2016 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
VEHICLE ELECTRONICS AND ARCHITECTURE (VEA) TECHNICAL SESSION
AUGUST 2-4, 2016 - NOVI, MICHIGAN

DESIGN OF A LOW-COST ORIENTATION MEASUREMENT UNIT FOR MILITARY VEHICLES

Ronnie L. Wright, Ph.D.
Systems Engineering Dept.
DCS Corporation
Littleton, MA

Chad J. Wilson
Vehicle Electronics & Architecture
TARDEC
Warren, MI

Millard E. Petty
Michael C. Wong
Michael R. Smith
Systems Engineering Dept.
DCS Corporation
Littleton, MA

ABSTRACT

The OMU (orientation measurement unit), a combination of inertial (accelerometer, gyroscope), magnetometer and GPS/GNSS sensors, can play a significant role in the stabilization, orientation, navigation and munitions guidance applications performed in ground-based military vehicles. The raw data measured by the OMU's sensor array includes angular rate, acceleration, magnetic field strength as well as position. By blending these sensor measurements with the use of software algorithms (a.k.a. sensor fusion), the data can be transformed into orientation data (pitch, roll & yaw), commonly referred to as Euler Angles. OMUs have a wide range of price that depends on the quality of its individual device sensors, environmental packaging, standards met and the sophistication of the device firmware used to filter, correct and smooth the inertial inputs used in the computation of application output data. In the ground-based military vehicle industry, applications supported by the OMU could range from a simple rollover warning/prevention system to a sophisticated slew-to-cue director. The success of these applications depends greatly on the OMU's individual sensor quality/grade, which are tightly coupled with the sensor's technology type, cost and size. This paper focuses on how the OMU can be designed to achieve/approach the operational performance of the more costly and well-known Strategic/Navigation –grade military navigation sensor product offerings, for a fraction of the price. The OMU's expected applications, operational objectives and the resulting performance requirements, which lead to component selection, will be explained. The paper will also highlight the results of the effort to develop an OMU and provide a discussion of recent work related to device testing and integration.

INTRODUCTION

An OMU (*orientation measurement unit*) is a sensor system used in military vehicles to determine *attitude* (pitch, roll) and *heading* (yaw), otherwise known as *rotational* orientation data. An OMU utilizes an inertial sensor array which measures inertial data (*acceleration, angular rate*) and computes rotational orientation data (*pitch, roll & yaw*), also known as Euler Angles, using sensor fusion algorithms. Inertial sensor arrays can be found in a wide range of applications/systems spanning commercial, industrial and defense products. Basic OMUs are usually comprised of a 9-DOF (*degrees of freedom*) sensor array, often consisting of a 3-axis Gyroscope, 3-axis Accelerometer and 3-axis Magnetometer. However, more advanced systems will sometimes incorporate measurement data such as barometric pressure, temperature and GPS (*position, velocity, time*). The OMU can be designed and implemented in a variety of ways, but the implementations discussed in this paper primarily focus on COTS-based design solutions that incorporate the use of either AHRS *(attitude heading reference system*) or INS (*inertial navigation system)* hardware.

APPLICATIONS

Inertial sensors and their applications contribute to multiple industries and function in a variety of environments. Inertial sensors are found in the aerospace and defense industries, where they are traditionally used for avionics, flight analysis and UAV (*unmanned aerial vehicle*) guidance/control purposes. Additionally, these sensors are found in unmanned/manned ground vehicle military systems, where applications such as positioning, orientation, navigation and munitions/guidance are important. Outside of the aerospace/defense industry, inertial sensors play an important role in industries such as construction, precision agriculture and mining, where measurement data such as position, orientation are important to machine control, especially for unmanned equipment. Inertial systems are used in car motion analysis to help study/characterize the acceleration, trajectory and steering of high-speed vehicles. Inertial systems are also found in unique/niche vehicle areas such as Image Georeferencing as well as mobile mapping. In the marine environment, inertial sensors are utilized for offshore drilling platforms, buoys and ship vessels. Each of these marine systems requires stabilization and knowledge of the platform's position, velocity and *linear* orientation data (*sway, heave & surge*). Lastly, inertial sensors play a role in the measurement and data collection related to objects or people for indoor positioning systems found in manufacturing/assembly plants as well as virtual reality and gaming systems. Regardless of industry, the underlying relationship of the various system platforms involving their dependence on inertial sensors is that they require knowledge of their position, linear/rotational orientation and the rates at which the system moves. As stated previously, the inertial sensor is a major component of the OMU and can be found in multiple industries, serving a large variety of applications. However, the focus of this paper will be on the impact/application of the inertial sensors within the ground-based military vehicle domain.

OMU PERFORMANCE

The OMU's applications dictate the performance required of the OMU's individual sensors. The OMU applications specific to this paper include orientation (*pitch, roll, yaw*) measurement and heading estimate. Effectiveness and quality of the OMU is determined by how accurate the OMU measures orientation angles and estimates heading under *static/dynamic* conditions. The OMU's overall performance is attributed to the performance of its individual components (see Figure 1) and is directly impacted by its mounting provisions, operating environment and the design specifications of its associated components. The inertial sensors found in the OMU (and similar platforms) measure an object's angular (rotational) rate as well as its acceleration for the purposes of determining orientation and position. A device which measures angular/rotational rate is known as a *gyroscope*. Said differently, the gyroscope measures how quickly an object turns or measures the rate of change of orientation. This ability enables the gyroscope to detect the orientation deviation of an object from an inertial reference frame. Gyroscopes can be divided into two main categories, depending on whether the angular velocity or orientation is being measured [1]. Rate gyroscopes measure the angular velocity, or the rate of rotation of an object. Angle gyroscopes, also called Rate Integrating gyroscopes, measure the angular position or orientation of an object directly.

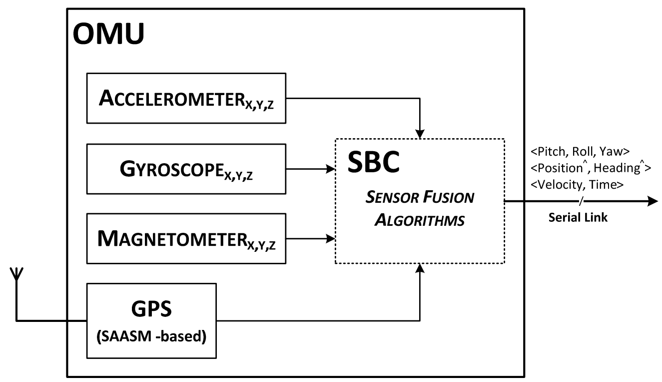


Figure 1: High-level OMU architecture.

A device which measures/senses body acceleration is known as an *accelerometer*. Given the ability to measure the acceleration of an object (vehicle) enables the OMU (and similar systems) to determine the object's velocity and position by performing successive mathematical integrations of the acceleration with respect to time. The magnetometer and GPN/GNSS sensors play a key role in assisting the OMU with the determination/calculation of the heading angle. For the purposes of navigation the magnetometer is primarily used to measure magnetic field strength (*G*) and/or the direction of the magnet field at some point on earth. A magnetometer, like a compass, will point towards the earth's magnetic north pole, which can be used to estimate an objects' heading angle relative to magnetic north. However, direction finding based solely on the use of a magnetometer may be unreliable due to the magnetometer's possible performance degradation caused by exposure to static or dynamic magnetic fields or proximity to ferrous metal. A physical phenomenon which also hampers the direct use of magnetometer readings by navigation equipment is magnetic declination, which is the horizontal angle (variation) or difference between True North and the magnetic north pole at some point on earth. To overcome the limitations of magnetometers, navigation systems are integrated with GPS/GNSS sensors. The GPS/GNSS sensors, while moving, are able to receive Position (*latitude/longitude*), Velocity, Time and (True North) Heading updates from the satellites within their view. However, use of the GPS/GNSS receiver measurement data requires vehicle movement. To provide a True North heading estimate when the vehicle is not moving, navigation systems blend together their magnetometer readings with the GPS/GNSS receiver position to determine the magnetic variation at that position, using a World Magnetic Model (WMM) or other geographic magnetic models. The magnetometer's reading is then augmented with the WMM (or another) magnetic declination value to arrive at a True North heading estimate.

INERTIAL SENSOR DESIGN PARAMETERS

There are many design parameters associated with inertial sensor performance. However, there are four key design parameters which directly contribute to inertial sensor measurement accuracy and are commonly used for gyroscope/accelerometer performance comparison:

i. *Angular/Velocity Random Walk* (°/√hr, µg/√Hz),
ii. *Bias (In-Run) Stability* (°/hr, m/s^2),
iii. *Bias Repeatability* (°/hr, m/s^2),
iv. *Scale Factor Error* (% or *ppm*).

The *Angular/Velocity Random Walk* is a measure of the noise inherent to the device, resulting from electrical or mechanical (friction/vibrations) disturbances. The *Bias (In-run) Stability* is a measure of how stable the output of the sensor is over a specified time period. For the OMU's sensor fusion algorithms, it is highly desirable that the inertial sensors consistently output the same value for the same input detected. In general, a gyroscope with lower bias stability will lead to lower errors in position estimates for an inertial measurement system. In the case of the accelerometer the bias stability units are also given in "*g*", where a single "*g*" unit of acceleration is equal to earth's gravity at sea level (*i.e.* 9.81 m/s^2 or 32.2 ft/s^2). *Bias Repeatability* is a measure of how good the output is every time you power on the sensor. Reliable navigation/orientation equipment requires that this measure be consistent across multiple power cycles. The Bias Repeatability specification is difficult to meet, as multiple/frequent power on cycles of the device, while achieving good repeatability, requires very good stability and control over the devices thermal, mechanical and electrical characteristics. And last, *Scale Factor Error* is the ratio of the sensor output over the change in sensed input. Scale Factor Error is typically expressed as a *percentage* or *parts-per-million* and has been shown to vary with the device working temperature [10, 12].

INERTIAL SENSOR ARCHITECTURE

Another feature contributing to the performance characteristics of the OMU (and similar devices) is the inertial system's design architecture, which usually falls into two main categories: (1) *Stabilized (or Gimbaled) Platforms* and (2) *Strapdown Systems*. An exhaustive review of these design architectures is beyond the scope of this paper. However, an advanced study of *stabilized vs. strapdown* technologies can be found in [11, 13, 14]. The major difference between the stabilized and strapdown categories relates to the reference frame in which the rate gyroscopes and accelerometers are mounted. The stabilized (gimbaled) platform type is characterized by inertial sensors that are mounted on a common base platform that is surrounded by concentric rings or gimbals interconnected to the platform and each-other through the use of ball-bearing shafts (spindles). This arrangement allows the base platform freedom in three axes and serves to provide isolation from any external rotational motion experienced by the global frame (or vehicle). The platform motion freedom/isolation is accomplished by the use of electric torque motors mounted to each gimbal, where the output of the base platform mounted gyroscopes is fed to each gimbal's torque motor so as to cancel out any rotations experienced by the vehicle such that the base platform remains perfectly aligned. Orientation is computed by reading the angle pick-offs (gimbal movement) between adjacent gimbals. Whereas to calculate the position of the device, the signals from the base platform mounted accelerometers are double integrated. In contrast, strapdown systems rigidly mount inertial (gyroscopes/accelerometers) sensors to the vehicle structure so that they move with the vehicle. Unlike, the stabilized architecture, the strapdown systems do not use gimbals or electric torque motors to maintain body frame reference alignment. Instead, alignment of the inertial system's body frame of reference is maintained electrically through the use of a continuously running digital processor. In the strapdown architecture, inertial sensors are mounted along mutually orthogonal axes, such that the gyroscopes measure changes in the angles about the pitch, roll, and yaw axes, as the accelerometers measure accelerations along the pitch, roll, and yaw axes. In this approach orientation is determined by integrating signals from the rate gyroscope. Position is determined using three accelerometer signals that are resolved into coordinates using the known orientation. The acceleration signals are then integrated, similar to the stable platform's approach. Stablized and strapdown architectures are similar in that they are based on the same underlying principles. Strapdown systems have reduced mechanical complexity and tend to be physically smaller than stabilized platform systems. These benefits are made possible by the use of increased computational complexity and resources. Due to the cost decrease of high-speed (digital) processors strapdown systems have become the dominant type of inertial system platform.

INERTIAL SENSOR TECHNOLOGY IMPLEMENTATION

Another factor that contributes to the size, performance and cost of the OMU and similar inertial platforms, is the gyroscope/accelerometer sensor technology used. To be brief, gyroscopes fall into three main technology classes: (i) Mechanical, (ii) Optical and (iii) MEMS. *Mechanical gyroscopes* are comprised of moving parts, such as a freely spinning wheel/sphere that is surrounded by frictionless gimbals. When the mechanical gyroscope experiences a rotation its wheel will remain at a constant orientation and the angles between adjacent gimbals will change. The vehicle platform orientation is determined by measuring the angles between adjacent gimbals by reading the angle pick-offs, similar to the stabilized systems previously discussed. *Optical gyroscopes* come in two forms: (i) FOG (fiber optic gyroscope) and (ii) RLG (ring laser gyroscope). In the FOG technology orientation is sensed using the *Sagnac* effect, where light is fired into a coil of optical fiber and is split into two separate light beams traveling in opposite directions. As the light beams exit the coil they undergo interference due to a *phase-shift* introduced during the *Sagnac* effect. This results in a combined beam whose intensity depends on the angular velocity of the gyroscope. Thus, the FOG is capable of measuring angular velocity by measuring the intensity of a combined light beam. In the case of the RLG technology, which also capitalizes on the *Sagnac* effect, laser beams are directed around an enclosed triangular path using mirrors as opposed to optical fibers. However, angular rotation is determined by the measuring the *frequency-shift* interference associated with two counter-propagating laser beams as they undergo the *Sagnac* effect. Neither, the FOG nor the RLG gyroscope technologies use moving parts. MEMS (*micro electro mechanical systems*) gyroscopes are built using silicon micro-machining techniques. Principally based on the *Coriolis Effect*, MEMS gyroscopes are machined to contain vibrating structures which measure angular rate. MEMS gyroscopes, like FOGs and RLGS, do not contain any mechanically moving parts. In addition, MEMS gyroscopes are smaller and less expensive to manufacture as compared to mechanical and optical gyroscopes. However, until recently the MEMS gyroscope measurement performance significantly lagged that of its predecessors. Nowadays, due to advances in the MEMS manufacturing process, MEMS based gyroscope performance(s) are only lagging those of the optical group by (1 – 2) orders [1, 4].

Accelerometer technology classes fall into two categories: Mechanical and Solid State. *Mechanical* accelerometers consist of a mass suspended by springs. The displacement of the mass is measured using a displacement pick-off, giving a signal that is proportional to the force F acting on the mass in the direction of the input axis [11]. Newton's second law F = ma is then used to calculate the acceleration acting on the device. Accelerometers of the *Solid State* variety fall into many groups, including surface acoustic wave, vibratory, silicon and quartz devices. These sensor types often apply *Piezoelectric*, *Piezoresistive*, *Capacitve*, *Hall Effect* and *Heat-Transfer* properties in their technology implementations, which have been embedded into board and component -level form-factors using traditional integrated circuit fabrication techniques. These days, the MEMS fabrication process has found its way into the accelerometer industry. Without going into detail the MEMS accelerometers are based on the same operational principles as the mechanical and solid state technology classes. Use of the MEMS process for accelerometer implementation results in devices that are smaller, lighter, lower power consuming, shorter start-up times and lower cost. However, the performance of the MEMS accelerometers significantly lags the performance obtained from mechanical and traditional solid state implementations.

INERTIAL SENSOR GRADES

Inertial sensors can be classified into about four sensor grades, as shown in Table 1. The sensor grades are termed *Strategic*, *Navigation*, *Tactical* and *Industrial/Consumer* [1,4,16]. Inertial sensor grades are distinguished by their performance, which is usually related to the sensor's technology type. The strategic grade sensors are the highest performance sensors, typically found in applications/systems associated with space and military aircraft/systems as well as pointing, slewing and stabilization. The industrial and consumer grade sensors have the lowest performance of the sensor grades. They can be found in industrial/automotive controls, computers, cameras, games, smartphones and other less critical areas. Higher performing sensors, found in the strategic and navigation classes are the most expensive. Table 1 provides a survey of the cost of inertial navigation systems, selected for attitude (*pitch/roll*) and heading (*yaw*) purposes, as it relates to sensor grade performance and orientation accuracy.

The data generally indicates that INS cost depends on the gyroscopes accuracy and subsequent technology type, where FOG/RLG based systems will usually provide the highest performance and the most expensive cost. Due to improvements in the MEMS (*micro electro mechanical systems*) fabrication process, MEMS gyroscope and accelerometer performances, stability and reliability are dramatically improving and slowly finding their way into Tactical and perhaps Navigation grade equipment/products. Their major advantage over their optical/mechanical predecessors is their small form-factors, low power consumption and affordable cost. Research comparing FOG-based and MEMS-based INS products reported that the surveyed MEMS-based INS equipment lagged the surveyed

FOG INS products by less than 20-30 percent, under specific real-time navigation test conditions [8, 15].

			Sensor Grades			
Component	**Performance Specs.**	**Units**	**Strategic**	**Navigation**	**Tactical**	**Industrial/ Consumer**
Gyroscope	*Bias Stability*	°/hr	0.001 - 0.010	0.010 - 0.100	0.100 - 10	10 - 1000
	Angular Random Walk	°/√hr	< 0.0002	< 0.002	0.05 – 0.5	< 5.0
	Scale Factor Accuracy	ppm	1 - 10	10 - 100	100 - 1000	1000 - 10000
	Technology Type		***FOG, RLG***	***FOG, RLG***	***FOG, RLG, MEMS***	***MEMS***
Accelerometer	*Bias Stability*	mg	< 0.03	< 0.05	< 1	< 10
	Velocity Random Walk	g/√Hz	< 5 μg/√Hz	< 25 μg /√Hz	< 1mg/√Hz	> 50mg/√Hz
	Scale Factor Accuracy	ppm	< 10	< 100	< 1000	< 10000
	Technology Type		***Mechanical***	***Mechanical Solid State***	***Solid State MEMS***	***MEMS***
Inertial Navigation System	*Pitch / Roll*	(°)	< 0.005	< 0.050	< 0.200	< 2.000
	Yaw	(°)	< 0.020	< 0.200	< 1.000	< 2.000
	Cost	**($)**	**> $100k**	**$(60 – 100)k**	**$(5 – 60)k**	**$(0.5 – 5)k**

Table 1: Sensor grade vs. performance/cost.

OMU PROJECT REQUIREMENTS

To satisfy the project requirements the OMU must meet three main objectives. First, the OMU is expected to operate in a military ground tactical vehicle environment. To survive the tactical environment, it is necessary that the OMU meet a number of key DoD standards including but not limited to MIL-STD-810F (*Environmental Test Methods and Engineering Guidelines*), MIL-STD-1275D (*Characteristics of 28 Volt DC Electrical Systems in Military Vehicles*) and MIL-STD-461G (*Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*) at a minimum. Second, the functional performance demands of the OMU are that it be capable of providing 0.2° attitude (*pitch/roll*) accuracy along with 1.0°/2.0° degree (static/dynamic) heading (*yaw*) accuracy. The primary purpose of the attitude measurement is to provide safety for the vehicle occupants. The OMU's attitude measurement assists the vehicle's position and navigation software with the ability to provide detection and warning of possible roll/tip –over conditions. Due to the vehicle's suspension, size and weight distribution, rollovers are a frequent concern for various ground tactical vehicles. In addition, the narrow wheelbase and high profile of many vehicle variants also makes them prone to rollovers. So the vehicle position and navigation software must continuously monitor the OMU's attitude measurements and warn/alert if the roll angle exceeds the rollover threshold. The heading measurement is required to assist the vehicle's position and navigation software with general direction pointing as well as DOT (*direction of travel*) computation. And third, the OMU must be *low cost*, not to exceed $7500. The cost criterion has proven to be the more difficult requirement to meet because inertial navigation equipment that is high performance, rugged, adheres to the minimum DoD standards (noted above), almost always is accompanied by a high price. To meet the project objectives for the OMU, three possible design approaches were investigated. These OMU design approaches are detailed in the sections that follow.

OMU (INITIAL) DESIGN APPROACH

The OMU's initial design concept was very simple. It involved the selection and integration of a rugged COTS (*commercial-off-the-shelf*) INS with the vehicle's position and navigation software, shown in Figure 2. The proposed OMU solution would interface with the vehicle software via a serial connection. The initial OMU design concept was further explored by conducting a navigation equipment survey, which focused on comparing many *Strategic, Tactical,* and *Navigation* -grade inertial navigation systems. The equipment surveyed was ranked according to product performance (*i.e.* attitude/heading), compliances met, interfaces and price. The survey revealed that the selected navigation systems were capable of meeting the OMU's functional performance and compliance standards requirements, but far exceeded the project's price point and was economically infeasible. This cost dilemma forced the OMU development to explore different design paths that would better meet the project cost objectives for the OMU, while continuing to meet the expected performance and functional requirements.

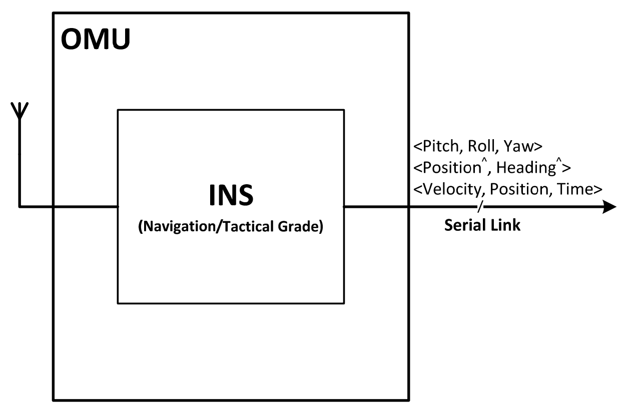


Figure 2: Initial OMU design concept.

OMU (MEMS-BASED) DESIGN APPROACH

Based on the initial INS survey, which compared performance vs. cost of multiple *Strategic, Tactical,* and *Navigation* -grade product offerings, it was evident that a COTS navigation unit (*e.g.* TALIN, TACNAV, T-10 Navigator, LN-270, Athena 511/611) of that grade/class, would far exceed the project's OMU budget to support equipment installations in a long-term vehicle enhancement program. This determination resulted in the preparation of a new OMU design path, which focused on significantly optimizing the OMU's inertial sensor cost while maintaining the desired operational performance. The first step in the new OMU design path was to select a lower cost inertial sensor and/or navigation system. This selection was initiated by a second survey. The second survey focused on the ranking of lower cost MEMS-based INS products and was extended to include MEMS-based AHRS equipment as well. A further look at the OMU functional requirements revealed that an AHRS would be an adequate measurement sensor, as it was capable of providing the essential attitude/heading angle measurements stipulated by the project.

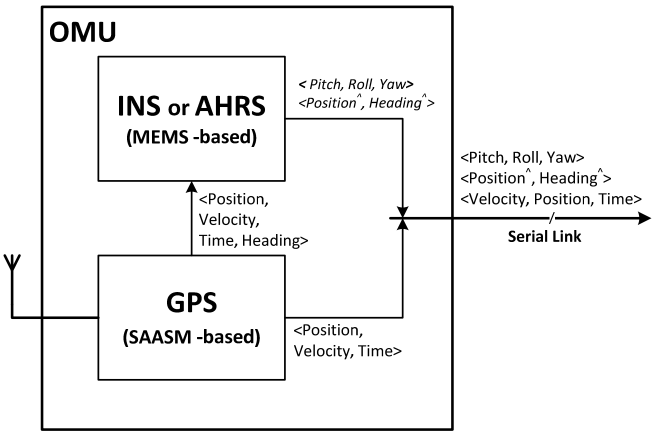


Figure 3: MEMS-based OMU design concept.

The equipment survey found that an INS or AHRS sensor system combined with a GPS unit (see Figure 3) would meet and/or exceed the OMU's functional requirements. Minimally, the INS/AHRS sensor systems measure, filter and distribute low level sensor (*Gyroscope, Accelerometer, Magnetometer*) measurement data. The INS/AHRS sensor systems utilize SFAs (*sensor fusion algorithms*) which integrate the 3-axis inertial and magnetometer sensor measurement data to determine *Euler Angles*, a.k.a (*pitch, roll & yaw*). The sensor fusion algorithms correct for gyroscope drift by the use of gravity and magnetic field reference vectors, which is supposed to result in a drift-free orientation. The AHRS sensor primarily provides pitch/roll and yaw measurements as well as raw sensor measurements. The INS class sensor delivers the same output as an AHRS, but it also has capabilities beyond those of the AHRS device class. The INS device class exceeds the AHRS device class in functionality by offering *navigation capability* in the presence of GPS outages. Specifically, the INS sensor class is capable of providing reasonable (depends quality/cost) heading and position estimates (for 1-2 minutes) when the INS onboard GPS becomes unavailable. GPS denied circumstances can occur intentionally or unintentionally due to jamming or satellite visibility challenges, respectively. Cost surveys show that the INS class sensor is typically more expensive than the AHRS class. This is primarily due to the more advanced/complex sensor fusion algorithms running on the INS platform, which provide the position/heading estimates during GPS outages. To further exhaust plausible low cost OMU design options, a third design approach that considered custom SFA software development along with custom sensor integration was explored.

OMU (Custom) Design Approach

The third OMU design approach considered the integration of an IMU (*inertial measurement unit*) or individual 3-axis inertial sensors (Accelerometer$_{x,y,z}$, Gyroscope$_{x,y,z}$), 3-axis Magnetometer$_{x,y,z}$ and a GPS/GNSS sensor (Figure 4). The approach requires the development of custom software operating on a dedicated microcontroller or microprocessor. This dedicated software entity would contain sensor fusion algorithms which digitally filter and correct for the bias/drift errors present in the individual sensor output signals. In addition, the custom SFAs would require computation to generate the necessary orientation angles (*pitch, roll, yaw*). Along with custom software development and integration of complex sensor fusion algorithms and digital filters, custom hardware packaging of the individual sensors as well as custom cabling would be required for this design approach to meet the compliance criteria for successful operation in the vehicle environment. It was determined that a savings in material cost could possibly be achieved. However, due to the lack of in-house navigation algorithm development expertise there was very high risk associated with the custom software development aspects of this design concept. Because of the perceived impact to schedule associated with developing custom SFAs/software and other hardware entities, the custom OMU design approach was considered very risky.

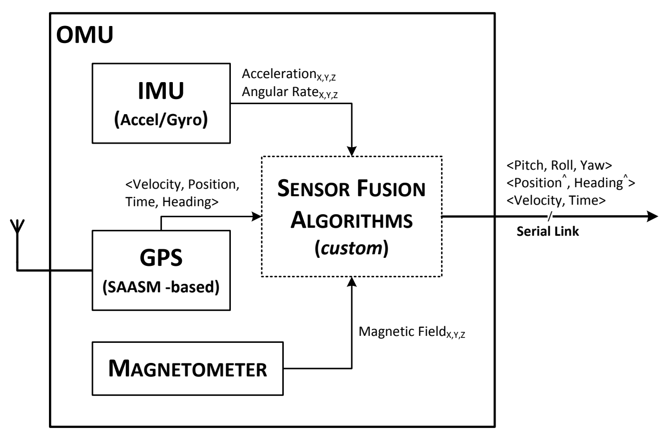


Figure 4: Custom OMU design concept.

OMU Design Approach Selection

The three OMU design approaches (*Initial, MEMS-based, Custom*) were compared to one another from Performance, Risk and Cost perspectives. It was determined that the initial

OMU design concept, which was basically comprised of *Strategic, Navigation* and *Tactical* -grade inertial navigation equipment offered the superior Orientation and Position performance of all design approaches. However, the cost ($25k - $100k), of these sensor grades exceeded the range permitted by the project. After examining the custom OMU design concept, it was determined that the cost range of this path's basic hardware components was the most attractive. However, the custom design path would likely have the highest technical/schedule risks due to the required design and development of custom SFAs, custom (Kalman) digital filtering and other hardware design logic. These perceived risks overshadowed any possible savings obtained from the lower cost hardware components. As a result, it was determined that the MEMS-based OMU design approach would be the best selection in terms of project cost, performance adherence and acceptable schedule risk.

OMU IMPLEMENTATION/INTEGRATION

Execution of the low-cost OMU design approach basically comes down to the following: (a) selecting an appropriate (*high performance*) MEMS-based inertial sensor (INS or AHRS), (b) interfacing that sensor with a SAASM (*Selective Availability Anti-spoofing Module*) -based GPS, (c) interfacing the inertial and GPS sensor outputs with the computational and I/O resources of an SBC (*single board computer*), (d) installing these electronic packages within an environmentally sound enclosure suitable for operation in a military vehicle, and (e) determine the vehicle mounting location which enables the OMU's best performance for its designated applications. A significant contributor to the OMU's heading estimation performance is the incorporation of GPS (*position, velocity, time* and *heading*) input data, which helps to improve the SFA solutions. A complete discussion of GPS technology, specifically SAASM–based GPS technology is beyond the scope of this paper. However, briefly stated, SAASM modules are heavily used in U.S. military/government GPS equipment because they enable the decryption of precision GPS observation data, provide a means to reduce spoofing (mimicking an authorized transmitter) and provide anti-jam capability. For vehicle integration purposes it was expected that the selected inertial sensor would undergo some physical modifications before it could be effectively integrated into the vehicle environment. Expected modifications included the redesign of the sensor's power/data cables to be heavily shielded and ruggedized with circular MIL connectors. A second modification would entail the enclosure repackaging of the selected inertial sensor. This activity involves placing the selected inertial sensor inside of another enclosure system that will ensure resistance to water penetration and is capable of meeting MIL-STD-810F. And third, an electrical input power protection and EMI filtering system may be installed at the input of the selected inertial sensor. These additions ensure that the OMU's selected sensor, which could be devised for "commercial" needs, survive the 28V power characteristics expected of military vehicle equipment (*i.e.* MIL-STD-1275D) as well as minimize the propagation/transmission electrical noise/interference (discussed in MIL-STD-461G). These activities result in the proposed OMU architecture and vehicle system interface shown in Figure 5.

A short list of MEMS-based inertial sensors was found after conducting a survey. The orientation measurement vectors transmitted from the INS/AHRS sensors were found to be in a satisfactory/usable format (*i.e.* degrees/radians) and did not require additional computational or numerical processing. However, it is expected that modest filtering by the vehicle's software and control client may be necessary.

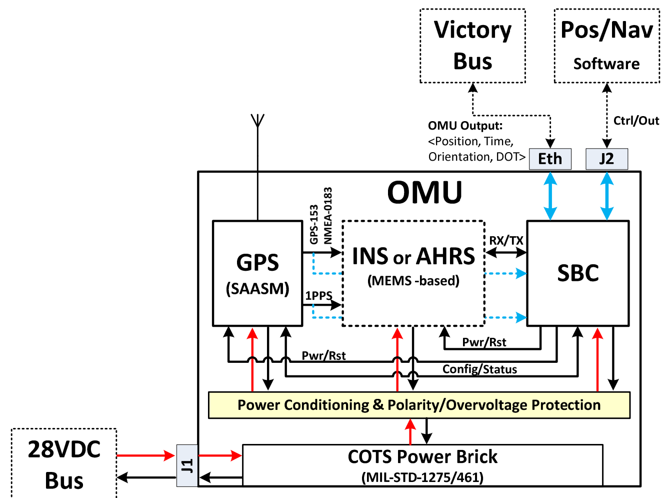


Figure 5: Proposed OMU architecture.

INTEGRATION EFFORT (PHASE I)

The OMU's initial implementation consisted of a MEMS-based AHRS, known as AHRS-MS for the purposes of this paper. From a datasheet review, the AHRS-MS device was characterized as capable of meeting the performance criterion outlined in Table 2.

Performance	Static	Dynamic
Heading (Yaw)	1.0°	3.0°
Attitude (Pitch/Roll)	0.2°	1.0°
Magnetic Field	±4G	±4G

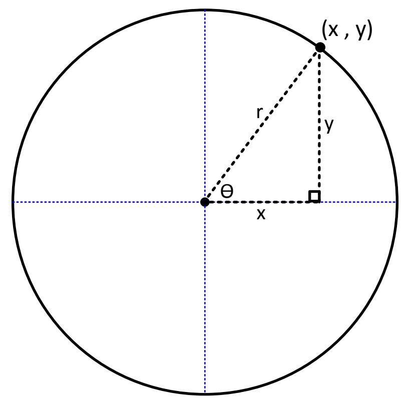
Table 2: Initial OMU performance requirements.

Initial bench/SIL testing demonstrated that the attitude performance of the AHRS-MS appeared to be in the range of the advertised datasheet benchmarks. Initial heading performance was inconclusive in the lab environment due to lab's noise/interferences. The AHRS-MS was eventually integrated in the vehicle environment, and mounted in the vehicle's inner cab area. The result of the integration was that the AHRS-MS heading measurements were severely hampered and consistently incorrect. The AHRS-MS device manufacturer concluded that the vehicle's high ferrous metal content was most likely interfering with the AHRS magnetometer sensor operation, which was likely responsible for the erroneous heading measurement. On the advice of the AHRS-MS manufacturer it was recommended that we physically relocate the AHRS-MS device to an exterior vehicle location and propagate GPS measurement (*Position, Velocity, Time, Heading*) vectors to the AHRS sensor, which would allow improved heading calculations as the vehicle moved. This advice was taken. However, use of the AHRS-MS device did not result in satisfactory heading performance, even after multiple firmware upgrades were performed. As the OMU's initial test and integration phase continued, a new requirement to support *slew-to-cue* behavior emerged. Slew-to-cue is an application whereby the vehicle's weapon system (main gun) is commanded to precisely "slew" or point in the direction of a target (*cue*). A key performance parameter in the accuracy of the *slew-to-cue* operation is the vehicle's heading angle provided to the vehicle's position and navigation software and/or targeting system, which would presumably be determined by the OMU. Due to the poor performance of the AHRS-MS device along with the project's new *slew-to-cue* requirement, use of the AHRS-MS in the OMU design was discontinued, and the search for a more reliable and higher performing MEMS-based inertial/navigation sensors was undertaken.

INTEGRATION EFFORT (PHASE II)

The new search for MEMS-based inertial/navigation equipment was undertaken mainly due to the reliability and performance issues encountered with the AHRS-MS device. However, the new *slew-to-cue* requirement placed on the project reinforced the fact that a more accurate inertial sensor was required. The basic *slew-to-cue* requirements for the project involved slewing in a target's direction that was located at most 1609 meters *(1 mile)* away from the targeting vehicle, with a target size (length) of roughly 20 ft. (6.1 meters).

A rudimentary heading/distance error analysis (See Figure 6, Figure 7), describing how one matches the prospective inertial sensor's heading performance to meet the OMU's slewing requirement, is depicted in Figure 8. This view illustrates how *Error Distance* between a target's actual location and estimated (slewed) location vary as a function of the inertial sensor's *Heading Error*. A precise view of the heading accuracy necessary to meet the *slewing* requirement is depicted in Figure 9. Under ideal circumstances, such as perfect wind, temperature and pressure conditions along with fault-free ballistic calculations, a navigation sensor having a maximum heading error of ≤ 0.217° is necessary to meet the *slew-to-cue* requirement, where a target is located at a maximum distance of 1609 meters from the "slewing" sensor system. The 0.217° heading error would theoretically result in a maximum error distance of 6.095 meters, which is just inside the target's maximum size/length. Briefly stated, relatively high-end INS/AHRS sensors having a heading error of 0.217° or less are required to accurately target six meter wide objects from a distance of 1600 meters. Lower-end INS/AHRS sensors with heading errors of (0.25 - 3.00)° could result in target misses in the (7 - 84) meter range.

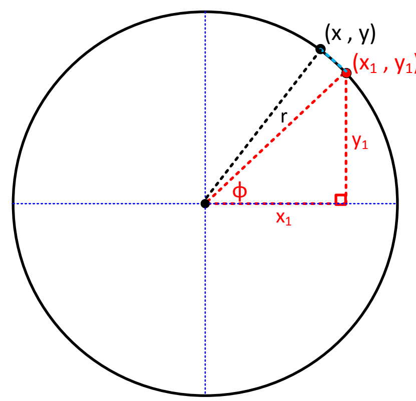


[1] $x = r \cdot cos(\Theta)$, $y = r \cdot sin(\Theta)$

[2] $x^2 + y^2 = r^2$

[3] Each $\Theta_i \rightarrow (x_i, y_i)$ about unit circle

Figure 6: Slew position estimate given heading angle.



[1] $\Phi \rightarrow (x1, y1)$

[2] $|\Phi - \Theta| > 0 \rightarrow \Theta_{Err} \rightarrow$ Error Distance

[3] Error Distance $= \left((x_1-x)^2 + (y_1-y)^2\right)^{½}$

Figure 7: Slew error distance given heading error.

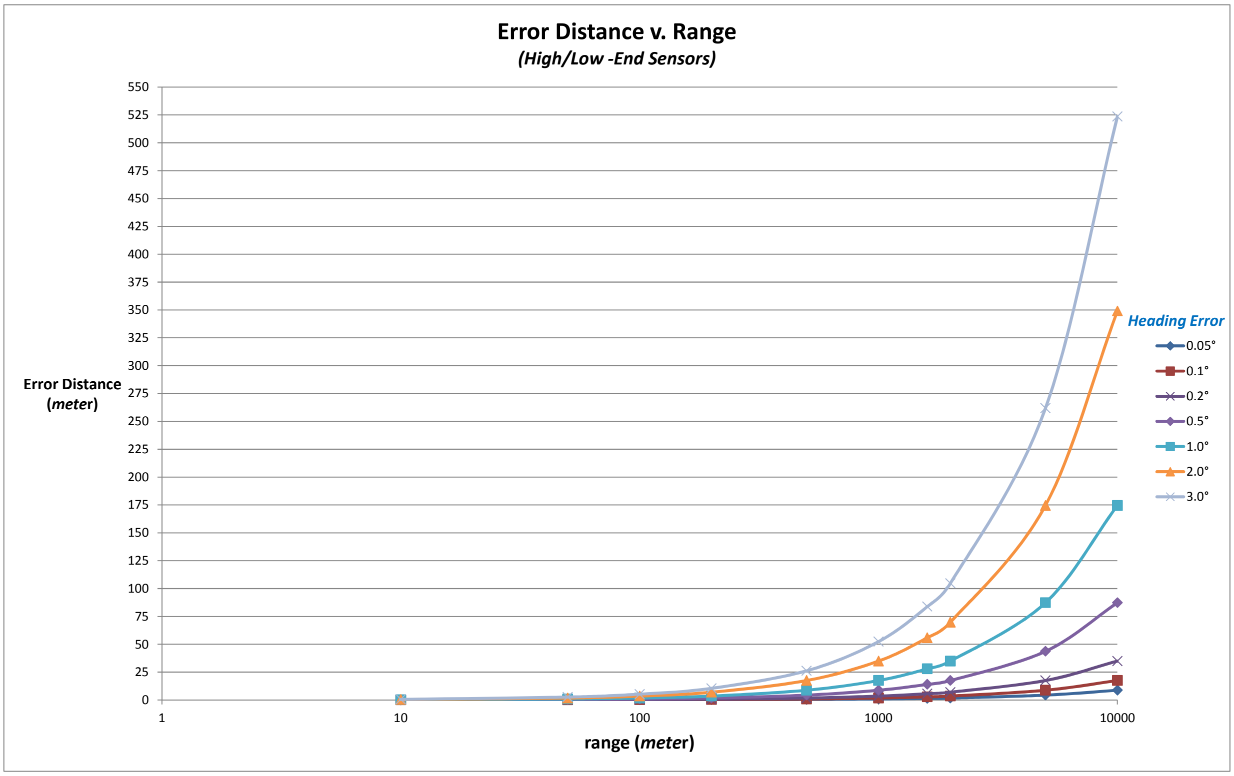


Figure 8: Error Distance v. Range.

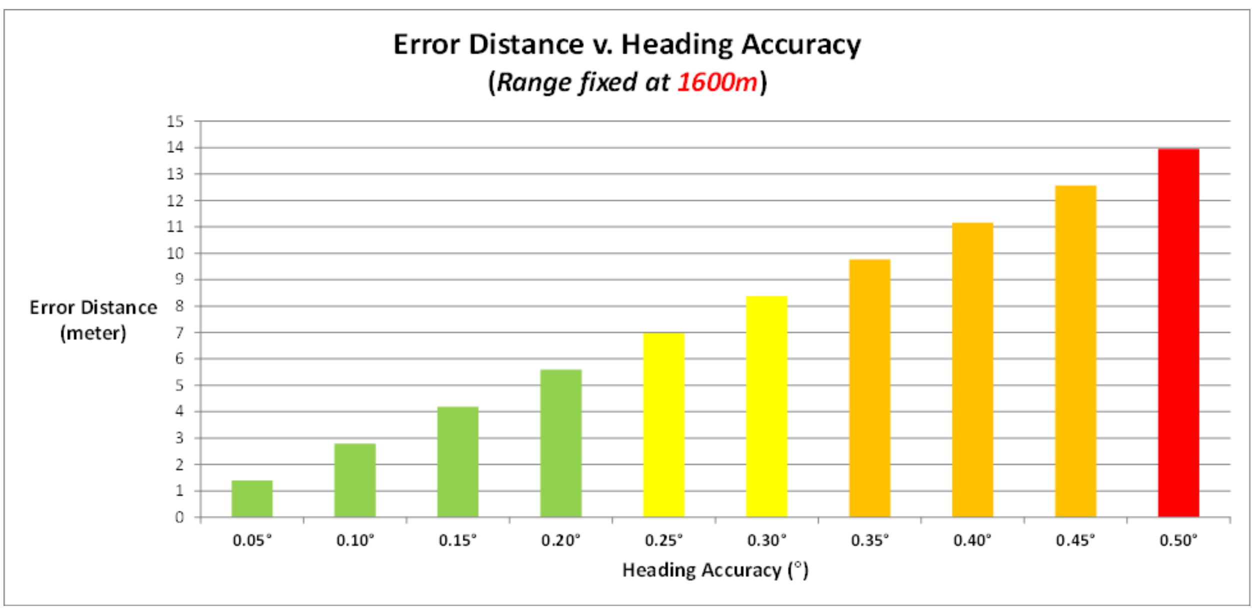


Figure 9: Error Distance v. Heading Accuracy.

INERTIAL SENSOR SELECTION

The new sensor search identified three devices that were purchased for evaluation. For the purposes of this paper these devices will be referred to as the INS-IL, INS-R1 and INS-MS navigation sensors. Each device from the new equipment selection belongs to the INS (inertial navigation system) category and contains MEMS-based gyroscope and accelerometer technology. The INS-MS/INS-R1 devices utilize MEMS-based magnetometer technology, whereas the INS-IL utilizes Fluxgate magnetometer technology. Each device is GPS-aided as they are integrated with an internal GNSS/GPS receiver. However, the GNSS/GPS receivers are not SAASM-based. Cost-wise, the INS device selections along with their required accessories (antennas, power/data cables, *etc*.), were all in the $5000 - $5500 price range. The meaningful (advertised) performance data for each equipment offering is shown in Table 3.

	(New) MEMS-based Navigation Equipment Selections					
	INS-MS		INS-R1		INS-IL	
Performance	*Static*	*Dynamic*	*Static*	*Dynamic*	*Static*	*Dynamic*
Heading (Yaw)	1.0°	3.0°	0.5°	0.5°	0.4°	0.1°
Attitude (Pitch/Roll)	0.2°	0.2°	0.1°	0.1°	0.08°	0.08°
Magnetic Field	±1G	±1G	±2.5G	±2.5G	±1.6G	±1.6G
Position Accuracy	±2.5m	±2.5m	±2.5m	±2.5m	< 1.5m	<1.5m

Table 3: New MEMS navigation equipment selection.

ATTITUDE EVALUATION

Very basic (*static*) pitch and roll testing was conducted on the three sensor systems. A sensor platform assembly was constructed to mount each of the sensors (see Figure 12-15). Before testing commenced, each of the sensors was initialized, with the inertial bias measurements subtracted from the platform's origin position. During the attitude testing, the sensor assembly platform was directed to various orientation angles, where the vendor specific demonstration software for each navigation sensor was used to measure the Pitch/roll angles encountered. Using a manual tilt platform the attitude angles were measured for each of the devices (see Table 4). In this measurement category the three devices were evenly matched.

Pitch Actual(°)	Measured Pitch(°)			Roll Actual(°)	Measured Roll(°)		
	INS-MS	INS-R1	INS-IL		INS-MS	INS-R1	INS-IL
0.0	0.04	-0.10	0.05	0.0	0.02	0.07	-0.08
+2.0	2.05	2.06	2.08	+2.0	2.11	2.08	2.03
+5.0	5.32	5.12	5.08	+5.0	5.11	5.11	5.09
+7.0	7.16	7.17	7.11	+7.0	7.03	7.08	7.15
+10.0	10.11	10.26	10.19	+10.0	10.17	10.20	10.15
+12.0	12.07	12.31	12.18	+12.0	12.08	12.11	12.02
+15.0	15.24	15.19	15.10	+15.0	15.22	15.29	15.03
+20.0	20.34	20.24	20.11	+20.0	20.13	20.36	20.09

Table 4: Attitude evaluation data.

HEADING EVALUATION

A sensor platform assembly which securely mounted all inertial sensors (INS-IL, INS-MS, INS-R1) was constructed. During the vehicle testing the sensor assembly platform was mounted in each of the four sensor placement areas about the vehicle, *i.e.* the (No-Riser, 1Ft-Riser, 4.5Ft-Riser and Mini-Riser) mounting locations (shown in Figures 12 – 15). The risers were used to position the sensors outside the range of static magnetic influence caused by the vehicle's ferrous metal content, which is known to interfere with the navigation system's magnetometer performance and subsequently degrade the OMU's heading performance. A magnetic alignment procedure was run on each system to calibrate its magnetometer for operation at each riser mounting location. Static and dynamic heading tests were conducted, along with position testing under GPS available and GPS denied conditions. The demo software for each sensor was used to initialize, control and log measurement data. All sensor measurements were compared to measurements from a USB GPS, which served as a reference for the vehicle's speed and direction as the vehicle navigated the driving course (Figure 10) at FBTX.

The ideal heading angles for the vehicle direction around the course are shown in Figure 11. Performance results related to the sensors' ability to estimate Heading (°), Speed (mph) and Position (Lat°/Long°) across all placement locations and relative to a GPS reference system are presented in Tables (5, 6, 9, 10). Figure 16 along with Tables 7-8 depict the best overall performance (4.5 Ft riser) under GPS available conditions. Figure 17 along with Tables 11-12 depict inhibited performance (1.0 Ft. riser) under *partial* GPS–denied conditions.

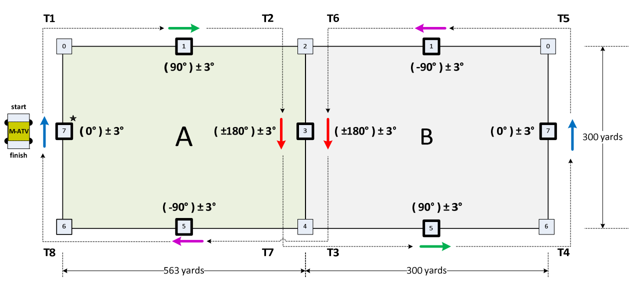


Figure 10: Driving course.

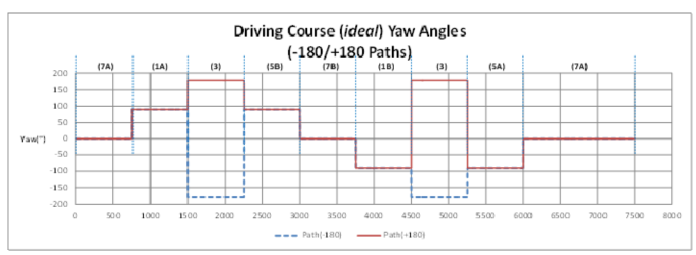


Figure 11: Course "ideal" heading angles.

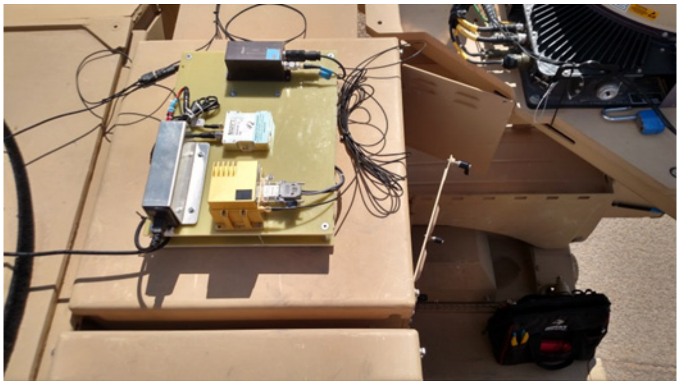


Figure 12: No riser placement.

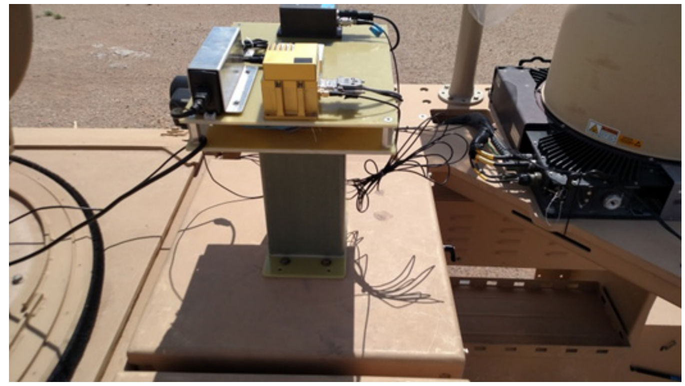


Figure 14: 1-Ft riser placement.

Figure 13: 4.5-Ft riser placement.

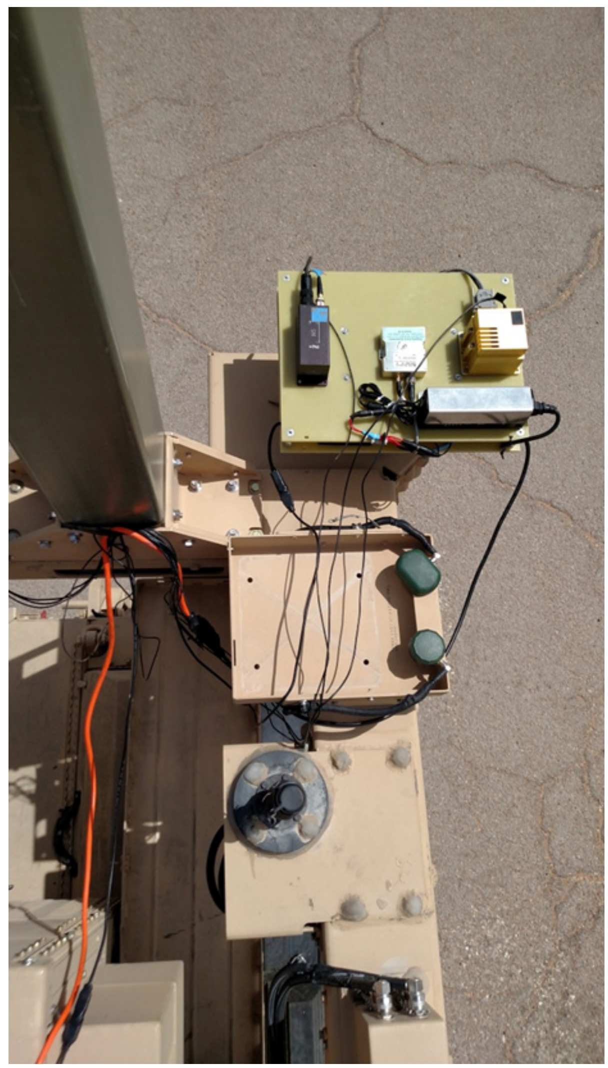


Figure 15: Mini riser placement.

HEADING RESULTS SUMMARY

Under GPS available conditions all sensors performed well when placed at the 4.5-Ft riser location. Mounting location appeared to play a slight role in the performance of the inertial sensor's ability to estimate heading. The INS-R1 sensor appeared to consistently demonstrate poor yaw measurement accuracy during the (1A, 5B, 1B, 5A) stops, such that those measurements severely skewed its statistical results. The remaining course stops for the INS-R1 yielded much better yaw measurement accuracy. Position estimation accuracy appears to be very even across all sensors and placement locations. However, under the GPS-denied conditions, all sensors performed unfavorably, with rms (*root mean square*) error in the two order range.

	Average (μ) of Yaw During Stop				*Std. Dev. (σ) of Yaw During Stop*			
Stop	**Ref(°)**	**INS-IL(°)**	**INS-R1(°)**	**INS-MS(°)**	**Ref(°)**	**INS-IL(°)**	**INS-R1(°)**	**INS-MS(°)**
7A	1.161	0.481	6.009	3.446	0.013	0.008	0.442	0.225
1A	89.249	90.253	68.413	90.474	0.090	0.101	0.678	0.555
3	178.159	179.158	172.228	178.091	0.006	0.193	1.144	0.670
5B	91.967	91.443	69.029	90.766	0.169	0.246	0.649	0.512
7B	3.792	3.601	4.747	0.268	0.075	0.014	0.402	0.210
1B	-90.054	-88.441	-66.192	-89.397	0.155	0.273	0.571	0.259
3	-178.700	-179.885	-169.783	-176.921	0.125	0.074	1.529	0.594
5A	-85.237	-85.018	-65.209	-86.125	0.225	0.260	0.540	0.284
7A	-0.730	-0.563	-5.248	-3.724	0.000	0.051	0.559	0.491

Table 7: 4.5-Ft riser Yaw average (during Stops).

GPS AVAILABLE RESULTS:

Performance (GPS-Aided)	***No Riser***			***Mini Riser***			***1.0 Ft Riser***			***4.5 Ft Riser***		
	INS-IL	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***
Yaw(°)	1.580	11.626	1.839	1.656	10.348	2.585	1.291	8.870	1.297	0.844	14.301	2.130
Speed(mph)	0.054	0.159	0.259	0.070	0.148	0.184	0.054	0.143	0.213	0.056	0.145	0.229
Latitude(°)	0.000043	0.000055	0.000046	0.000037	0.000059	0.000041	0.000060	0.000061	0.000060	0.000047	0.000049	0.000046
Longitude(°)	0.000029	0.000030	0.000038	0.000056	0.000062	0.000054	0.000054	0.000046	0.000060	0.000033	0.000043	0.000034
Table lists Static performance (RMS Error relative to GPS reference device).												

Table 5: Static performance (GPS available).

Performance (GPS-Aided)	***No Riser***			***Mini Riser***			***1.0 Ft Riser***			***4.5 Ft Riser***		
	INS-IL	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***	***INS-IL***	***INS-R1***	***INS-MS***
Yaw(°)	2.214	14.344	3.137	4.419	13.649	7.213	2.003	11.159	3.183	1.759	17.561	3.066
Speed(mph)	0.313	1.011	0.550	1.547	1.962	1.743	0.548	1.175	0.699	0.457	1.207	0.573
Latitude(°)	0.000044	0.000045	0.000041	0.000048	0.000068	0.000046	0.000066	0.000064	0.000064	0.000059	0.000064	0.000053
Longitude(°)	0.000048	0.000054	0.000046	0.000122	0.000165	0.000115	0.000082	0.000072	0.000076	0.000059	0.000078	0.000070
Table lists Dynamic performance (RMS Error relative to GPS reference device).												

Table 6: Dynamic performance (GPS available).

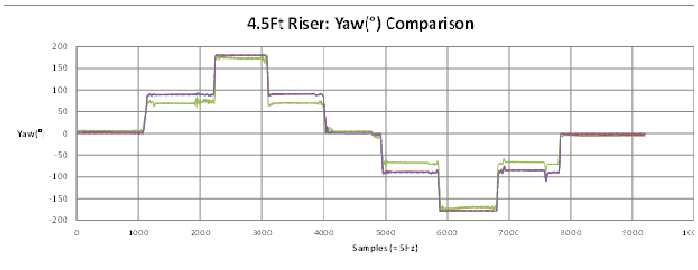


Figure 16: 4.5-Ft riser Yaw performance.

	RMS Error During Transitions			
Transition	**Ref(°)**	**INS-IL(°)**	**INS-R1(°)**	**INS-MS(°)**
T1	0.000	1.287	14.189	2.317
T2	0.000	1.619	18.424	2.691
T3	0.000	2.032	19.213	4.439
T4	0.000	1.618	19.745	3.033
T5	0.000	2.034	15.467	3.799
T6	0.000	1.638	17.477	2.308
T7	0.000	1.964	15.793	3.347
T8	0.000	2.039	19.450	3.081

Table 8: 4.5-Ft riser Yaw performance (Transitions).

This poor performance could stem from the manner in which the GPS denied test was conducted as well as problems synchronizing the sampling rates/timing of each of the sensor demo software programs within the Windows 7.0 environment. One major problem with the GPS-denied test was obtaining a mechanism to obstruct the antenna's receipt of the L1/L2 GPS signals. Obstructing the antenna's line of sight with *tin foil or sheet metal* did not work, so we resorted to disconnecting the antennas from the sensors to force them to operate without GPS (*heading, position, velocity, time*) updates during four stops/transitions of the driving course, followed by reconnecting the antennas after the completion of the 4th stop (5B). Disconnecting the antennas appeared to cause all sensors to experience some form of numerical instability, such that large MSE (*mean squared error*) was accumulated in the yaw solutions, which was not able to be filtered out during the remainder of the course runs. It was also observed that each of the sensors appeared to lose its ability to estimate velocity during the forced GPS outage. Some of the velocity estimates generated during the GPS outage were extremely unreasonable and unrealistic. In short, the GPS-denied testing approach needs improvement to confirm proper validation of performance during GPS outages. Hence, the data collected under the GPS denied conditions may be somewhat erroneous due to the unknown operational effects on the inertial sensor's hardware as a result of the antenna removal. Unfortunately, all antennas could not be disconnected (re-connected) simultaneously. This process occurred sequentially and required different amounts of time for each sensor device. Thus, the error measurements for the GPS denied testing may be higher than normal or uncharacteristic due to this non-uniform method of disconnecting/connecting the antennas.

	Average (μ) of Yaw During Stop				Std. Dev. (σ) of Yaw During Stop			
Stop	Ref(°)	INS-IL(°)	INS-R1(°)	INS-MS(°)	Ref(°)	INS-IL(°)	INS-R1(°)	INS-MS(°)
7A	1.065	1.237	-3.962	-1.039	0.444	0.686	1.357	0.826
1A	90.165	91.668	121.084	88.685	1.018	0.761	4.072	1.184
3	178.918	178.611	167.642	179.363	0.446	0.534	0.694	0.474
5B	90.788	91.354	121.319	88.903	0.625	0.795	20.594	0.766
7B	3.232	4.340	2.212	2.398	0.164	0.564	0.854	0.013
1B	-88.957	-90.783	-103.644	-89.812	1.605	1.255	0.875	1.307
3	-179.250	-179.047	-177.215	-179.359	0.696	0.678	0.911	0.568
5A	-88.545	-88.653	-104.175	-90.470	7.594	7.240	7.324	7.229
7A	-0.180	0.542	-3.166	-1.243	0.000	0.660	1.001	0.188

Table 11: 1-Ft riser Yaw average (during Stops).

	RMS Error of Yaw During Transitions			
Transition	Ref(°)	INS-IL(°)	INS-R1(°)	INS-MS(°)
T1	0.000	4.387	25.071	14.664
T2	0.000	5.665	36.345	4.351
T3	0.000	2.345	8.086	7.668
T4	0.000	5.106	11.910	6.598
T5	0.000	9.989	13.691	25.143
T6	0.000	2.506	15.590	4.627
T7	0.000	10.416	10.691	24.235
T8	0.000	0.019	4.537	2.520

Table 12: 1-Ft riser Yaw performance (Transitions).

GPS DENIED RESULTS:

Performance (GPS-Denied)	No Riser			Mini Riser			1.0 Ft Riser			4.5 Ft Riser		
	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS
Yaw(°)	2.912	13.791	3.160	2.567	18.047	2.596	1.685	22.887	2.036	10.000	14.164	2.643
Speed(mph)	5.558	1030.251	20.414	7.408	377.881	20.062	6.114	2806.984	58.010	5.919	702.541	24.780
Latitude(°)	0.000870	0.705023	0.000859	0.000743	0.182856	0.000716	0.000908	0.188445	0.000874	0.000829	0.147549	0.000860
Longitude(°)	0.003178	0.143388	0.002943	0.003140	0.045937	0.002611	0.003431	4.026193	0.003228	0.003108	0.443661	0.003638
Table lists Static performance (RMS Error relative to GPS reference device).												

Table 9: Static performance (GPS denied).

Performance (GPS-Denied)	No Riser			Mini Riser			1.0 Ft Riser			4.5 Ft Riser		
	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS	INS-IL	INS-R1	INS-MS
Yaw(°)	10.802	17.406	16.582	8.451	12.498	9.966	5.714	17.555	13.064	11.196	19.837	9.786
Speed(mph)	6.115	1032.790	18.139	9.974	193.472	17.613	5.848	2084.754	41.054	7.084	386.532	11.921
Latitude(°)	0.000941	0.671216	0.000935	0.000772	0.064200	0.000778	0.000706	0.136217	0.000693	0.000453	0.046400	0.000453
Longitude(°)	0.003280	0.119622	0.003266	0.003047	0.039685	0.003046	0.002695	3.017700	0.002714	0.002534	0.211587	0.002548
Table lists Dynamic performance (RMS Error relative to GPS reference device).												

Table 10: Dynamic performance (GPS denied).

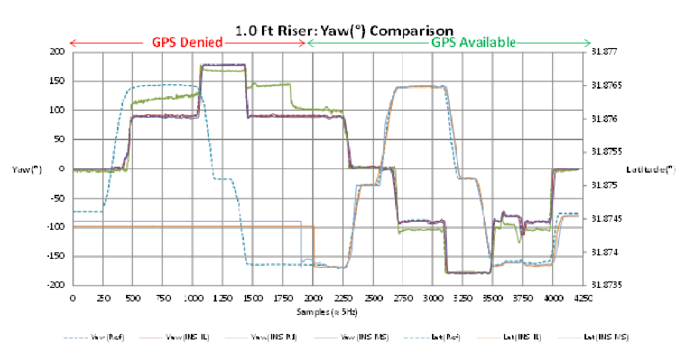


Figure 17: 1 Ft Riser Yaw Comparison (GPS-Denied).

Overall the testing went well. From the results of the GPS available test, the **INS-IL** sensor has shown to be the most *accurate* and *stable* sensor of the group for all mounting location placements and course driving (*static/dynamic*) conditions. Performance-wise the **INS-MS** follows *second* with the **INS-R1** concluding with *third* place.

FUTURE WORK

The initial inertial sensor system background studies as well as product offering surveys provided a good start for the low-cost OMU design effort. Upon the generation of this manuscript three MEMS-based INS sensors were evaluated to determine attitude and heading performance. More precise (higher quality) performance testing should be conducted on the selected sensors. Once, the preferred MEMS-based sensor product offering is determined, the next phase of development involves integrating that inertial navigation device with a SAASM-based GPS along with the computational and I/O resources provided by a SBC (*single board computer*) to arrive at a complete orientation measurement and reporting system that meets the project's application performance requirements. Next, these elements should be repackaged into a rugged enclosure along with the necessary electronics to meet MIL-STD-1275D, MIL-STD-461G and MIL-STD-810F standards, as discussed in the OMU performance specification. Lastly, the OMU Victory interface, which is responsible for writing *Position, Time, Orientation* and *Direction of Travel* elements to the Victory Data Bus, should be implemented using the SBC computational and I/O resources along with the OMU sensor measurement data.

CONCLUSION

This paper described an OMU design effort, whose goal was to achieve/approach the operational performance of the more costly Strategic/Navigation/Tactical –grade military navigation sensor product offerings, for a fraction of the price. Surveys conducted during the project indicated that the well-*known Strategic, Navigation, Tactical* -grade INS devices, commonly made for the military vehicle environment, could range in price from ($25k - $100k), which exceeded the project budget. The key to achieving low-cost navigation capability was predicated on finding outstanding MEMS-based INS/AHRS product offerings that could be repackaged (if required) to meet minimum DoD standards and environmental compliances necessary for reliable operation in the military vehicle environment. Aside from inertial sensor grade selection, it was determined that other factors such as GPS integration and vehicle mounting location could impact the OMU's performance. The project specific OMU performance goals, decisions made and decision consequences were presented. Finally, attitude and heading evaluations for three MEMS–based inertial navigation equipment offerings (INS-MS, INS-R1, INS-IL) were shown. The attitude evaluations, which were static in nature, demonstrated that all product offerings were evenly matched from a performance perspective. The static and dynamic heading evaluations, where the sensors were mounted at four distinct locations about the vehicle, demonstrated decent performance for all sensors when they were placed in the 4.5ft riser location. Firstly, specific to the 4.5ft riser mount location, it was the INS-IL product (for GPS–available test runs), that demonstrated the clear performance advantage. However, during a single GPS-denied test run, the INS-MS product offering was the better performer. Secondly, the mini riser location for all sensors, reported the least favorable performance for GPS available/denied conditions. Lastly, in all cases, the INS-R1 heading performance significantly lagged the performances of the INS-IL and INS-MS products. This outcome may have been caused by device configuration or interference.

ACKNOWLEDGEMENTS

The authors of this paper would like to express acknowledgements and appreciation to Eric Bennett, Lawrence Winkelman, and APO MRAP. In addition, the authors are grateful for the effort provided by Patrick Delehanty, William Scarpa, Jim Fraser, Charles Colegrove, Roger Call, Chris Bidlak, Ralph Oullette, Harry Giles and Pete Ingram of DCS Corporation for their support in acquiring a test vehicle, preparation of the vehicle, design of sensor mounting platforms and vehicle driving. The contributions made by the acknowledged individuals helped to make the experimental component of this paper a success. Thanks very much for your support.

REFERENCES

[1] Alexander A. Trusov, "Overview of MEMS Gyroscopes: History, Principles of Operations, Types of Measurements", University of California, Irvine, CA, May 2011.

[2] Joseph M. Struss, Michael Kirkpatrick, and James W. Sinko, "GPU/IMU Development of a High Accuracy Pointing System For Maneuvering Platforms", Inside GNSS, pp 30-37, March/April 2008.

[3] Vladimir Vukmirica, Ivana Trajkovski, Nada Asanović, "Two Methods for the Determination of Inertial Sensor Parameters", Scientific Technical Review, Vol. 60, No.3-4, pp.27-33, 2010.

[4] KVH, "Guide to Comparing Gyro and IMU Technologies – Micro-Electro-Mechanical Systems and Fiber Optic Gyros", KVH Industries White Paper, pp 1-10, 2014

[5] Erick Macias, Daniel Torres, Sourabh Ravindran, "Nine-Axis Sensor Fusion Using the Direction Cosine Matrix Algorithm on the MSP430F5xx Family", Texas Instruments Application Report SLAA518A, pp. 1-15, February 2012

[6] Neil M. Barbour, "Inertial Navigation Sensors", Charles Stark Draper Laboratory, White Paper, 2011

[7] N. Barbour, R. Hopkins, A. Kourepenis, "Inertial MEMS Systems and Applications", Charles Stark Draper Laboratory, White Paper, 2011

[8] Chris Goodall, Sarah Carmichael, Naser El-Sheimy, and Bob Scannell, "INS Face Off: MEMS versus FOGs", Inside GNSS, pp. 48-55, JULY/AUGUS T 2012

[9] Francesco Montorsi , Fabrizio Pancaldiy and Giorgio M. Vitetta, "Design and Implementation of an Inertial Navigation System for Pedestrians Based on a Low-Cost MEMS IMU", in proc. IEEE ICC, Budapest, pp. 57-61, 2013

[10] Eugenio Denti, Roberto Galatolo, Francesco Schettini, "An AHRS Based On A KALMAN Filter For The Integration Of Inertial, Magnetometric and GPS Data", 27th International Congress of the Aeronautical Sciences, Vol. 5, pp. 3568-3576, September 2010

[11] Oliver J. Woodman, "An introduction to inertial navigation", University of Cambridge – Computer Laboratory, Technical Report No. 696, pp. 1-37, 2007

[12] Raymond Chow, "Evaluating inertial measurement units", EDN Network, pp. 34-37, Nov 2011

[13] Paul G. Savage, "Blazing Gyros: The Evolution of Strapdown Inertial Navigation Technology for Aircraft", AIAA Journal Of Guidance, Control, And Dynamics, Vol. 36, No. 3, May-Jun 2013, pp. 637-655

[14] Rommel E. Mandapat, "Development and Evaluation of Positioning Systems for Autonomous Vehicle Navigation", University of Florida – M.S. Thesis, 2001, pp. 16-41.

[15] Chris Goodall, Sarah Carmichael and Bob Scannell, "The Battle Between MEMS and FOGs for Precision Guidance", Analog Devices – Technical Article MS-2432, pp. 1-6, 2013

[16] Zhang Liu, "Introduction to Inertial Navigation and Pointing Control", Northrop Grumman, pp. 1-26, Dec. 15, 2011