Miniature IMU/INS with Optimally Fused Low Drift MEMS Gyro and Accelerometers for Applications in GPS-denied Environments

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I. Abstract

TAI's multi-sensor fusion technology is accelerating the development of accurate MEMS sensor-based inertial navigation in situations where GPS does not operate reliably (GPS-denied environments). TAI has demonstrated that one inertial device per axis is not sufficient to produce low drift errors for long term accuracy needed for GPS-denied applications. TAI's technology uses arrays of off-the-shelf MEMS inertial sensors to create an inertial measurement unit (IMU) suitable for inertial navigation systems (INS) that require only occasional GPS updates. Compared to fiber optics gyros, properly combined MEMS gyro arrays are lower cost, fit into smaller volume, use less power and have equal or better performance. The patents TAI holds address this development for both gyro and accelerometer arrays. Existing inertial measurement units based on such array combinations, the backbone of TAI's inertial navigation system (INS) design, have demonstrated approximately 100 times lower sensor drift error to support very accurate angular rates, very accurate position measurements, and very low angle error for long durations. TAI's newest, fourth generation, product occupies small volume, has low weight, and consumes little power. The complete assembly can be potted in a protective sheath to form a rugged standalone product. An external exoskeleton case protects the electronic assembly for munitions and UAV applications. TAI's IMU/INS will provide the user with accurate real-time navigation information in difficult situations where GPS is not reliable. The key to such accurate performance is to achieve low sensor drift errors. The INS responds to quick movements without introducing delays while sharply reducing sensor drift errors that result in significant navigation errors. Discussed in the paper are physical characteristics of the IMU, an overview of the system design, TAI's systematic approach to drift reduction and some early results of applying a sigma point Kalman filter to sustain low gyro drift.

II. Introduction

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TAI's newest, fourth generation, product occupies small volume, has low weight, and consumes little power. The complete assembly can be potted in a protective sheath to form a rugged standalone product. An external exoskeleton case protects the electronic assembly for munitions and UAV applications. TAI's IMU/INS will provide the user with accurate real-time navigation information in difficult situations where GPS is not reliable. The key to such accurate performance is to achieve low sensor drift errors. The INS responds to quick movements without introducing delays while sharply reducing sensor drift errors that result in significant navigation errors.

Other key features available now or in the future for use as an IMU/INS device include: 1) user friendly settings making it simple to operate; 2) when operating on battery power, embedded power management provides long duration field operation; 3) initial bearing accuracy consistent with tactical requirements; 4) unaffected by varying magnetic dip angles and other magnetic field disturbances since it does not use a magnetic compass for bearing estimation; 5) Integrated Advanced Heading Reference System(AHRS) with a nonlinear optimization filter, the Sigma Point Kalman Filter (SPKF) to estimate and maintain accurate azimuth bearing; 6) dual non-interfering conversion channels for parallel processing of each MEMS subarray to facilitate accurate north-finding and gyrocompass tracking if required; 7) IMU performance improvement due to array performance multiplier effect as individual MEMS inertial sensors characteristics improve; 8) an asynchronous serial connection to enable GPS-aided operation if desired; 9) A simple fabrication process for large-quantity production to lower unit cost significantly.

III. MECHANICAL DESIGN AND PACKAGING

In late 2010, Tanenhaus and Associates started over with a clean sheet of paper to develop and test a new hardware solution that would significantly simplify the assembly and test as well as upgrade the performance of an existing miniature IMU/INS system. This simplified hardware solution leveraged the proven ability to attach three identical semi-rigid flex components to a master semi-rigid flex board wrapped around the smaller components to make up the complete assembly. The core, consisting of the three identical semi-rigid flex components, was folded and potted into cubes. Each cube contains the array of MEMS gyros, a high G accelerometer, and dual ADC devices to convert gyro data simultaneously at two different levels of resolution. The cubes are positioned such that both the gyros and the high G accelerometers are orthogonally positioned on three axes. Each cube is pre-tested to verify functionality and expected performance levels. Each cube records the sensors' changes to temperature enabling algorithms operating in the background to compensate for temperature changes. The trio of cubes is set for a maximum oversampling rate, then an optimum average rate is established for each suite of gyros to control the IMU's gyro output sample rate. The digital output bus is identical for each cube. The main processor wrap-around board contains a three-dimensional accelerometer array that is synchronously slaved to the IMU's gyro sample rates.

The main processor board contains two DSP devices. The first DSP processes all 100 sensors simultaneously at high sample rates. A second embedded processor houses a suite of INS algorithms. The under-utilized processor architecture is available to contain guidance and control algorithms together with the I/O for actuator controls, and/or a real time video-frequency processing link to enable the system to operate together with other system components in the same case. A GPS receiver module embedded on the board can be used or its bus can be bypassed for external GPS inputs.

The IMU/INS (figure 1) in its exoskeleton case (figure 2) contains over 100 sensor data channels processed for real-time operation. It's contained in a volume of 3 cubic inches, weighs 0.3 pounds, and consumes 2.4 watts of power. Its environmentally rugged design also accommodates both an optional GPS receiver and a barometer embedded in the processor board. The exoskeleton case can be fabricated either from metal or high-impact plastic. The I/O and power connector can be either exposed for easy access or recessed and sealed for ruggedization.

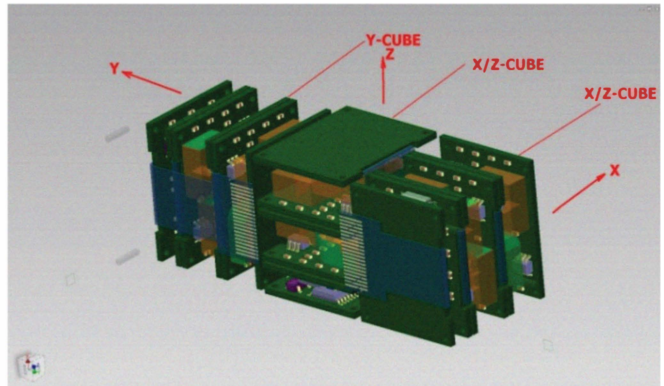

Figure 1a. Unpotted gyro cubes each orthogonally positioned before attachment to main board

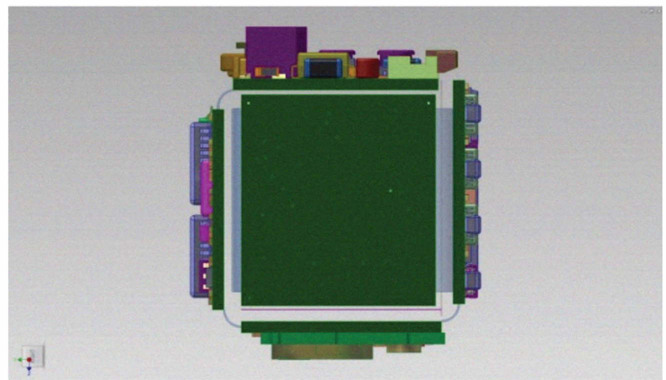

Figure 1b. Main processor board wrapped around the 3 gyro cubes

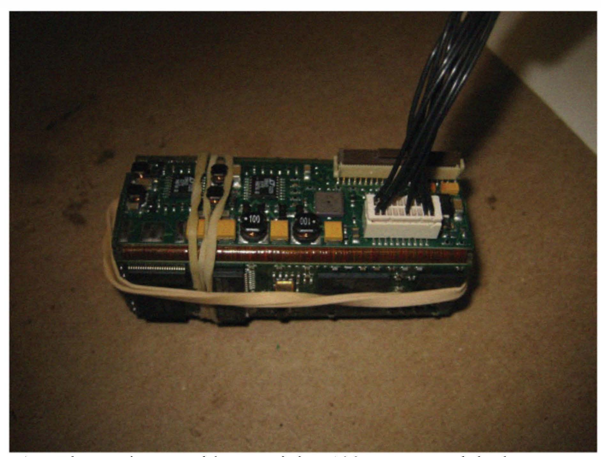

Figure 1c. Electronic assembly containing 100 sensors and dual processors

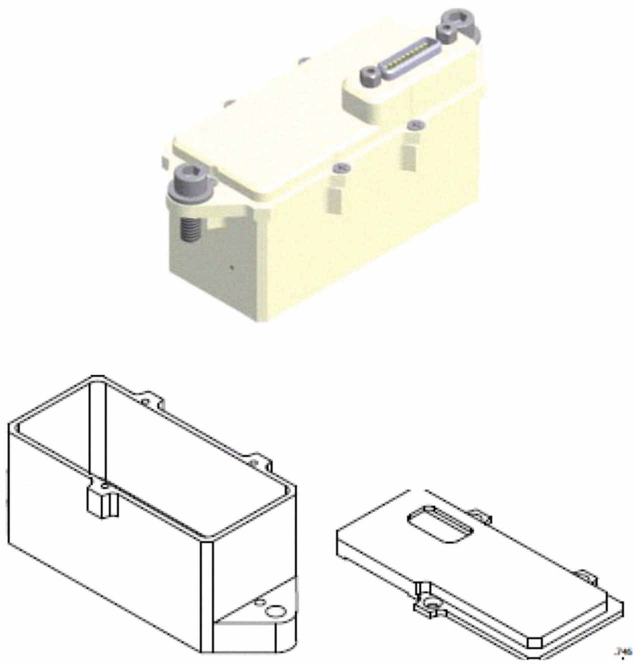

Figure 2. Top-Exoskeleton shock-protected sealed case; Bottom-Plastic case and cover

IV. SYSTEM DESIGN OVERVIEW

The IMU utilizes arrays of MEMS vibration-resistant inertial devices orthogonally positioned to provide 3D coverage. The sensor arrays are systematically combined in subarrays optimally weighted to minimize Angle Rate Walk, Bias Instability, and importantly, Random Rate Walk found to be the dominant source of long term angle drift. The optimization process leverages the correlation between sensors and it is constrained to not distort the signal being measured. By optimizing in both the angle and angle rate domains the combined gyro sensor outputs achieve the noise and drift reduction that would be expected from rate-integrated gyros. The same drift-reduction processing is also applied to the 3D accelerometer array. Upgraded real-time embedded operational code implements a mathematical morphology-based sensor denoising algorithm that is applied separately to both the gyro and the accelerometer arrays to optimize the transient response of each set of inertial sensors. This innovation replaces a wavelet-based denoising filter that contained transient artifacts from transformation between the time and frequency domains, and it significantly reduces throughput delay (latency).

Electronic calibration and alignment of the IMU is applied at the individual sensor level. The calibration and alignment parameters are determined offline from specified measurements, then latched into the embedded software. Sensor calibration compensates for coupled bias-offset and scale-factor errors, equalizing the sensors in each type of array. Orthogonalization adjustment of Cartesian axes is applied as needed. The 3D accelerometer array is precisely aligned with the exoskeleton case and the gyro-array cubes are then aligned with the accelerometers.

The key to low-drift performance In TAI's fourth-generation IMU/INS is optimal combining of the sensors in combinatorially-selected subarrays, to be described in more detail below. For the gyros, this is enhanced by Kalman-filter compensation referenced by the accelerometers' measurement of tilt relative to the gravitational vector.

The low-drift array optimization technique has been applied to the separate gyro and accelerometer axes with equal success. From our experiments and analysis we have observed that the resulting system will be capable, not only of accurate azimuth sensing, but also accurate earth rate detection for non-magnetic geodetic north finding to enable gyrocompassing in GPS-denied environments. Advanced algorithms under development and test will expand the instrument to a fully enabled north-finding product to be packaged with the navigation system, or the IMU's functions can be separated to create a suite of products for different user needs. The TAI low-drift IMU can provide all these capabilities with a full processing/connectivity hub for USB add-ons.

The architectural design permits the unit to interface with a host of sensors and systems. In fact, it will perform as a full processing/connectivity hub for both military and industrial systems. The unused parallel port will process real-time video or interface to a variety of high speed digital converters to process radar data; medium speed serial ports with SDLC-like protocols operate over RS422, and 2.0 USB is an option.

V. SYSTEMATIC APPROACH TO DRIFT REDUCTION

The underlying basis for achieving accuracy by using arrays of sensors is to combine them in complementary pairs to reduce noise and drift that induces errors in the time-integrated outputs. This principle is applied in several layers culminating in the optimum-weighted combination of paired subarrays. Of critical importance is the use of constrained optimization that prevents distortion of the external stimulus measured.

First, consider only the gyros, but the same observations apply to the accelerometers as the results to be presented will demonstrate. Earlier the impact on reduced error was achieved by moving from single gyros to an array of eight. The 8-element array, when additively combined, reduces ARW, the higher frequency white noise in the gyro rate that gives rise to a component of angle random walk. Bias instability, the short-term variance in the slowly fluctuating mean of gyro rate, is also reduced. But by the application of a proprietary combining technique, bias instability and ARW are reduced to a greater extent. Rate walk, the random walk in sensor bias, is also reduced. The improvement is readily seen in root-Allan variance which makes an ensemble-average estimate of variance followed by taking its square root. The remaining array optimization is aimed largely at reducing random rate walk, the component of gyro rate that is fluctuating very slowly. Rate walk dominates the error over long duration, magnified when integrated to angle, so the object is to drive it toward zero. The same considerations apply to the accelerometers where position errors are further magnified from double integration over time.

When we select subarrays of gyros in pairs from the available 8 on each axis, through combinatorial analysis (constrained by the assignment) we're actually discarding pairs of gyros that have high drift and retaining those that have lower random rate walk. The impact on Allan deviation is to flatten the curve in the rate walk region beyond the bias stability region but it can't be measured accurately from root Allan variance without enough averaging time requiring very long duration static measurements. Figure 3 below displays root Allan variance (deviation about the mean) for a set of 24 randomly selected gyros. It can be seen from this set of curves that as the gyro quality improves the curves shift downward and to the right. There is not much change in ARW, but the bias stability values improve. Most importantly, for longer-duration drift error the curves flatten in the rate walk region to the right of the zero-slope region of bias stability estimation. As the quality of the gyros, or gyro sets formed from optimally combined gyro arrays, improves the rate walk region becomes obscured by insufficient ensemble averaging unless extremely long time-duration data measurements are available.

Because measurement of root Allan variance over very long duration is not practical, we devised metrics that measure the actual angle drift after integration of gyro rate (and accelerometer velocity and position) to guide combinatorial selection of subarrays and facilitate optimization. These metrics take into account the random bias offset which Allan variance does not.

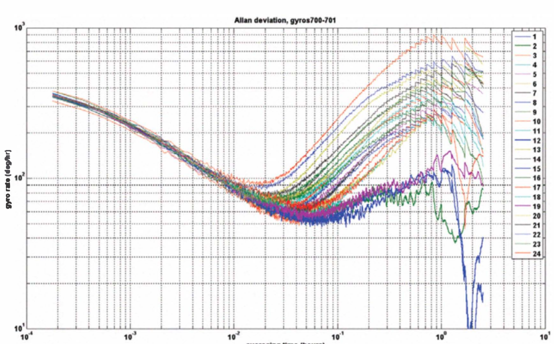

Figure 3. Root Allan variance for 24 randomly selected gyros

Below are shown some graphical results that illustrate the comparative reduction achieved in IMU angle drift error and accelerometer position error when the array combining methods are applied. In these graphical illustrations single gyros and accelerometers are compared with the random assignment of 8 sensors per axis, low-drift subarrays selected from the 8 sensors assigned, and optimally combined pairs of subarrays using combining weights determined from constrained optimization. The measurements were taken over a 47-minute duration. Figure 4 compares integrated gyro rate for three cases: a single randomly selected gyro, 8 combined gyros positioned to reduce common-mode effects, and an optimally weighted subarray pair.

A revealing metric comparison, useful for making optimal sensor selection and combining, is shown in figure 5 for gyros and in figure 6 for accelerometers. This metric is similar to root Allan variance in method but computes the RMS error that retains the effect of the slow bias mean drift, not just the variance about the mean, and it is applied directly to the integrated sensor output. Figure 5 compares different cases of sensor combining, plotting ensemble average RMS values of angle error (integrated gyro rate). Figure 6 compares different cases of sensor combining, plotting RMS error of position (double-integrated acceleration).

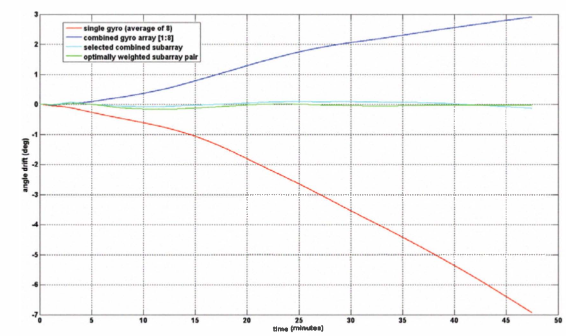

Figure 4. Mean angle drift comparison

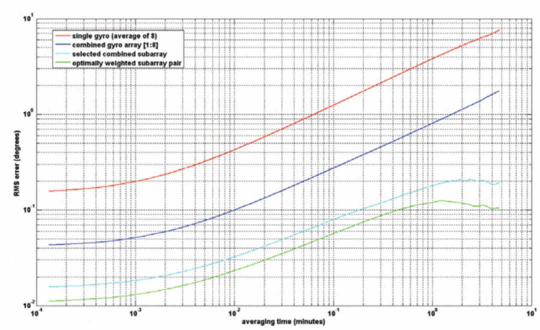

Figure 5. Ensemble average of RMS angle drift error

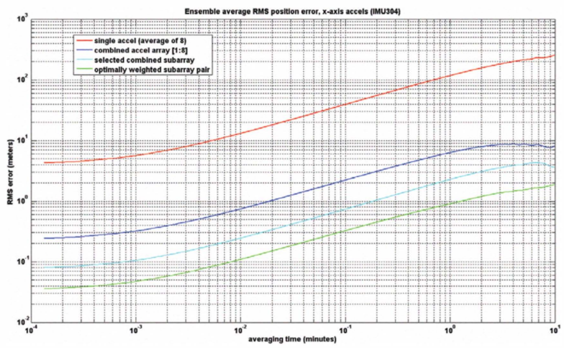

Figure 6. Ensemble average of RMS position drift error

The ratio in improvement between the combined 8-element array and the optimally weighted subarray pair is 6.6 times (16.4 dB) for accelerometers and 4.2 times (12.5 dB) for gyros. The improvement over the single sensor average is much greater, 42 dB for accelerometers and 37 dB for gyros.

To illustrate a practical benefit of optimally combined subarrays we show below the results of a simulated estimate of earth rate, comparing 8 randomly-selected combined gyros with optimally combined subarrays derived from the same set of 8 gyros. The analysis was based on adding a synthetic component of earth rate to the actual noise and drift of the stationary gyros. The injected earth rate was calculated for 60 degrees north latitude (Helsinki, Finland) bearing 45 degrees from geodetic north. The resulting value of earth rate is approximately 0.0015 degrees/sec. Figure 7 shows the estimate using the 8 randomly-selected combined gyros. It is evident that the estimate is far from the true value. Figure 8 shows the result for optimally combined subarrays selected from the random set.

It is evident that the estimate is quite accurate suggesting that north-finding can be achieved in a relatively modest observation and processing interval.

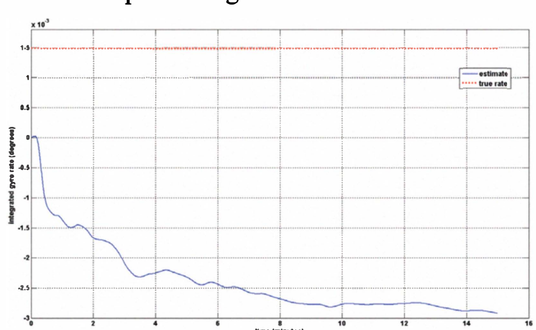

Figure 7. Mean estimate of earth rate – 8 combined gyros

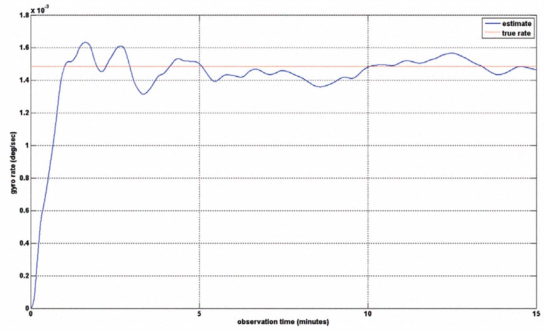

Figure 8. Mean estimate of earth rate – optimally combined gyro subarrays

Initial error reduction results have shown the ability to measure position from accelerometers over 20 minutes with a maximum error of less than 10 meters before a GPS update is needed. There is still room for improvement in performance in terms of sensor drift reduction as well as reduced attitude angle errors. Several new approaches to error reduction are being explored.

VI. SPKF Gyro Compensation

After optimization of the gyro arrays, a Kalman filter, implemented as a sigma point Kalman filter (SPKF), is employed to restore any reduction of variance that was yielded in the interest of reducing rate walk which has dominant impact on angle drift (and similarly for acceleration walk with respect to velocity and position errors). The SPKF will reduce variance as a consequence of the cross-referenced gyros and accelerometers. It also appears to extend the time duration over which angle accuracy can be sustained.

Initial tests were made of the SPKF as applied to the combined-array IMU outputs measured over 47 minutes from static IMU hardware employing a newer and better grade of gyros. Two types of combined array measured data were employed, outputs from the random assignment of 8 sensors per axis, and 4-element subarrays selected by combinatorial analysis from the assigned 8. The figures presented below show early results of the analysis measuring the accuracy of estimating Euler angles which should be zero for the static conditions (no external rotation).

Figure 9 shows the accuracy achieved over a 47-minute duration of static operation when the SPKF was applied to the random combination of 8 assigned gyros per axis. It is evident that the drift errors in the combined-array IMU inputs to the SPKF have been reduced substantially and are smaller for the pitch and roll axes than for the yaw axis, as expected.

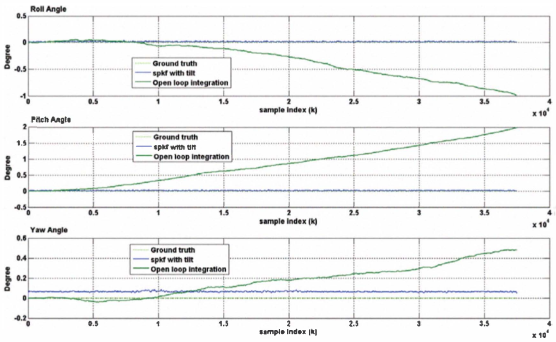

Figure 9. SPKF Euler angle estimates for 8 randomly combined gyros

Figure 10 shows the accuracy achieved over the same duration of static operation when the SPKF was applied to optimally-selected gyro subarrays.

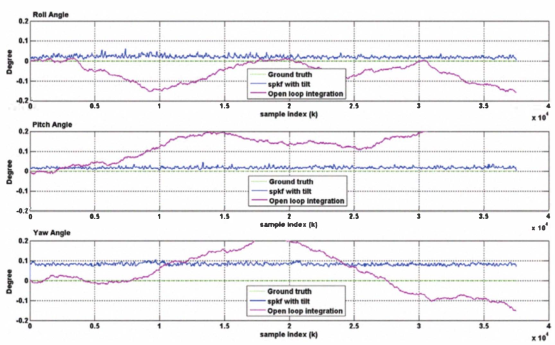

Figure 10. SPKF Euler angle estimates for selected gyro subarrays

Notice that the yaw angle error for the SPKF processing of the selected subarrays, that have smaller drift than the random combination of 8, is slightly worse. This suggests that an improved noise model for the lower-drift IMU needs to be created for the SPKF, taking accurate account of rate walk as well as ARW and bias instability.

VII. Summary

For UAV and similar applications we have observed that both the low drift angle and the position error improvements could extend GPS-denied update requirements from 90 seconds to nearly 1 hour using the combined and optimized gyro and accelerometer arrays to minimize angle, velocity, and position drift errors. Selection of the averaging filter for the sample rate, and the optimum denoising filter cutoff-frequency setting for each gyro and accelerometer subarray will optimize transient response of the optimally combined gyro and accelerometer channels separately and precisely.

Presently, funded MEMS gyro development is focused on the ability to attain low noise and low-drift through the development of rate-integrating gyros to achieve accurate angle estimation. This development is expected to take several more years to develop a better gyro, not a complete IMU solution. TAI has achieved equivalent performance using MEMS sensor arrays and optimal array combining algorithms to minimize noise and drift. By optimizing in the measureable output angle, velocity and position domains, as well as the rate and acceleration domains, we have designed and fabricated a miniature IMU with fused 3D integrated-rate equivalent gyros and fused double-integrated equivalent accelerometers with accurate performance that will match the expected performance from rate-integrated sensors. This design also retains the gyro rate needed together with linear velocity to measure the Coriolis component of acceleration, and we have retained the acceleration needed to maintain gravitational tilt needed to reference the gyros in a complementary Kalman filter used to maintain low drift over time. In addition, several supplementary techniques to enhance error and drift reduction are being explored.

TAI has taken manufacturing steps to produce a medium-quantity, low-cost, accurate unit for the military and commercial market. TAI has teamed with a manufacturer of high volume military ordnance devices to fabricate and support the manufacturing of these units to lower the cost in high-volume quantities.