NavChip^{TM} White Paper

Introduction

Navigation applications are prolific. Most navigation solutions integrate measurements from an Inertial Measurement Unit (IMU) and fuse them with measurements from other sensors. A range of IMU technologies fill a large trade space between performance and size, weight, power, and cost (SWaP-C). Reaching into that trade space to select an IMU for a particular application requires an understanding of the trade space axes and where the application fits onto those axes.

The Thales NavChip^{TM} IMU represents a unique combination of performance and SWaP-C for industrial-grade IMU applications. This white paper is intended help a designer parse the large IMU trade space to determine whether the NavChip (or any other IMU) is an optimal choice for any particular application. To do this, the paper defines the IMU technologies that create the trade space, defines IMU performance metrics typically used to index into the space, and maps applications into that space. Furthermore, this paper describes how the NavChip fits into each concept.

IMU Technologies

In February 1953, Charles Stark Draper's Space Inertial Reference Equipment (SPIRE) -- a 2700 pound inertial navigation system -- guided a B-29 bomber on a 2250 nautical mile autonomous flight from Bedford, Massachusetts to Los Angeles California. This event dramatically demonstrated the potential of inertial navigation (https://cambridgehistory.org/innovation/Draper%20Labs.html). From these high-SWaP-C, military roots, inertial instruments have diversified into technologies that offer a broad range of SWaP-C and accuracy for integration into a wide variety of applications, from space stations to smart phones. This section introduces terminology and technologies needed to discuss modern, inertial instruments.

Terminology

Before continuing further, it is important to highlight some relevant terms that will contribute to a better understanding of this white paper discussion.

- **Inertial:** not accelerating.
- **Inertial coordinate system:** a non-accelerating coordinate system. In such a system, an object can hold its position without requiring any acceleration. The Earth is NOT an inertial coordinate system - it exerts gravity and it rotates. Gravity causes all points in the coordinate system to accelerate toward the center of the Earth. Rotation causes all points in the coordinate system to rotate around the Earth's axis, accelerating toward the Earth's axis.
- **Proper Acceleration:** acceleration in an inertial coordinate system. The Earth does not define an inertial coordinate system, but acceleration in the Earth coordinate system can be converted to Proper Acceleration by subtracting the acceleration of the Earth system itself (e.g. gravity, rotation around the Earth axis, and Coriolis Effect for moving objects).
- **Inertial Angular Rate**: angular velocity in an inertial coordinate system. The Earth does not define an inertial coordinate system, but angular velocity in the Earth coordinate system can be converted to Inertial Angular Rate by subtracting the angular velocity of the Earth system itself (e.g. rotation around the Earth's axis).

- **IMU** (Inertial Measurement Unit): a device that measures inertial angular rate, proper acceleration, and optionally other signals, such as magnetic field and/or atmospheric pressure. An IMU typically includes A/D conversion to extract the measurements, and filtering and temperature compensation to “improve” them.

  A functional block diagram for a conventional IMU is shown in figure 1. A typical IMU includes a gyroscope, an accelerometer, temperature sensor and supporting algorithms. After necessary data acquisition, it is sensor fusion algorithm block that numerically integrates and solves the data for rotation angle (ΔΘ) and linear velocity (Δ**V**). Calibration and compensation is performed next to correct any misalignment or sensor biases etc. A user, in this case, has an option to rotate (ΔΘ) and (Δ**V**) from IMU module internal axis (NavChip in this case) to the mounted body (Vehicle’s) frame of reference before transmitting the final data.

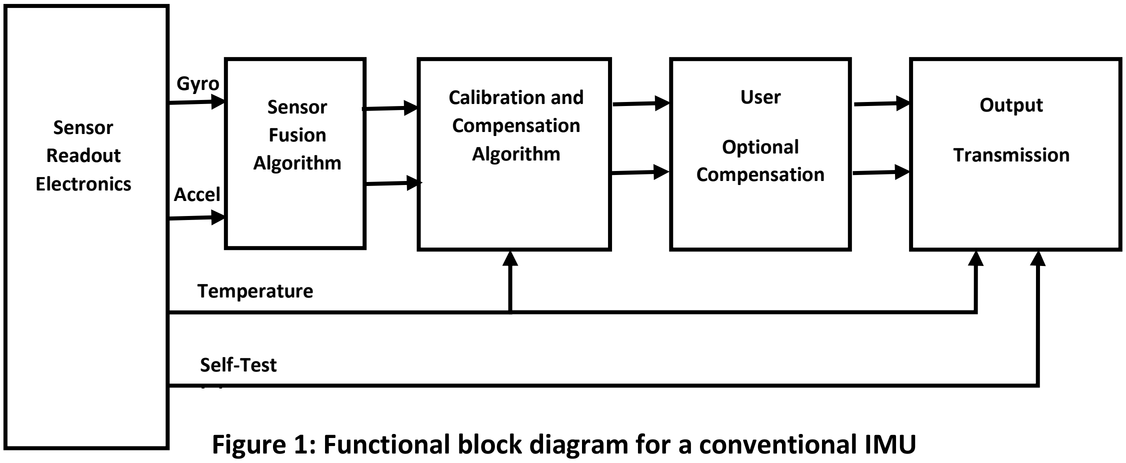

Figure 1: Functional block diagram for a conventional IMU

- **Axis:** a quantity measured by an IMU. Space is three dimensional, so an IMU typically measures angular rate and proper acceleration in three dimensions each, for a total of 6 axes. The IMU may also measure 3D magnetic field and 1D pressure, for a total of 9 or 10 axes. The term “Axis” follows from considering the IMU output as an N-vector, representing a point in N-dimensional space, which has N Axes. This term can cause confusion because the IMU’s sensors are typically aligned on three orthogonal, physical axes in 3D space, giving two conflicting meanings to the two uses of the word “Axis”.
- **DoF** (Degree of Freedom): an alternative term for Axis. Using this term avoids giving “Axis” two conflicting definitions. Depending on the forum, the terms “DoF” and “Axes” may be used interchangeably, or using the disfavored term may provoke heated debate.

Gyroscopes

Gyroscopes (“gyros”) measure inertial angular rate (angular velocity), the change in rotation angle per unit time. This can be integrated to estimate orientation change. Four types of gyros are listed below.

- **Mechanical Gyro:** a mass spinning on one axis that, when rotated on a second orthogonal axis, conserves angular momentum by torqueing the third orthogonal axis, proportional to the new rotation’s angular rate. If the mass spins on an axle, the torque can be measured as force that is exerted at the axle’s bearing. Mechanical gyros tend to have high SWaP-C and require frequent maintenance.

- **Ring Laser Gyro (RLG):** splits a laser beam into two beams that travel in opposite directions around a looping path (a "ring"). They meet again and form an interference fringe on a detector (the Sagnac effect). If the ring rotates during the transit, the detector moves along the ring, shortening one beam's path and lengthening the other's, causing the interference fringe to shift proportional to the speed of rotation. RLGs have no moving parts and are more reliable, lighter, and more accurate than mechanical gyros.

- **Fiber Optic Gyro (FOG):** an RLG whose single ring is replaced with a fiber optic coil. The beams travel the same loop many times, and their interference fringe shifts proportional to both the coil's rotation rate and the enclosed area of the coil, allowing the same detector to resolve much smaller rotation rates than an RLG in a given volume.

- **Micro Electro-Mechanical System (MEMS) Gyro:** a microscopic mass in a 2D frame that is orthogonal to the gyro axis. The mass is spring loaded along one axis of the 2D frame, and driven back and forth at a known velocity profile along the other axis. If the frame rotates about the gyro axis, then to maintain its velocity relative to the 2D frame, the mass must accelerate in the spring-loaded direction, proportional to the rotational velocity. Observed from the rotating frame, the mass appears to experience equal and opposite acceleration. This is called the Coriolis Effect. Spring loading on the velocity-orthogonal axis converts acceleration linearly to displacement, which the gyro measures. Linear acceleration along the velocity-orthogonal direction would have the same effect, so it is common to drive two masses in opposite directions along the same axis, such that Coriolis Effect produces equal and opposite displacements, but linear acceleration produces identical displacement. Subtracting the two measurements cancels much of the linear acceleration effect. MEMS gyros are less accurate than optical gyros. They are very simple and inexpensive compared to a mechanical gyro of the same accuracy.

NavChip uses MEMS gyros to achieve moderate precision at very low size and relatively low cost.

Accelerometers

Accelerometers ("accels") measure proper acceleration. This can be converted to acceleration in a local coordinate system by adding accelerations from gravity and Earth rotation. Those accelerations can then be integrated to estimate velocity change, which can then be integrated again to estimate position change.

Almost every accelerometer consists of a mass connected to a case by a spring or a deformable cantilevered beam. When the case accelerates along the spring axis, or orthogonal to the long axis of the beam, the mass deflects by an amount that is proportional to the acceleration. The deflection of the mass relative to the case can be measured by forming a potentiometer or capacitor from the mass and case; or, it can be measured by inserting a piezoelectric crystal between mass and case, so that the mass does not actually deflect, but rather exerts a force that the crystal converts to voltage; or, it can be measured by vibrating the cantilever beam and measuring the change in vibration frequency as the beam bends.

Accelerometers can be very small. MEMS accels (typically a mass hanging from a cantilever beam with deflection measured by capacitance between mass and case) can be as small as several microns, and can be co-packaged with gyro and electronics to form very small IMUs. They tend to be less accurate than larger accels that have larger proof masses and proportionally less interference from extraneous factors, such as manufacturing tolerances.

NavChip uses MEMs accelerometers to achieve very low size and relatively low cost.

Magnetometers

Magnetometers measure magnetic fields (in Gauss or Tesla). In free space (e.g. attached to a flying airplane), they measure the Earth's static, mapped magnetic field; and the orientation difference between measurements to map can reveal the magnetometers' absolute yaw (which gyros cannot do). Even without a map, changes in magnetometer readings correspond to magnetometer rotation. They can be combined with gyro and accel readings to estimate biases associated with each sensor, allowing gyros and accels to be integrated more accurately to determine position and orientation.

However, magnetic fields can be complex, unmapped, and distorted near magnetized iron ("hard iron distortion") and metallic objects such as iron and nickel ("soft iron distortion"). They also become time-varying near motors or electrical wiring. Thus magnetometers may have very little utility in man-made environments, when operating on wheeled robots, or when attached to humans carrying metal tools. Further, magnetometers increases an IMU's SWaP-C. Thus, 6 axis IMUs without magnetometers may be preferable when gyro and accel biases can be calibrated or estimated by some other sensor.

The NavChip does not incorporate magnetometers.

IMU Performance Metrics

Navigation software typically monitors an IMU's orientation and velocity by integrating inertial angular velocity and proper acceleration measurements from the IMU's gyros and accels. Those measurements are biased, scaled, and noisy compared to the true angular velocity and acceleration, so the software typically estimates biases and scale factors, and uses the estimates to infer "truer" measurements that are closer to the true angular velocity and acceleration. These truer measurements are still corrupted by noise and any errors in the bias and scale estimates, so integrating them still produces orientation and velocity estimates that steadily drift away from the truth.

IMU performance metrics quantify the impact of the physical mechanisms that contribute to this navigation drift. Here we describe the most important of these metrics. Table 1 gives example values against these metrics for the NavChip Series 3 IMU (Class A).

- **Range:** minimum and maximum angular rate and acceleration that the gyros and accels can reliably estimate. Angular rate is typically given in degrees per second. Acceleration is typically given in g's, where one g is 9.80665 m/s^2, the Earth's gravitational acceleration. Large range prevents accels and gyros from outputting erroneous measurements (incurring drift) when they experience occasional shocks (high accelerations or fast rotations).

- **Random Walk:** expected amount of navigation drift due to gyro and accel noise. Navigation software integrates noisy angular rate and proper acceleration measurements to estimate orientation and velocity. If the noise on these measurements is zero mean, Gaussian, and uncorrelated in time, then the integrated noise follows a random walk, causing orientation and velocity errors to grow with the square root of time. To reflect this expected error, angle random walk (ARW) and velocity random walk (VRW) typically are reported as degrees per root hour and meters per second per root hour, respectively.

- **Noise Density:** another way to express random walk. Gyro noise density is typically expressed in degrees per second per root-Hertz, or degrees per hour per root-Hertz, each of which differs from Angle Random Walk only by a factor of 60 to convert the units to degrees per root hour. Accel noise density similarly is expressed in g's per root Hertz, or similar units, that convert easily into the meters per second per root hour of Velocity Random Walk.

- **Bias Drift, (in-run) Stability, or Instability:** expected drift rate of gyro and accel biases. Biases drift over time in a bounded, non-linear way that is difficult to parameterize, so stability is typically reported as the amount that the bias can change over a fixed amount of time, in the same units as the measurements and bias: °/hr for gyros, m/s^2 or mg (milli-g) for accels. Lower drift rates let navigation software better estimate bias by interpreting measurement jitter as noise, not fast-changing bias. Bias stability is measured on a stationary platform at equilibrium temperature at 1-g acceleration to determine the effect of the sensor stability alone, unaffected by thermal calibration inaccuracies or external changes to rotation rate or accelerations.

- **Bandwidth:** maximum frequency of input signal that can be measured well by the gyros and accels. Spring loaded masses in mechanical accels and gyros need time to fully respond to incoming accelerations, so they under-respond to, and thus under-report the magnitude of high frequency inputs. Bandwidth is typically specified as the frequency at which the accels or gyros report only half of the input signal (the "-3dB point"). Higher bandwidth sensors can be sampled at a higher rate, allowing higher accuracy integration to estimate velocity and orientation.

- **Bias accuracy over operating temperature range:** amount by which the IMU's internal software may mis-estimate its gyro and accel biases due to changes in temperature. High-performing IMUs have gyro and accel biases factory calibrated as a function of temperature, and they apply this calibration to estimate the biases in real time. Reported accuracy for the NavChip is the maximum error seen when sweeping through the entire operating temperature range in both directions, and is measured in units of angular rate and acceleration - the same as the gyro and accel measurements and biases. A small magnitude bias accuracy over temperature allows navigation software to better estimate biases (and thus avoid drift) by providing a bound on acceptable bias estimates. IMUs without factory calibrated biases typically report magnitude and repeatability of biases at turn on, rather than bias accuracy over temperature range.

- **Scale Factor accuracy over temperature range:** amount by which the IMU's internal software may mis-estimate its gyro and accel scale factors. It is analogous to bias accuracy over temperature, above, except that it is measured as a percentage or in parts per million, which convert easily to an "error" scale factor.

- **Scale Factor linearity:** percent by which gyro and accel measurements may be incorrect based on assumptions that their outputs vary linearly with angular rate and proper acceleration. The linear model is only approximately true. A smaller linearity percent translates to more accurate measurements and higher confidence in integrated navigation signal.

- **Axis Mutual Alignment:** angle by which the three gyros or accels in an IMU may not be quite orthogonal to each other. Navigation software must account for correlation between measurements on non-orthogonal axes, either by explicitly estimating the non-orthogonality, or by reducing confidence in the measurements and, therefore, in the navigation solution.

- **G Sensitive Bias:** additional bias experienced by gyros when they accelerate, reported as angular rate per g of acceleration. In the MEMS gyros described earlier, this bias occurs when the two masses are not driven exactly in opposition, for instance, due to manufacturing limitations. G sensitivity may be the largest source of measurement error in applications with large, unpredictable accelerations or vibration.

Table 1. NavChip^{TM} Performance Illustrating the IMU Performance Metrics Defined Above

Performance	Gyro		Accel	
Technology	Typical	Max	Typical	Max
Range (Full Scale)	± 2000 °/s	± 2000 °/s	± 16 g	± 16 g
Random Walk	0.18 °/$\sqrt{hr}$	0.3 °/$\sqrt{hr}$	0.02 m/s/$\sqrt{hr}$	0.02 m/s/$\sqrt{hr}$
Noise Density		0.005 °/s/$\sqrt{Hz}$		83 µg/$\sqrt{Hz}$
In-Run Bias Stability	4 °/hr	5 °/hr	0.006 mg	0.01 mg
Bandwidth (-3dB)	250 Hz		250 Hz	
Bias Accuracy over Operating Temperature Range	± 0.2 °/s	± 0.3 °/s	± 3 mg	± 15 mg
Scale Factor Accuracy over Operating Temperature Range	±0.05 %	±0.4 %	±0.09 %	±0.2 %
Scale Factor Linearity	0.01 %	0.05 %	0.06 %	0.2 %
Axis Mutual Alignment	±0.03 °	±0.2 °	±0.03 °	±0.2 °
G Sensitive Bias	0.004 °/s/g	0.03 °/s/g		

Table 2. NavChip^{TM} Physical Dimension and Electrical Parameters

Performance	Specifications
Dimension	12.5mm x 24.5mm x 5.4mm
Weight	3 g
Power Consumption	3.25V – 5.5v at 40mA, 135 mW
Initialization time	< 1s
Sample Rate	200 Hz, Selectable (1Khz)
Interface	TTL UART or SPI (selectable)

Matching IMU to Application

Different IMU applications require different technologies and, therefore, have different SWaP-C.

Applications

A number of applications are listed below.

- **Controllers.** Many mass-market applications use accelerations and angular rates directly, or they accommodate slow-drifting estimates of orientation and velocity and, therefore, can accept noisy and biased measurements. Examples include controlling games on smart phones; monitoring head orientation for virtual reality; monitoring articulation of body parts for physical therapy or sports training; and identifying and damping low frequency vibration in industrial robots, cameras, and antennas. IMUs for these applications must be low cost, and are typically low performance.

- **Navigation.** Many applications involve monitoring the position and orientation of automobiles, unmanned ground/air/underwater vehicles, factory robots/workers, and regular people, either to help plan routes or to monitor where vehicles/people are located. These applications typically require higher accuracy measurements.

- **Placement.** Many modern industrial vehicle applications require higher precision navigation in order to guide a vehicle to a precise location. For instance, an Advanced Driver Assistance System (ADAS) may wish to keep a car within a certain lane; a road construction vehicle may need to position a tool precisely relative to a bridge; smart farming vehicles dispense seeds, fertilizer, and pesticides at precise locations to minimize cost and runoff. These applications are similar to navigation in that they require higher precision IMUs to allow for more precise positioning, and to overcome longer outages of their aiding sensors. Applications tend to be installed on vehicle platforms, which are able to support larger sensors.

- **Augmented Reality (AR).** A head mounted display can augment information and virtual objects into a user's forward view. This is already done to provide critical situational awareness for military pilots. This technology is currently being researched for use by air traffic controllers, soldiers, firefighters, and police who need information quickly via a natural interface. Sensors must have low noise, high update rate (human eyes do not tolerate jitter or lag), and small size (to be head mounted). Bias accuracy is less critical, because an AR system must include other aiding sensors to maintain long term drift resistance.

IMU Grades

People generally categorize IMUs into grades that map to the applications. Below are some standard grades that are ordered by increasing SWaP-C and accuracy. Different sources threshold accuracy differently. Figure 1 depicts our mapping of accuracy to IMU grades.

- **Consumer grade** IMUs are mass-produced and tiny, making them useful as controllers.

- **Industrial grade** IMUs are used in navigators that integrate measurements over short intervals and avoid longer term drift by fusing with measurements from GNSS or other aiding sensors. Industrial IMUs typically can be larger than consumer IMUs, as they are body-worn or built into vehicles. AR and Placement applications fall into this bin.

- **Tactical and Navigation grade** IMUs have the accuracy to operate for longer without needing aiding sensors to avoid drift. They can be larger and more expensive as they are generally used with larger and high-priced vehicles such aircraft.

- **Strategic grade** IMUs are the largest and most expensive, having accuracy suitable for long term navigation without aiding sensors, useful for instance to submarines.

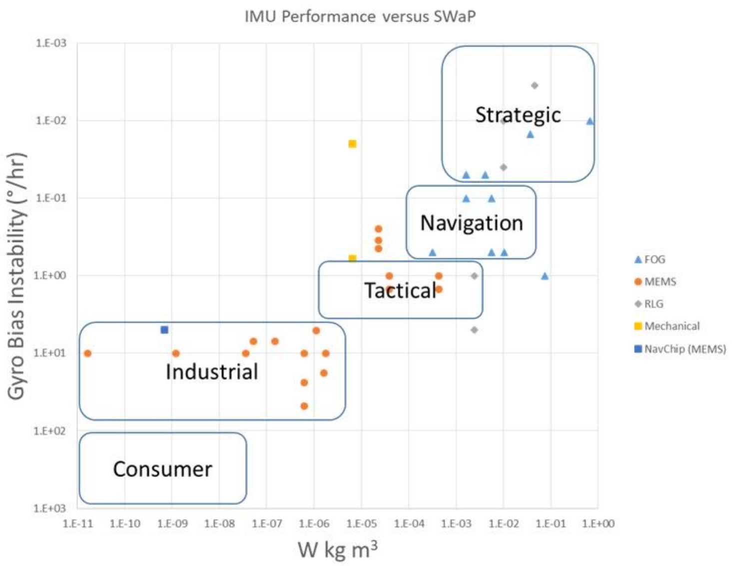

Figure 2. Map of IMU accuracy, SWaP, and grades.
The "best" IMUs are in the top left corner, with low instability and low SWaP.

Map

Figure 2 shows a map of the locations where the IMU grades and technologies fit on a graph of performance versus SWaP.

The graph shows (typical) gyro bias stability, though other metrics exhibit similar trends. Larger, heavier, and higher power sensors produce better measurements. SWaP-C is shown as a product, as DARPA used to do (https://www.gps.gov/governance/advisory/meetings/2014-12/lutwak.pdf), except excluding cost, as cost data are unstable and hard to acquire. No data points are shown for consumer IMUs, which tend not to have published drift rates, perhaps because drift is not critical for controller applications.

The NavChip sits near the top-left (high accuracy, low SWaP) of the industrial grade range, suitable for Augmented Reality, other high-end industrial applications, and low-end tactical applications. NavChip represents uniquely high performance for its SWaP-C, or low SWaP-C for its performance.

Conclusion

This paper has defined various critical parameters related to the selection of an IMU. Depending on an application, some parameters are more important than others: designers can prioritize these key parameters based on their applications. The NavChip family has an edge over its competitors based on these key parameters summarized in Tables 1 and 2.

The NavChip family also provides additional features such as selectable data output interface, format, and sample rate. Its state of the art supporting algorithms make its performance robust against any interference, drift stabilization, and vibration/shock.

Thus based on its size, weight, and power requirement the NavChip family provides an IMU capability that supports the Industrial need category with a drift rate of 5^0/hr. NavChip can also support the Tactical grade market-space as it has demonstrated even better and repeatable drift rates approaching 1^0/hr.