Inertial MEMS Systems and Applications

N. Barbour, R. Hopkins, A. Kourepenis
The Charles Stark Draper Laboratory (P-5325)
555 Technology Square
Cambridge, MA 02139-3563
USA

email: nbarbour@draper.com

ABSTRACT

This paper provides a survey of some of the available MEMS Inertial Measurement Units (IMUs) and some of the applications that MEMS are fulfilling. Inertial MEMS have been under development for over 20 years and numerous suppliers world-wide now exist. The performance of these IMUs spans the range from consumer/automotive grade (low performance) to tactical grade (~1 deg/hour, ~1 milli g). Tactical-grade IMUs were primarily developed for defense applications to reduce reliance on GPS. The application of automotive quality IMUs to three gun-launched munition tests is described. This is followed by a description of a path that led to a tactical grade IMU and subsequently to gun-hard common guidance IMUs. Other non-gun-hard tactical grade IMUs are mentioned. A brief discussion on packaging improvements that permitted size reduction is presented. Some of the current MEMS IMUs at various levels of performance are described and typical defense and commercial applications are described. Finally, a brief insight into ongoing performance improvement initiatives and what the future may bring are presented.

1.0 INTRODUCTION

MEMS inertial sensors and systems have become indispensable to the future of navigation [Ref. 1]. Also, navigation itself has become much broader than just providing a solution to the question ‘Where am I?’ It has moved into new areas such as games, geolocation, virtual reality, timing, tracking; all of which have been enabled by MEMS technology. Their small size, low power and weight, and low cost have led to increased use, new applications, increased mobility, increased integration (hence better performance) and extended operation. They are also very rugged and can survive tens of thousands of g’s. It been estimated that 752 million units of MEMS accelerometers and gyros were produced worldwide in 2008 with the market dominated by automotive and consumer electronics applications [Refs 2 – 4]. Reference 2 also predicts that the MEMS inertial market will be $3billion by 2013 of which $500million will be for defense and aerospace.

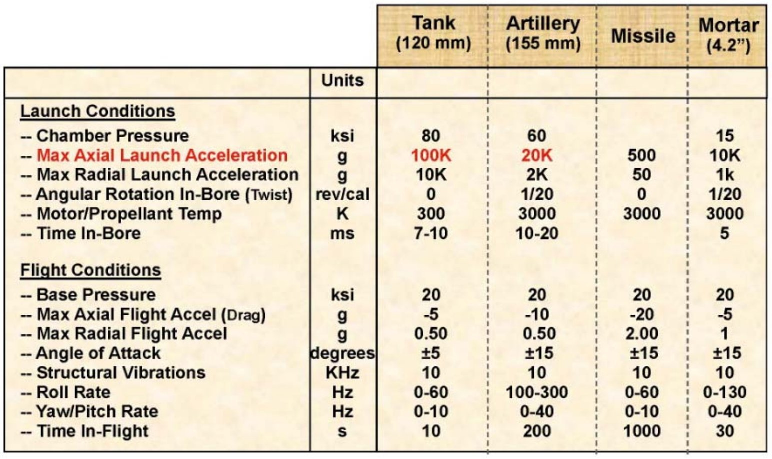
Numerous consumer/commercial grade inertial MEMS systems have been available for several years. These have been integrated with augmentation sensors, such as magnetometers and velocity meters, and GPS aiding to provide an adequate navigation solution. In fact the near universal availability of GPS and other satellite navigation systems means that navigation-on-demand is now expected. The major problem is that GPS is not always available or cannot be acquired quickly enough (for short term applications of a few seconds) so that reliance on the inertial system is necessary. Nor can GPS provide the same flight control/autopilot capability that the inertial system can. This resulted in the development of higher performance MEMS inertial sensors and systems. Several manufacturers now provide all-MEMS inertial measurement units (IMUs) with tactical-grade quality performance (approximately 1 deg/h for the gyro and 1 milli g for the accelerometer), which has enabled MEMS IMUs to be used in numerous military applications such as missiles, munitions, soldier navigation, etc. The performance limitation to tactical grade is due to the gyro not the accelerometer. Current MEMS gyro technology is based on sensing the Coriolis induced force on a vibrating structure, which limits the gyro to behaving as a rate gyro [Ref. 5]. Reference 5 provides a broad description of inertial navigation sensor technology status and developments, including initiatives to develop alternate gyro technologies.

This paper describes some of the applications of inertial MEMS systems. It begins in Section 2with the evolution of MEMS inertial systems for gun-launched applications. It continues with the development of tactical grade IMUs in Section 3. Section 4 provides a brief description of packaging for size reduction. Current MEMS IMUs and their applications are discussed in Section 5. Section 6 outlines what the future may hold.

2.0 EARLY GUN HARD MEMS IMU APPLICATIONS

Current 5-inch gun-launched munitions are limited in range to about 12 nmi and as a consequence of dispersion effects (unsteady winds, propelling charge performance, aiming errors, etc) are not precision weapons and thus are not adequate for Naval Surface Fire Support. Rocket motors can be used for extra boost post gun-launch to increase the projectile range, however without an on-board guidance and control system, the uncertainty of the projectile impact point increases dramatically. The evolution to tactical grade performance is a direct result of advances made in key technology areas originally driven by gun-launched projectile requirements [Refs. 6 – 12]. These applications have a unique combination of requirements including, performance over temperature, high-g launch survivability, fast initialization and startup, small size, and relatively low overall system cost. Table 1 shows typical environments for tank, artillery, missile, and mortar munitions.

Table 1: Munition Environments.



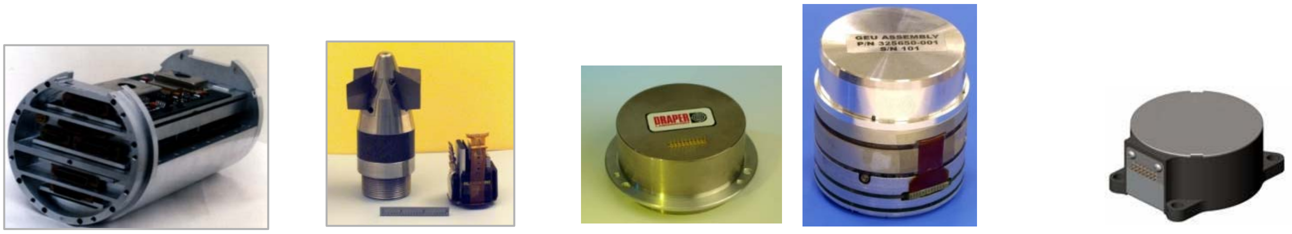
	Units	Tank (120 mm)	Artillery (155 mm)	Missile	Mortar (4.2")
Launch Conditions					
-- Chamber Pressure	ksi	80	60		15
-- Max Axial Launch Acceleration	g	100K	20K	500	10K
-- Max Radial Launch Acceleration	g	10K	2K	50	1k
-- Angular Rotation In-Bore (Twist)	rev/cal	0	1/20	0	1/20
-- Motor/Propellant Temp	K	300	3000	3000	3000
-- Time In-Bore	ms	7-10	10-20		5
Flight Conditions					
-- Base Pressure	ksi	20	20	20	20
-- Max Axial Flight Accel (Drag)	g	-5	-10	-20	-5
-- Max Radial Flight Accel	g	0.50	0.50	2.00	1
-- Angle of Attack	degrees	±5	±15	±15	±15
-- Structural Vibrations	KHz	10	10	10	10
-- Roll Rate	Hz	0-60	100-300	0-60	0-130
-- Yaw/Pitch Rate	Hz	0-10	0-40	0-10	0-40
-- Time In-Flight	s	10	200	1000	30

Ref 12 Brown et al, "Strap-Down Micromechanical (MEMS) Sensors for High-G Munition Applications", IEEE Transactions on Magnetics, Jan 2001

The first MEMS gyroscope was developed by Draper Laboratory in the 1980s. At the beginning of the 1990s the possibility of MEMS IMUs with reasonable performance, when aided by GPS, had become a reality. The capability of MEMS technology in gun-hard applications was demonstrated through a series of technology demonstrations: the Extended Range Guided Munition (ERGM) Demonstration in a munition with rocket motors used for boost post gun-launch; the Competent Munitions Advanced Technology Demonstration

(CMATD) in a 5-inch artillery shell, and the Low Cost Guidance Electronics Unit (LCGEU) in an extended range munition. ERGM Demonstration and CMATD involved guided projectile tests of MEMS INS/GPS systems utilizing the best MEMS sensors available at Draper Laboratory at that time. LCGEU utilized COTS MEMS in a modular INS/GPS designed to be robust to GPS jamming [Ref. 13].

Another program with the goal of reaching tactical grade IMU performance was the DARPA MEMS IMU (MIMU) program in the early 2000s. The culmination of much of this technology evolution was incorporated into the Common Guidance IMU (CGIMU) program, which had the goal of incorporating tactical grade MEMS across multiple tactical weapon platforms. MMIMU and CGIMU are discussed in Section 3. Figure 1 provides a top-level description of the technology roadmap for the ERGM, CMATD, MMIMU, LCGEU, and CGIMU systems.



1995-1997	*1996-2000*	*2000-2002*	*2002-2004*	*2002-2009*
ERGM Demo INS/GPS	CMATD INS/GPS	MMIMU	LCGEU INS/GPS	Common Guidance IMU
Vol = 126 in^3 (2065 cc) Six 1-axis MEMS sensors 500°/hr, 20 mg IMU 24 Watts 6,500-g gun launch	Vol = 13 in^3 (215 cc) Six 1-axis inertial modules 50°/hr, 1 mg IMU 10 Watts 12,500-g gun launch	Vol = 8 in^3 (131 cc) Two 3-axis inertial modules 1°/hr, 100 μg IMU < 3 Watts	Vol = 20 in^3 (328 cc) Two 3-axis inertial modules 300-500°/hr, 10 mg IMU < 12 Watts > 10,000-g gun launch	Vol = 2 in^3 (33 cc) (3 in^3 w/GPS) Single 6-axis inertial module 0.3°/hr, 100 μg IMU < 5 Watts 20,000-g gun launch
C/A to P(Y) Code GPS Tightly Coupled Hybrid Technology	Miniature P Code Engine Direct P(Y) Re-acquisition Tightly Coupled MCM /ASIC Technology	GPS not included P(Y) Code GPS Add-on Deep Integration Compatible BGA/ASIC/MCM Technology	Deep Integration GPS Direct P(Y) Re-acquisition BGA/ASIC/MCM Technology	Deep Integration GPS SAASM GPS Direct P(Y) Re-acquisition ASIC Chip Set

Figure 1: System Technology Roadmap.

2.1 ERGM Demonstration INS/GPS

In March 1995, the Naval Surface Fire Support branch initiated a proof-of-concept demonstration for the Extended-Range Guided Munition (ERGM). The ERGM Demonstration program was the first successful demonstration of a gun-launched MEMS-based INS/GPS system. The system consisted of a 126 in^3 (2065 cc) avionics package containing a 6-degree-of-freedom MEMS inertial system, a Rockwell-Collins C/A-to-P(Y) code reacquisition GPS receiver with L1 tracking only, a TMS320C30 flight processor and power conversion and regulation electronics, which were sectionally mounted into a Deadeye Projectile.

The relatively generous volume of 126 in^3 (2065 cc) allowed conservative, rugged packaging technologies to be used to meet the required survivability goals. Five PWBs were hard-mounted to rigid aluminum frames and bolted into a cylindrical housing with end plates that served as the primary load bearing structure. The sensors and their discrete electronics were packaged using thin-film hybrid MCM-C technology and mounted in bulky hermetic metal housings structurally bonded to standard PCBs. The ERGM Demonstration sensor electronics packaging appears in Figure 2.

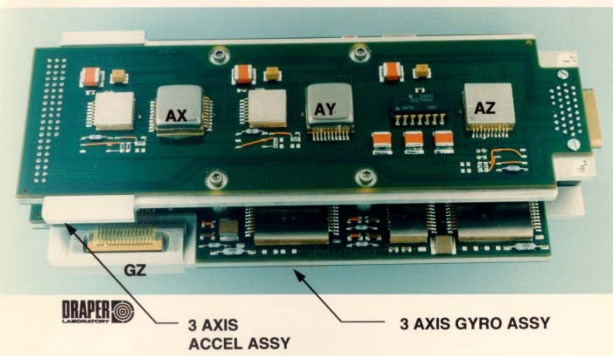


Figure 2: ERGM Demonstration Sensor Electronics Packaging.

A photo of the first of three (November 1996 and two in April 1997) successful ERGM Demonstration test flights is shown in Figure 3. This effort first demonstrated successful reacquisition of GPS after gun launch and proved the survivability and ability of MEMS inertial components to operate after launch and accurately measure body rates and accelerations. The MEMS-based system was composed of repackaged automotive-grade inertial components (Draper Laboratory TFG gyros and pendulous accelerometers with uncompensated performance of 1,000 deg/hr and 50 mg) and was able to perform down-determination successfully and provide inputs for a full navigation solution.

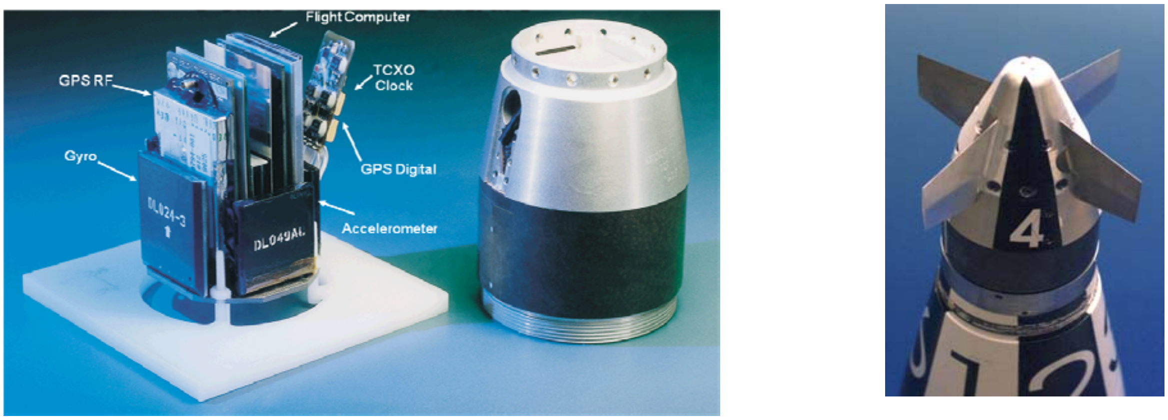
Figure 3: ERGM Demonstration Flight Test.

2.2 CMATD INS/GPS

From March 1996 through February 2000, under funding from the Office of Naval Research, a series of three flight tests for the Competent Munitions Advanced Technology Demonstration (CMATD) Program was completed. The objective was to demonstrate MEMS-based guidance, navigation, and control (GN&C) within the fuze section of unguided artillery rounds. Figure 4 is a photo of the CMATD 5-inch (127 mm) projectile in-flight, 20 ms after the 6,500-g gun launch. The system GN&C is 13 in^3 (215 cc) total, with 8 in^3 (131 cc) for the G&N electronics. Although the MEMS gyros and accelerometers were similar to ERGM Demonstration, the CMATD sensor electronics were the first to be ASIC-based. This contributed to an order of magnitude improvement over ERGM Demonstration performance.

Figure 4: CMATD Projectile in Flight.

The volume constraint of 8 in^3 (131 cc) for the electronics assembly was very aggressive, and is shown in Figure 5. This system consists of a flight computer module, three orthogonal accelerometer modules, three orthogonal gyroscope modules, a two-card GPS receiver, a TCXO clock board, and a voltage regulator card. A backplane and flex cables provide electrical interconnection between modules and external interfaces for system initialization. The modules are over-molded with epoxy to provide mechanical and environmental protection and assist with thermal management. Modules fabricated in this manner have survived centrifuge tests in excess of 30,000 g and more than 400 thermal shocks from -55°C to +125°C.



(a) CMATD Electronics Assembly **(b) Integrated into Mk64 Guidance**

Figure 5: CMATD Electronics Assembly.

The CMATD Program culminated in flight tests of three projectiles at Yuma Proving Ground on August 3, 1999, August 5, 1999, and February 2, 2000. All projectiles were launched at a setback acceleration of approximately 6500 g with initial velocities of approximately 2200 ft/s (670 m/s).

The initial flight tests demonstrated survivability of the overall projectile design and subsystem functionality and performance. From the telemetry data acquired from the first two flights, all six MEMS instruments survived the gun launch and operated as expected and provided accurate in-flight measurements. The lessons learned in these test flights regarding the control actuation system (CAS), roll control software, and launch signal subsystems were modified for the third projectile. Test Flight 3 was conducted February 2, 2000, and the GN&C system survived gun launch and all systems operated. GPS was reacquired successfully at 31 seconds after launch and the closed-loop guidance, navigation, and control executed as designed.

A modified CMATD IMU was evaluated in a Precision Guided Mortar Munition (PGMM) application. The IMU was used for flight control during and after launch without GPS aiding. The PGMM was successfully tested in 2001 through a 7,900 g launch environment.

2.4 LCGEU INS/GPS

The following information is taken from Reference 13. The US Navy initiated an investigation into providing alternate guidance electronic unit technology to address survivability across gun-shocks and enable a significantly lower unit production cost. The LCGEU program’s goal was to develop a gun-hard, low cost INS/GPS system using COTS inertial sensors and other COTS components. The LCGEU contains Analog Devices gyros and accelerometers and is designed to be modular so as to fit into various airframes. The IMU is a 20 cu in (328 cc) system, hardened to 18,000g, and has deep integration software for enhanced GPS anti-jam capability. It was the first ‘common’ guidance unit for US Navy projectiles and was successfully tested in long range guided flights of two Ballistic Trajectory Extended Range Munition (BTERM) in September 2003 (range 53.6 nmi) and in one EX-171 Extended Range Guided Munition (ERGM) in October 2003 (range 44.8 nmi). The two BTERM projectiles impcted 20.5 and 21 meters from the target; the Ex-171 ERGM impacted 10 meters from the target. The BTERM projectile is a rolling airframe (15 – 25 Hz) employing a single actuator driving a pair of canards to compensate for trajectory dispersions along a nominal ballistic trajectory to the target. The Ex-171 ERGM is a non-rolling airframe utilizing four independently articulated canards to stabilize the projectiles orientation and steer it to the target along a boost-glide trajectory. Figure 6 shows an exploded view of the LCGEU.

Figure 6: Low Cost Guidance Electronics Unit.

Because the LCGEU uses commercial grade sensors, the navigation error increases dramatically with loss of GPS. To compensate for this additional anti-jam GPS antenna electronics were included and the navigation filter-formulated data used Draper's Deep Integration algorithms.

Previously, in December 2001, BAE Systems also participated in successful ERGM Control Test Vehicle flight tests in which their SiIMU was used [Ref. 14].

3.0 PATH TO TACTICAL GRADE PERFORMANCE

As long as GPS is available then the use of low performing inertial sensors is acceptable. However, to reduce reliance on GPS, the need for MEMS to reach tactical grade or better is essential. The size, weight, power and cost advantages that MEMS offers would also make MEMS IMUs very competitive with RLG and FOG systems. Therefore significant effort was (and still is) put into improving the performance of MEMS IMUs.

3.1 MMIMU

The Special Projects Office of the Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL) sponsored Draper Laboratory from 2000 to 2002 to develop and demonstrate the world's highest performance MEMS IMU, the DARPA MMIMU [Ref. 15]. The performance requirement was a 10 deg/h, 500 μg IMU with a performance goal of 1 deg/h, 100-μg, and with a unit production cost goal of \$1200. Designed as a low-cost, smaller, low power alternative to Honeywell's ring laser gyro-based tactical-grade HG1700 IMU, the MMIMU is 2.7 inches (68.5 mm) in diameter and 1.4 inches (35.5 mm) high (8 in^3) with a weight of 260 grams. The IMU was designed to perform over a temperature range of -40 to +85°C and consume less than 3 W.

Development experience and the need to design for ease of manufacture and low cost drove the MMIMU designs to much simpler implementations. The MMIMU assembly shown in Figure 7 features a set of four plug-in modules with screw attachments. From top to bottom are the IMU processor, power conversion electronics (PCE), accelerometer, and gyro modules. Each module consists of a PCB mounted to a Kovar frame, and alignment pins are used to guide module-to-module assembly and connector mating. Top and bottom seam-welded covers provide a hermetically-sealed system.

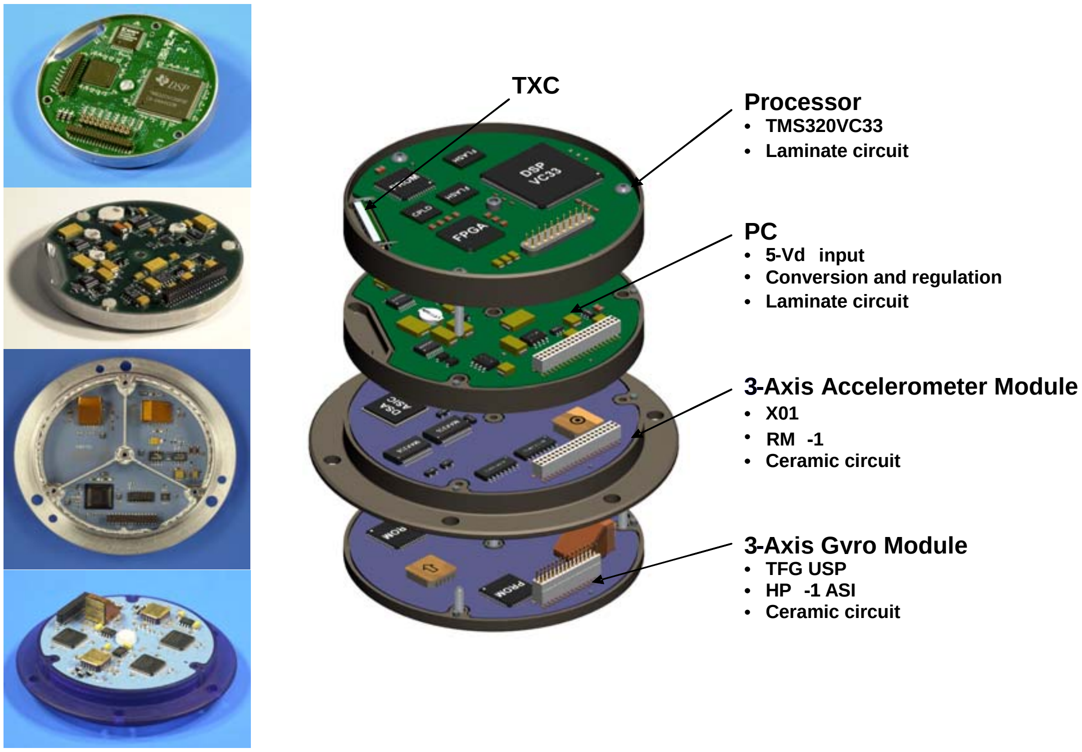


Figure 7: MMIMU Assembly.

To meet the volume constraints, a novel planar stacked disk approach was developed for system packaging. Inertial sensors are hermetically sealed in an leadless ceramic chip carrier (LCCC). A separate 3-axis accelerometer and 3-axis gyroscope instrument module are configured with ASIC electronics, further improved to reduce the number of off-chip components. The two 3-axis inertial instrument modules contained the latest MEMS TFG and pendulous accelerometer sensor designs. Ceramic mounting blocks are employed for the orthogonal set, and a separate mixed-signal CMOS ASIC in a chip-scale package operates each sensor.

ASIC electronics implemented in CMOS processes provide excellent performance at low power and cost, while enabling the small size objectives to be met. Much of the gains in performance experienced in TFG development are directly attributable to the ASIC electronics. The MMIMU gyro ASIC, the High-Performance Gyro digital ASIC (HPG-1), was developed under the DARPA MMIMU Program. This third-generation ASIC uses a high-speed Σ–Δ converter to acquire the gyro rate information directly from the preamplifier. All sense axis processing is performed digitally, eliminating errors associated with drift in the baseband electronics while achieving dynamic ranges in excess of 140 dB. The accelerometer electronics form a differential capacitive measurement system consisting of a carrier signal generator and demodulator circuitry providing a DC output proportional to acceleration. During closed-loop operation, control compensation and rebalance drive circuitry are added. An existing second-generation analog ASIC (RMA-1) was used for the accelerometer. The ASICs were packaged in custom ball grid array packages.

Build of two MMIMUs was started, with one completed and tested by August 2002. Table 2 presents a summary of the MMIMU goals and the actual IMU test data. As of today (2010) these results still represent the highest published performance data attained to date on an all-Silicon MEMS IMU. The DARPA MMIMU Program was the culmination of three years of focused development on advancing the performance of MEMS gyroscopes. This effort leveraged 10 years of development and over $100M of Draper IR&D and government investments in the development of MEMS inertial technology.

Table 2: MMIMU Sensor Performance.

Parameter		***Gyros***		***Accelerometers***	
		Goal	**Actual**	**Goal**	**Actual**
Bias Turn-on Repeatability	*deg/h or mg*	1 (1σ)	3 (1σ) (1)	0.5	2 (1σ) (1)
Bias In-run Stability	*deg/h or mg*	1 (1σ)	5 (1σ) (2)	0.1 (1σ)	1 (1σ) (2)
Bias Drift	*deg/h or mg*		5 (1σ) (3)		2 (1σ) (3)
Scale Factor Turn-on Repeatability	*ppm*	140 (1σ)	70 (1σ) (1)	210	125 (1σ) (1)
Scale Factor In-run Stability	*ppm*	140 (1σ)	100 (1σ) (2)	210	600 (1σ) (2)
Axis Misalignment	*mrad*	0.5	1	0.5	1
Input Axis Repeatability	*mrad*	0.1	0.2	0.1	0.2
Maximum Input	*deg/s or g*	1,000	1,000 (4)	50	45 (4)
Bandwidth	*Hz*	150	150 (4)	100	100 (4)
Angle Random Walk	*deg/√h or m/s/√h*	0.030	0.050	0.035	0.02

Notes: (1) Turn-on to turn-on over 0°C to +70°C, power-down, and mount/dismount, 14 days
(2) Post-compensation over 0°C to +70°C
(3) RSS of turn-on and in-run performance
(4) Typical; other ranges available

3.2 CGIMU

The goal of the US Army's Common Guidance IMU program was to develop a new system that extends the capabilities of the previous systems further yet in terms of highest performance with high launch loads, anti-jam GPS, decreased volume, and low production cost ($1200 per IMU and $1500 per INS/GPS in high volume) [Ref. 16]. CGIMU was a multi-year program in three phases as shown in Table 3 [Ref. 16]. Significant development effort was planned within the scope of this program to shrink packaging volume, power and overall system cost while improving sensor performance. The ultimate goal was to develop a common system for use in the majority of the Department of Defense's tactical applications.

Table 3: CGIMU [Ref 16].

Parameter	IMU Volume	Gyro Performance	Accelerometer Performance	Expected Completion
Phase 1	8 cu in	200 °/h (3σ)	9 mg (3σ)	April 2003
Phase 2	4 cu in	20 °/h (3σ)	4 mg (3σ)	October 2004
Phase 3	2 cu in	1 °/h (3σ)	0.3 mg (3σ)	October 2006

Initially several organizations participated in the CGIMU program. Honeywell, in partnership with Draper Laboratory, was funded in 2001 with the MMIMU technology as the Phase 1 baseline. During this development period effort was also expended on improving anti-jam capability through improved algorithms. Figure 8 (courtesy of Honeywell) outlines Honeywell's Common Guidance technology progression through the subsequent phases; the HG1930 being 4 cu in and the HG1940 2 cu in.

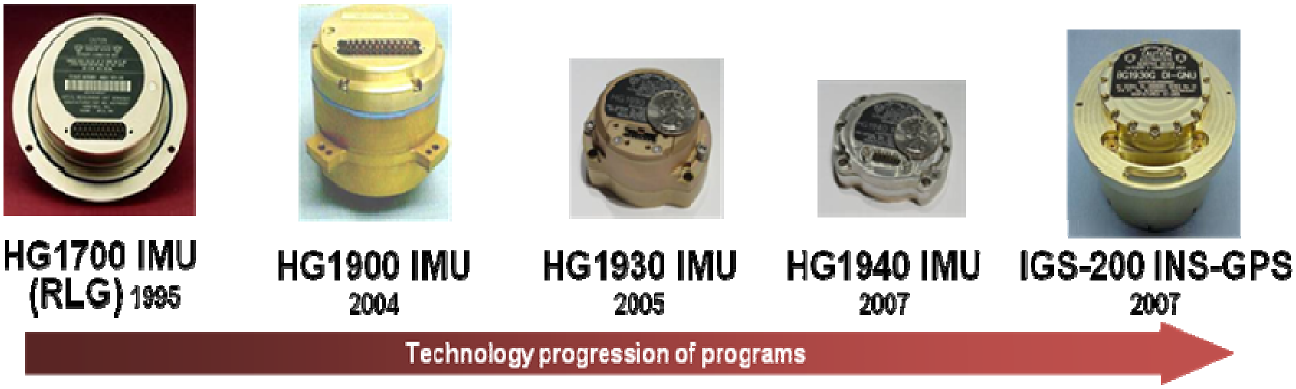


Figure 8: Honeywell's Common Guidance Technology Progression (Published with permission of Honeywell).

3.3 Tactical Grade MEMS IMUs

There now exist several suppliers of tactical grade IMUs and INS/GPS systems. Honeywell has the HG1930 and HG1940 IMUs. In 2006 Integrated Guidance Systems (IGS), a Honeywell and Rockwell Collins joint venture, introduced family of Deeply Integrated Guidance and Navigation Units (DIGNUs) [Ref. 17]. IGS's first product was the IGS-200, a 13.7 cu in (225 cc) gun-hardened system. Subsequent products are the IGS-202 (16.5 cu in) and IGS-250 (7.8 cu in) INS/GPS systems [Ref 17]. BAE Systems (now Atlantic Inertial Systems (AIS) a B. F. Goodrich Company)), Northrop Grumman LITEF, and Systron Donner Inertial (SDI) have all developed tactical grade MEMS IMUs. AIS have the SiIMU02 (~5 cu in) and SiIMU04 (~8 cu in) IMUs as well as the SiNAV (~20 cu in) Inertial Navigation System [Refs. 18 - 20]. LITEF have developed a 20 cu in IMU [Ref. 21] for AHRS applications. SDI have developed the SDI500 IMU (~19 cu in) shown in Figure 9 (courtesy of Systron Donner Inertial). The SDI500 is based on quartz technology. The high signal to noise ratio of the piezoelectric readout from quartz gives the SDI500 very low Angle Random Walk. Systron Donner also has the SDN500 (~25 cu in) miniature integrated GPS/INS system [Ref. 22].

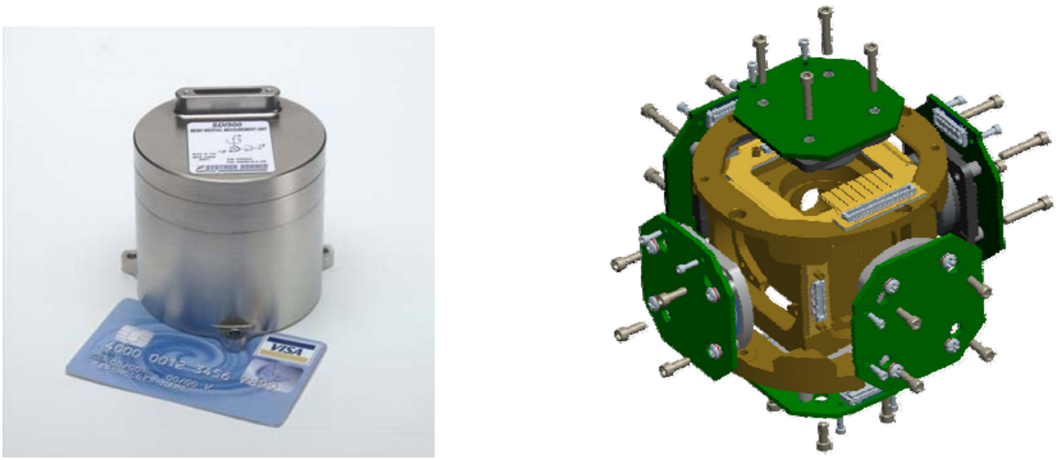


Figure 9: SDI500 with Schematic of Internal Mounting of the Sensors (Published with permission of SDI).

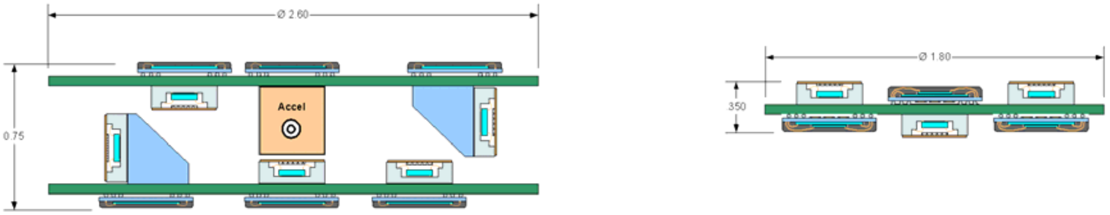
It should be noted that, while the existence of tactical grade IMUs has reduced reliance on GPS, they have not eliminated the need for GPS (whenever available) or other augmentation sensors to ensure mission success. For example, in purely inertial mode, a tactical grade IMU's position error would be around 150 meters in 3 minutes.

4.0 PACKAGING

Packaging considerations are very important for performance as well as survivability and significant packaging challenges arise when trying to minimize the size and cost of a product expected to last 20 years in an uncontrolled environment. In particular, for very high g applications, typical environments may include a 20,000 g setback acceleration, angular rates up to 250 revolutions per second, and a 5000 g set-forward acceleration upon exit from the gun barrel. Also, MEMS sensors tend to have a fairly high sensitivity to external vibration. Therefore, the inertial sensors and electronic assemblies must be properly mounted, especially if they are to survive a gun launch environment. Shock mounts are typically employed for inertial components to attenuate and dampen the high-g launch loads and in-flight vibration inputs.

The size of the inertial sensor modules originally dominated the size of MEMS IMUs. This was not due to the size of the sensing element itself, but from the electronics. Initially, commercial field programmable gate arrays (FPGAs) were often used for many digital functions. Subsequently the electronics were packaged in Application Specific Integrated Circuit (ASICs) with configurable gate arrays (CGAs) to replace FPGAs, and passive conditioning electronics into a custom ball grid array (BGA) package. As ASIC development became more advanced it virtually eliminated all off-ASIC components on the board. This resulted in a ~50% volume reduction in board size. Current packaging is now able to stack (bump bond) 7 or 8 chips in one BGA about 2 mm high. Other advanced packaging techniques use Flat No Leads packages, using landing pads not BGAs.

Another major advance in packaging size reduction resulted from the design and fabrication of planar sensors that could measure in-plane (x-axis and y-axis) or out-of-plane (z-axis) rate or acceleration. Originally, three-axis measurements were achieved by rotating sensor packages on ceramic mounting blocks as shown in Figure 10(a) to get measurements along x, y, and z axes. The ability to use planar mounting of all the sensors further minimizes overall system packaging volume since the ceramic mounting blocks are eliminated. Utilizing a combination of these new sensor technologies and the aforementioned ASIC electronic advances with CGA devices custom packaged in a BGA format enables the realization of a complete 6-axis inertial instrument module as shown in Figure 10(b). This yields a total volume reduction of >75 percent over that in Figure 10(a).



(a) Two 3-Axis Sensor Modules (MMIMU) **vs.** **(b) One 6-Axis Sensor Module**

Figure 10: Improved Packaging.

5.0 CURRENT MEMS IMU APPLICATIONS

As of today, MEMS IMUs have been successfully demonstrated in numerous applications, including the high g applications (e.g., artillery shells, extended range (rocket assisted) munitions, mortar shells, anti-tank weapons) mentioned previously. MEMS IMUs can now be purchased for commercial and military uses from numerous companies. In fact, MEMS is poised to become the worldwide industry standard for the design of nearly all modern smart weapons. Table 4 [Ref. 23] shows typical generic inertial bias from 1991 for missile guidance applications (assuming no GPS, but with other initial or terminal aiding). As shown in the table, MEMS is now able to meet most of these bias requirements. The other major requirement is low noise and achieving this is still an issue for MEMS IMUs.

Table 4: Generic Bias for Missile (no GPS) [Ref. 23].

Mission	Gyro (°/hr)	Accelerometer (μg)
Air-to-Air	10 - 100	500 - 1000
Surface-to-Air	10 – 100	500 – 1000
Air-to-Surface	0.1 – 10	50 – 500
Mid-Course Guidance	0.01 – 1.0	20 – 200
Surface-to-Surface	0.001 – 0.1	5 – 100
Long-Range	0.001 – 0.01	5 – 50

Blue – MEMS can meet. Red – MEMS not yet demonstrated

Tactical grade MEMS IMUs have been fielded in a number of existing and developing weapon systems, such as Excalibur, Small Diameter Bomb, E-Paveway, Hellfire, Joint Common Missile, ERGM, BTERM, etc.

For many applications tactical grade performance, while desirable, is not essential and commercial grade MEMS, with appropriate GPS aiding and other augmentation sensors, will suffice. Table 5 [Ref. 24] shows typical generic bias, scale factor, and random walk for a GPS/inertial guided artillery shell and guided bomb. It can be seen that, even with a certain amount of jamming, inertial MEMS with commercial grade performance is sufficient. However, for the majority of the military applications a tactical grade IMU (or better) is required.

Table 5: Generic Bias, SF and RW for GPS/Inertial Guided Munitions [Ref. 24].

		Gyroscope			Accelerometer		
Range (km)		GPS Off (km)	Bias °/h	SF ppm	ARW °/√h	Bias mg	SF ppm
Guided Artillery Shell							
12	5.6	100	1000	20	70	1000	0.5
30	5.6	2400	1000	46	300	2000	1.7
Guided Bomb							
10.7	5.6	27	1000	0.3	4	1000	2
10.7	From Start	1.5	200	0.1	0.8	300	0.8

Commercial grade MEMS IMUs are currently available from numerous companies and are used in all types of applications. Many of the manufacturers are willing to custom design IMUs to meet the purchaser's specific requirements. The following examples of commercial grade MEMS IMU suppliers provide just a glimpse of the kinds of IMUs that are available worldwide; there are far too many to list. VectorNav's VN-100 provides a 9sensor axis IMU on a single surface mount module [Ref. 25]. It contains Analog Devices ADXL325 accelerometers, Invensense IDG-500 and ISZ-500 gyros, and Honeywell HMC6042 and HMC1041Z magnetometers. O-Navi's Gyrocube3 is a 6 degree of freedom inertial sensor module in just over 1 cu in (16.4 cc) volume. O-Navi also provides the FalconGX integrated digital IMU module in under 2 cu in volume and the PhoenixAX integrated IMU/GPS flight controller [Ref. 26]. Microstrain offers Inertia-Link, an IMU and vertical gyro combining a triaxial accelerometer, triaxial gyro, temperature sensors and an on-board processor running a sophisticated sensor fusion algorithm [Ref. 27]. Analog Devices has the ADIS series all under 1 cu in [Ref. 28]. Gladiator Technologies Inc has the LandMark series of IMUs and AHRS (some with GPS) and the MRM (Motion Reference Module) analog series [29]. Microbotics Inc has the MIDG INS/GPS in a 2 cu in package [Ref. 30]. Xsens has the MTi AHRS and the MTiG GPS aided AHRS [Ref. 31]. MEMSense offers the nIMU (nano IMU) at under 0.9 cu in plus a wireless IMU that transmits data through the Bluetooth protocol [Ref. 32]. Silicon Sensing has the DMU02, six degree of freedom dynamics measuring unit with 1 cu in volume [Ref. 33]. Invensense has the MPU-6000 family which claims the world's first 3-axis gyro and 3-axis accelerometer on the same silicon die together with an onboard digital motion processor in a Quad Flat No Leads (QFN) package [34].

Typical uses for commercial grade IMUs are in Integrated Navigation Systems, Attitude and Heading Reference Systems (AHRS), autopilots, dynamic environment monitoring and control systems. Typical applications are: Unmanned Aerial Vehicles (UAVs); drones; underwater vehicles; personal/pedestrian navigation; mobile mapping systems; human motion analysis; authentication; remote health monitoring; event monitoring (e.g., aircraft stores (weapon) separation); vehicle dynamic stabilization; motion gaming; optical image stabilization; antenna stabilization; platform stabilization; robotics; testing; targeting; and many others. The automotive industry is the second biggest MEMS market world-wide with many applications (such as navigation, roll detection, inclinometers, air bags) using low cost, low performance inertial sensors [Ref. 3]. For several applications, such as gun pointing and stabilization, only 2-axis or 3-axis MEMS rate gyro packages (such as Honeywell's GG5220 and GG5320 [Ref. 35]) are required.

An area of particular interest is soldier and pedestrian navigation and positioning in GPS unavailable environments. Numerous studies and field tests have been published, most of which have used commercial grade IMUs with various augmentation sensors. A common packaging technique is to combine the sensors into a boot as shown in Figure 11 from Carnegie Mellon University [Ref. 36]. References 37 - 39 describe soldier navigation systems that use a tactical grade IMU.

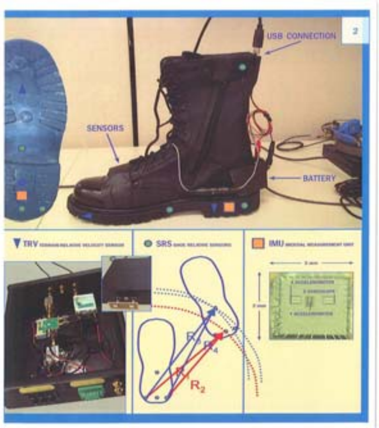


Figure 11: Boot Mounted Soldier Navigation [Ref. 35 Carnegie Mellon University].

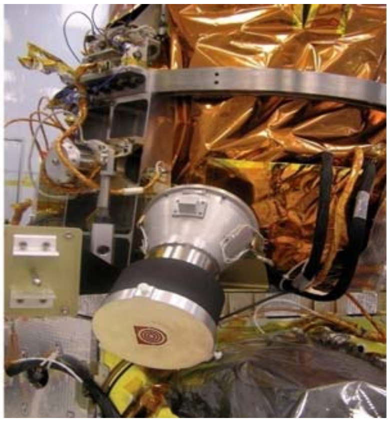


Photo Credit: Tye Brady

Figure 12: Inertial Stellar Compass [Ref 40].

Reference 37 also describes a range of typical miniature augmentation sensors that are currently being used in integrated navigation systems.

Another area of interest is the use of MEMS IMUs in space. The extremely low weight and low power requirements makes MEMS very attractive. The first MEMS gyro in space was JPL's clover leaf gyro followed by Systron Donner's quartz rate sensor on Mars Rover. In 2006 the Inertial Stellar Compass (ISC) was launched on a TacSat-2 spacecraft [Ref. 40]. The ISC was developed by Draper Laboratory and combined a MEMS inertial reference unit with a star camera and a processor. The ISC provides spacecraft attitude information at up to 5 Hz with accuracy <0.1 degree, at less than half the power of conventional systems. The European Space Agency (ESA) has funded several market analyses and feasibility studies [Ref. 41] based on European developments of MEMS gyros by companies such as BAE SYSTEMS (UK), Bosch (Ger), EADS CRC (Ger), LITEF (Ger), Sagem (Fr), Sensonor (Norway), and Thales (Fr). Desired goal is around 0.1 deg/h bias stability.

Since there are so many commercial grade IMUs with different characteristics and different performance, several performance comparisons of have been made. A recent study [Ref. 42] looked at the Crossbow 400CC IMU, the AXIS AIS402 GPS aided AHRS, and the XSens MTi IMU. The conclusion drawn was that individual calibration plus the use of post-processing algorithms significantly reduced the position drifts. Another study [Ref. 43] evaluated an IMU containing two dissimilar sets of MEMS accelerometers and gyros that could be combined differently. The gyro sets were two types of modified automotive grade gyros, the accelerometer sets were Bosch SMB225 and Colibrys MS9010. The IMU was calibrated and flown in a test aircraft with the IMU integrated with GPS. The results verified the calibration model and showed that good navigation results could be achieved with all sensor combinations.

Attempts to improve the low frequency drift and reduce the high frequency noise of MEMS IMUs are continuing.

In the area of AHRS and northfinding, the best tactical grade MEMS gyros are currently an order of magnitude worse than the application requirements. One approach has been to introduce gyrocompassing with gimbals to compensate for bias drift [Refs. 44 and 45]. The incorporation of miniature gimbals has also been shown to produce performance improvements by an order of magnitude by allowing periodic calibration and alignment. The problem is to make the gimbals small enough. Another technique to improve performance, especially over high dynamic range, is to use controlled arrays of MEMS sensors. This was used in the early development of guided artillery shells [Ref. 6]. Reference 46 describes a patent for optimally combining measurements from individual rate sensors into a significantly improved rate estimate. Results from a three year US Army component development program that investigated multiplexed COTS and custom accelerometer arrays, have demonstrated two orders-of-magnitude increase in dynamic range [Ref. 47]. Also shown was that the integration on the same chip of an angular rate sensor with an accelerometer array and temperature sensors improved gyro compensation for vibration and thermal effects. Co-location and integration of several devices on the same chip will not only reduce size of MEMS arrays significantly, but should also improve the overall performance.

6.0 THE FUTURE

For military applications, the major goals continue to be decreased reliance on GPS, increased system accuracy, reduction in collateral damage, and increased effective range, while at the same time minimizing size and cost. Several sensor technology developments, as discussed in Reference 5, need to occur for this to take place. This relies on the success of one or more of the following: (i) development of a rate integrating MEMS gyro (DARPA MRIG program [Ref. 48]); (ii) development of a navigation grade gyro (DARPA NGIMG program [Ref. 49]); (iii) development of miniature cold atom sensors; and (iv) development of optical MEMS gyros. The success of another important development program, DARPA Single Chip Timing and Inertial Measurement Unit (TIMU) [Ref. 50], is also key to enabling self-contained, chip-scale inertial navigation (no GPS) with micro-systems. Significant challenges are involved in TIMU: accurate sensors for a dynamic environment; reduction of long-term bias drift; deep integration of clocks with the IMU; development of innovative fabrication processes and advanced architectures integrating timing and IMUs. Success of the above programs will result in MEMS systems meeting over 90 percent of precision weapon guidance, navigation and control needs. It should be noted that even with high performance sensors, augmentation sensors and GPS aiding will likely still be used wherever possible.

Market trends in MEMS have been reported in Reference 2. The market for MEMS sensors and IMUs has increased steadily from ~\$1.8B in 2009 and is expected to reach ~\$3B in 2013. The market is currently dominated by automotive and consumer electronics applications, with the latter becoming the primary user of MEMS inertial by 2011. Use of MEMS in the defense area will grow due to the existence of tactical grade IMUs, which will open up a wide range of applications.

The vision for far future MEMS inertial systems therefore appears very promising, although many technical challenges need to be overcome. The possibility of one to two orders of magnitude gyro performance improvement exists. Accelerometers have already reached strategic grade performance in a laboratory setting.

Wafer-scale integration of high-performance planar array sensors, with multi-channel digital ASICs and multi-axis on-chip sensors, will create complete systems on a chip, offering a further order of magnitude reduction in volume. Using high-volume foundries, these sensors and IMUs will thereafter be reduced to commodity items and installed as chip sets in higher-level systems. Commercial applications will evolve to take advantage of the higher performance afforded by these technologies. Self-locating cell phones, intelligent vehicle highway systems, personal navigation, and autonomous control are all applications poised to integrate these technologies and exploit its utility. Analogous to the proliferation of GPS into common life, once these technologies are available, engineers and designers closest to the problems will find techniques to employ singular or integrated aspects of these technologies to address existing and new needs. Future INS/GPS system designers will be able to select inertial and GPS chip sets with desired performance attributes out of catalogs in the same manner that an analog circuit designer selects operational amplifiers today.

7.0 ACKNOWLEDGEMENTS

This paper is the latest updated version (for NATO Lecture Series SET-116 in 2011) of 'Inertial MEMS Systems Applications' that was previously presented at NATO Lecture Series SET-064 in 2003/2004 (Draper P-4153) and updated for SET-116 in 2008/2009 (Draper P-4703) and updated again for SET-116 in 2010 (Draper P-4993).

8.0 REFERENCES

[1] El-Sheimy N. and X. Niu, *The Promise of MEMS to the Navigation Community*, Inside GNSS, March/April 2007

[2] Yole Developpement, *MEMS Accelerometer, Gyroscope and IMU Market 2008 – 2013*, http://www.yole.fr 2009

[3] Dixon R. and J. Bouchard, *Prospects for MEMS in the Automotive Industry*, Think Small Feature Article, July 2007 www.wtc-consult.de

[4] Bouchard J., *Taking the Pulse of the MEMS Industry*, Think Small Feature Article, April 2007 www.wtc-consult.de

[5] Barbour N., *Inertial Navigation Sensors (SET 116),* NATO Lecture Series SET 116 on Low Cost Navigation Sensors and Integration Technology, March/April 2011

[6] Gustafson D., R. Hopkins; N. Barbour and J. Dowdle, *A Micromechanical INS/GPS System for Guided Projectiles,* ION 51st Annual Meeting, Colorado Springs, CO, June 5-7, 1995

[7] Dowdle, J. and K. Flueckiger, *An Integrated GPS/Micromechanical IMU for Navy 5" Projectiles*, The Institute of Navigation Conference, Cambridge, MA, June 18-20, 1996

[8] Connelly, J., and G. Brand, *Advances in Micromechanical Systems for Guidance, Navigation, and Control*, AIAA Guidance, Navigation and Control Conference, New Orleans, LA, 11-13 August 1997

[9] Gai, E., *Guiding Munitions with a Micromechanical INS/GPS System,* 4th St. Petersburg Conference on Integrated Navigation Systems, St. Petersburg, Russia, May 1998

[10] Kourepenis, A., J. Borenstein, J. Connelly, R. Elliot, P. Ward, M. Weinberg, *Performance of MEMS Inertial Sensors*, 24th Joint Services Data Exchange Conference, Anaheim, CA, November 16-20, 1998

[11] Anderson, R., D. Hanson, and A. Kourepenis., *Evolution of Low-Cost MEMS Inertial System Technologies*, ION GPS 2001, Salt Lake City, UT, September 11-14, 2001

[12] Brown, T. et al, *Strap-Down Microelectromechanical (MEMS) Sensors for High-G Munition Applications*, 10th Electromagnetic Launch Technology (EML) Symposium, San Francisco, CA, 25-28 April 2000. Journal: IEEE Transactions on Magnetics, vol. 37, no. 1, pt. 1, p. 336-42, January 2001

[13] Coskren D., Easterly T., and R. Polutchko, *Low-Cost GPS/INS Guidance for Navy Munitions Launches*, GPS World, Vol 16, Issue 9, September 2005

[14] http://www.baesystems.com/Newsroom/NewsRelease/2002

[15] Sitomer, J., J. Ha, A. Kourepenis and J. Connelly, *High-Performance MEMS Inertial Measurement Unit (MMIMU) for Tactical Applications*, IEEE PLANS 2002, Palm Springs, CA, April 2002

[16] Warnasch A., and A. Killen, *Low-Cost, High G, MEMS IMU Program*, IEEE PLANS 2002, Palm Springs, CA, April 2002 and US Army solicitation DAAE30-01-BAA-0101, 2002

[17] http://www.igsllc.com

[18] http://www.atlanticinertialsystems.com

[19] Sheard K., et al, *Gun Hard MEMS Sensor and Integrated Navigation Technology for Precision Guidance Applications*, NATO RTO SET-114 Symposium, Antalya, Turkey, October, 2007

[20] Habibi S., Coopert S., Stauffer J-M., and B. Dutoit, *Gun Hard Inertial Measurement Unit Based on MEMS Capacitive Accelerometer and Rate Sensor*, IEEE/ION PLANS 2008, Monterey, CA, May, 2008

[21] Geiger W. et al, *MEMS IMU for AHRS Applications*, IEEE/ION PLANS 2008, Monterey, CA May 2008

[22] http://www.systron.com/products

[23] Brown R., *Inertial System Requirements, Advanced Inertial Technologies and Competition Analysis,* R. G. Brown Associates Inc., 1991

[24] Barbour N., *Inertial Sensing – Where to Now?,* IEEE PLANS 2000, San Diego, CA, March 2000

[25] http://www.vectornav.com

[26] http://www.o-navi.com

[27] http://www.microstrain.com

[28] http://www.analog.com

[29] http://www.gladiatortechnologies.com

[30] http://www.microboticsinc.com

[31] http://www.xsens.com

[32] http://www.memsense.com

[33] http://www.siliconsensing.com

[34] http://www.invensens.com

[35] http://www.honeywell.com

[36] http://www.ices.cmu.edu/resources/iNews_Fall_08

[37] Hopkins R. et al, *Miniature Augmentation Sensors for Integrated Inertial/GPS based Navigation Applications*, NATO Lecture Series SET 116, March/April 2011

[38] Sherman P. and Holmes S., *Personal Navigation System*, Technical Report Natick/TR-06/004, October 2005

[39] Sherman P. et al, *Precision Positioning System – Autonomous GPS-Denied Navigation for the Dismounted Soldier*, WPI Indoor Personnel Location and Tracking for Emergency Responders, Worcester, MA, August 4 -5, 2008

[40] E*xplorations*, Draper Laboratory Publication, Spring 2007

[41] Dussy S. et al, *MEMS Gyro for Space Applications – Overview of European Activities*, AIAA GN&C Conference and Exhibit, San Francisco, CA, August 2005

[42] De Agostino M. et al, *Performance Comparison of Different MEMS-based IMUs*, IEEE/ION PLANS, Indian Wells, CA 2010

[43] Becker M. et al and Bott R.et al, *Evaluation of a Double Equipped MEMS IMU Based on Real Flight Trial Scenarios*, IEEE/ION PLANS, Indian Wells, CA 2010

[44] Ash M. and Martorana R., U.S. Patent 6,778,908 - August 2004; U.S. Patent 6,895,678 - May 2005

[45] Johnson B. et al, *Development of a MEMS Gyroscope for Northfinding Applications*, IEEE/ION PLANS, Indian Wells, CA 2010

[46] Bayard D. et al, *High Accuracy Inertial Sensors from Inexpensive Components,* US Patent 6,882,964 B2, April 19, 2005

[47] Hudson T., et al, *Multi-Sensor Inertial Array Technologies for Advanced Microsystems*, IEEE/ION PLANS 2006**,** Coronado, CA, April 2006

[48] http://www.darpa.mil/mto/solicitations/baa10-39, April 2010

[49] http://www.darpa.mil/mto/programs/ngimg

[50] http://www.darpa.mil/mto/solicitations/baa11-10, October 2010