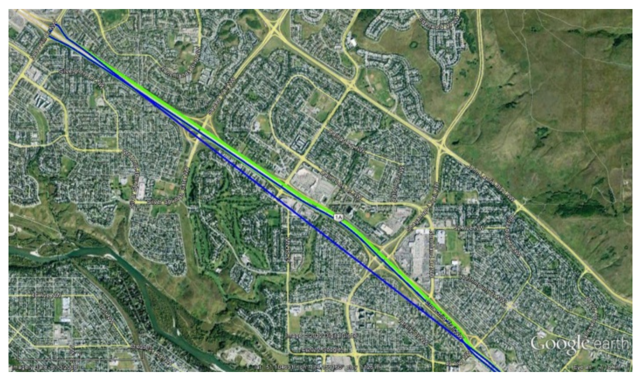

Figure 7. INS-Only Test Path

The FOG system performed very well during this GNSS outage period with a maximum drift of seven meters as shown in Figure 8. Typical drift performance of the FOG system after five minutes has been benchmarked to be 25 meters, so this particular outage was slightly better than typical performance.

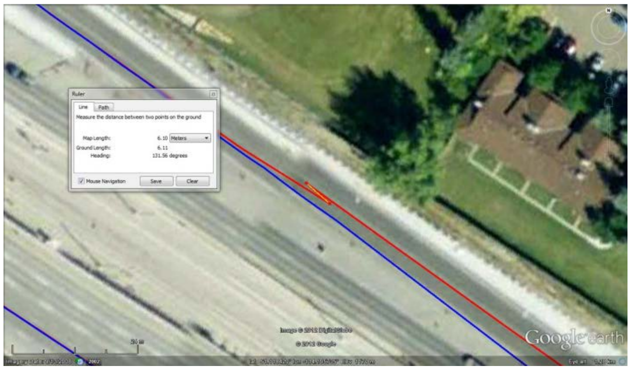

Figure 8. FOG-Only Drift

The MEMS system had a drift of 75 meters after 4.5 minutes without GNSS updates. Much of this drift was along-track error, which is mainly attributed to the accelerometers. The MEMS system has been benchmarked to have a typical drift of 75 meters after five minutes without GNSS updates, which is roughly 3× greater than the FOG drift.

Figure 9. MEMS-Only Drift

The OBDII update was added to the MEMS system and the drift improved to less than 10 meters, or equivalent to the FOG solution. Typical benchmark performance of the MEMS system with the OBDII produces a position drift of about 30 meters after five minutes without GNSS updates, which is also equivalent to the FOG benchmarking results.

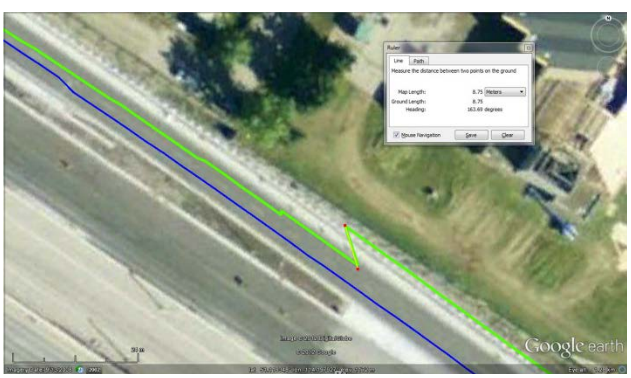

Figure 10. MEMS with OBDII Drift

CONCLUSION

The battle between FOGS and MEMS is a close one, especially now that the performance of MEMS is approaching FOG tactical grade performance levels. FOGs still have an advantage on performance, but are 10× more costly than MEMS. If GNSS is available and the purpose of the application is to operate in open sky, then MEMS can replace some low-end FOGs. If the application is to be used in degraded GNSS environments, then MEMS may also replace some FOG systems, at the expense of 20% to 30% performance.

For standalone INS performance, FOG's still have the advantage, but if the application can accept vehicle or platform speed updates then a MEMS system can be made to perform at the same level as a standalone FOG system.

With consistent advancement of MEMS technology, competitive pricing, and the aid of other sensors (e.g., OBDII), the replacement of FOG technology with MEMS may progress in the near future.

BIOGRAPHY

Dr. Chris Goodall is the CEO/CTO and a co-founder of Trusted Positioning, Inc. Chris has been working in developing, deploying, and evangelizing multisensor navigation systems for over eight years. He obtained his BASc in Systems Design Engineering at the University of Waterloo and his Ph.D in Geomatics Engineering from the University of Calgary. Chris has over 40 publications and six patent applications related to integrated navigation.

Sarah Carmichael is the marketing coordinator at Trusted Positioning, Inc., where she is responsible for all forms of marketing and communications material. Carmichael received her B.Comm. in marketing from the Haskayne School of Business at the University of Calgary.

Bob Scannell is a business development manager for Analog Devices, Inc., (ADI) inertial MEMs products. He has been with ADI for more than 15 years in various technical marketing and business development functions, ranging from sensors to digital signal processing to wireless, and previously worked at Rockwell International in both design and marketing. He holds a B.S. degree in electrical engineering from the University of California, Los Angeles, and an M.S. in computer engineering from the University of Southern California.

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