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21st CENTURY INERTIAL NAVIGATION SYSTEMS A REVIEW OF THE LATEST TECHNOLOGIES AND TRENDS

Asif Iqbal[1]
NESCOM
Islamabad, Pakistan

ABSTRACT

The development of highly precise and autonomous Inertial Navigation Systems (INS) has been one of the important engineering accomplishments of 20th Century. Inertial Navigation is a multidisciplinary field of engineering and science that combines the efforts of engineers, physicists, mathematicians, metallurgists, skilled technicians, and managers to bring inertial navigation to its present advanced state. This paper provides a general overview on the latest technologies and prognosis in the design and development of inertial navigation systems in 21st Century. Regarding the inertial rotation sensing the Ring Laser Gyro (RLG), Fiber Optic Gyro (FOG) and MEMS Gyros the three more attractive, prominent and emerging technologies are addressed in detail.

INTRODUCTION

An Inertial Navigation System (INS) is comprised of an Inertial Measurement Unit (IMU) and a computer. Inertial Measurement Units (IMUs) typically contain three orthogonal rate gyroscopes and three orthogonal accelerometers. Gyros measurements of inertial angular rate are used to determine the orientation of a triad of accelerometers. The accelerometer measurements, in turn, are integrated to estimate vehicle velocity and position. By processing signals from these devices the computer calculates the vehicle's position, orientation, and velocity with reference to its starting point. To initialize the INS an operator, a Global Navigation Satellite System (GNSS), or some other external input provides an INS with its initial position and velocity. Subsequently an INS can compute the position and velocity of a moving vehicle by integrating information received from its IMU. Many types of vehicles incorporate INS, including aircraft, UAVs, submarines, spacecraft, guided missiles etc. The first INS was developed at the MIT Instrumentation Lab for ballistic missile guidance [MacKenzie, 1993].

The advantage of an INS is that after initialization it requires no external references to determine its position, orientation, or velocity. So it is a self-contained, immune to jamming, inherently stealthy all weather positioning and attitude system. Moreover, the most important advantage of INS is that velocity, position and attitude of the vehicle can be provided with abundant dynamic information and excellent short term performance [Skaloud et al., 1999]. The INS mechanization is shown in figure 1. The equations of motion of INS are second order differential equations. In the most simplified form, for one dimensional motion it could be written as:

$$x(t) = \int_0^t\int_0^t a_x \, dt dt = x_0 + v_{x0}t + a_x t^2$$

[1]Chief Manager in NESCOM, Email: asiphiqbal@yahoo.com

It states that if the initial position, x_0 and velocity, v_{x0} are known then the position $x(t)$ at any instant, t of an object could be obtained by double integrating its acceleration, a_x. So the measurements provided by gyroscopes and accelerometers are used to determine the position of the vehicle in which they are installed [Grigorie et al., 2008]. By combining the two sets of measurements, it is possible to define the translational motion of the vehicle within the inertial reference frame and so to calculate its position within it. [Titterton, 2004]. However uncompensated low frequency noises and sensor biases reside as erroneous forcing functions in the differential equations. When integrated to get the velocity and position information, these uncompensated errors have detrimental effects on velocity and position accuracy of INS with progression of time. The major error sources in the INS are due to gyro and accelerometer imperfections, incorrect navigation system initialization, and imperfections in the gravity model used in the computations. But, in nearly all inertial navigation systems, the largest errors are due to the inertial sensors [Schmidt, 2014].

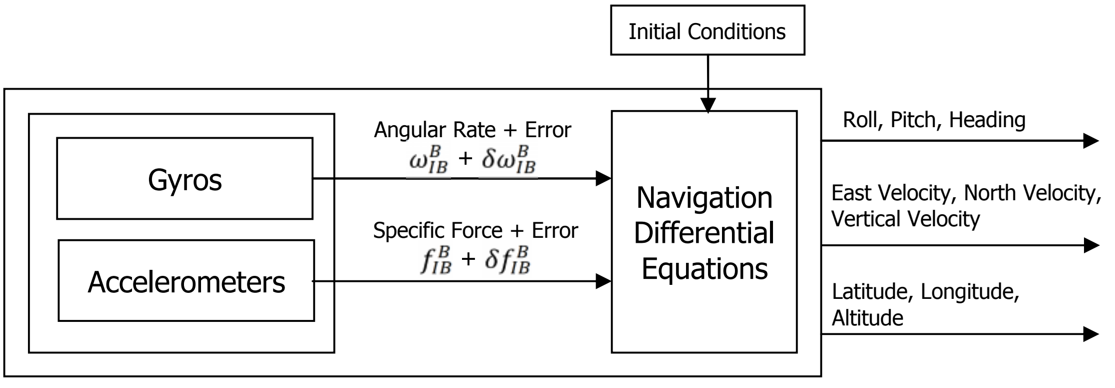

Figure 1: Inertial Navigation System

New challenges for scientists and engineers in field of inertial navigation were faced due to this temporal degradation of position accuracy. In order to accomplish the enhancement in accuracy and reliability of INS, multipronged approaches were adopted by inertial sensors and systems specialists in the past half century. The most focused approaches are:

1. Advancement in Inertial Sensors Technologies
    a. Accuracy and reliability enhancement of inertial sensors
    b. Identification of new sensors technologies

2. Integration of aiding sensors output by adopting optimal data fusion techniques

Besides that lot of work has been done for the improvement of supporting electronics. The inertial sensors output has to interface with navigation computer for further processing. The interfacing schemes are quite unique to meet the accuracy requirement of an INS. When the sensor output is analog as is the case with mechanical gyros and accelerometers, the analog to digital conversion process employed is quite accurate compared to what is seen in normal instrumentation system. In an INS, the conversion process error characteristics, if modellable, can become part of the sensor error model. To avoid the error in conversion as well as to provide simplification in electronics, digital rebalance sensor loop has been developed where the output can interface to a navigation computer. But not all inertial sensors can be designed with the digital rebalance loop, and as a result, both the conversion schemes are currently operational. Some later generation inertial sensors provide inherently digital output. The vibrating beam accelerometer and ring laser gyros come under this category.

HISTORY of INS DEVELOPMENT: CONVERSION FROM GIMBALED TO STRAPDOWN

The two basic designs adopted for INS with respect to the inertial sensors configurations are Gimbaled INS (GINS) and Strapdown INS (SINS). Because of the limited dynamic ranges, error sensitivities of earlier gyro technologies and computing limitations, GINS configuration was the most common before the 1990s. In these systems, the inertial instruments are placed on a stabilized platform that is gimbaled with respect to the host vehicle, making the measurements insensitive to rotational motion. Although gimbaled configuration is still in service in number of applications however the gimbaled arrangement is mechanically very complex. It contains number of rotating parts besides the rotors of mechanical gyros. Due to heat dissipation of motorized mechanism, temperature non uniformity is inevitable which necessitates the precise temperature control. This thermal stabilization and gimbal-motors drive electronics consumes more power. The GINS mechanical design management is also very complex. The design must accomplish with inherent static and dynamic gimbal balancing. In addition the system level maintenance of these systems is also cumbersome, requires high level of expertise and need surgically clean environment [King, 1998].

In most of the relatively modern GINS, Dynamically Tuned Gyros (DTGs) and flexure quartz accelerometers are used as inertial sensors [Savage, 2013]. The DTG exhibits excellent performance in gimbaled configuration due to power on to power off bias compensation during initial alignment of INS in addition to the fact that gyros had only to measure rotations up to a few tens of degrees per hour [Barbour et al., 1992]. This advantage of gimbaled mechanism eliminates the requirement of accurate and linear gyro scale factor. Additionally in GINS, rotation calibration can be provided by the gimbal assembly. In this test mode the gimbal assembly is considered as tiny three axes rate-position table residing inside the INS. By employing this technique the gyros and accelerometers biases can be estimated quite correctly and thus compensated. This special characteristic of GINS restricts the velocity and subsequently position error buildup. This unique feature of GINS eliminates the requirement of frequent calibration which is an attractive feature for many applications especially for aircrafts. Design improvements eventually increased commercial aircraft gimbaled INS reliability to 2,000 hours MTBF [Savage, 2013]. The gimbaled systems with accuracy point of view are in range of better than 0.5 nautical mile per hour (nmph). Some modern GINS are developed for long endurance submerged vehicles having accuracy even better than 1 nautical mile in 24 hours. However for such applications there is no constraint on system volume and normally the long readiness time is not considered as disability rather long term accuracy is of prime importance.

The strapdown system is mechanically uncomplicated because of the elimination of the complex and bulky gimballing mechanization [Chatfield, 1997]. In contrary to GINS in case of SINS the inertial sensors are strapped on INS sensor block thus experiencing directly the dynamic environment of the host vehicle. The host vehicle may be a submarine having low dynamics maneuvers and may be an agile fighter aircraft having supermaneuverability. In these cases the requirements for inertial sensors specs are significantly changed. The sensors must have excellent long term biases repeatability, stable and linear scale factors. In addition the sensor block must be manufactured such that it ensures the sensors mutual orthogonality and parallelism quite accurately for reduced error growth under dynamic conditions. Since the inherent calibration capacity is absent in SINS therefore in-run and long term bias and scale factor stability must be minimal to ensure the effectiveness long period between the successive calibrations. In addition the mechanical gyros and accelerometers have limitation of larger temperature dependent drift. Due large thermal hysteresis error these temperature drifts could not be modeled and compensated in software. Therefore to minimize this drawback most of the earlier SINS are furnished with precise thermal stabilization due to which system readiness time was increased. The system readiness time is dependent on the size of inertial sensors thermal mass.

For host vehicle stability and control, angular rates and accelerations in body frame are required which are directly available in case of SINS thus reducing the multiplicity of dedicated inertial sensors normally required for non-INS related functions. Many attempts were made to get rid of gimbaled configuration with mechanical gyros but could not be succeeded. Efforts were made to produce mechanical gyros having excellent long term bias repeatability, accurate and linear scale factor for development of SINS having accuracy better than 1 nmph. This could not be achieved with mechanical gyros due to their design limitations. The DTGs with accuracy better than 0.05^{o}/hour were developed by many companies in the world. Accurate alignment is crucial, however, if precision navigation is to be achieved over long periods of time without any form of aiding. Earlier SINS were based on strapdown DTGs and quartz flexure accelerometers with precise temperature control. Besides position and velocity initialization (normally entered by operator) the INS must needs to know its initial attitude angles (roll, pitch and true-heading) before switching to navigation mode. The accuracy of roll and pitch angles are predominantly dependent on accelerometer bias stability while the azimuth or heading error is a function of gyroscopic bias stability. A 1 milli-g accelerometer bias will have level error of about 1 milliradian while a gyro having drift 0.01°/h will result in a heading error of 1 milliradian at a latitude of 45° [Titterton, 2004]. So with strapdown DTG bias repeatability and stability of 0.01°/h was very difficult to achieve. The DTG based SINS has been used with external aiming techniques normally with help of theodolite for strategic missiles. Therefore it was obvious that an entirely different type of gyro would be needed before a significant increase in reliability could be expected. However it may be noted that even for these types of applications DTG is not an ideal candidate due to its delicacy.

BREAKTHROUGH IN INERTIAL SENSORS

There are many characteristics required in a gyroscope for strapdown applications. In general these include accuracy, long-term stability, low cost, high reliability, low maintenance, high tolerance to accelerations and vibration, small size and light weight, minimum start-up time, and low power consumption.

Ring Laser Gyro (RLG)

The first real enabler for strapdown systems was the Ring Laser Gyro (RLG). Unlike the conventional spinning gyroscope with its gimbals, bearings, and torque motors, the laser gyroscope is usually based on helium-neon laser in a sealed optical-cavity with ultra high-quality mirrors and electronics. When an anode and cathode are excited the cavity acts as an active resonator for the two counter-propagating beams. Depending on the input rotation, the Sagnac phase shift between these beams is detected with help of split photo-detector. The zero crossings generated by the interference pattern moving across the detector, produce a pulse which is designated to a CW or CCW change. Counting the pulses gives the accumulated angle. The RLG has exceptional scale factor stability and linearity, insignificant acceleration sensitivity, digital output, short readiness time, low temperature dependent drift, excellent stability and repeatability of bias. In addition the RLG's performance is very repeatable due to small temperature hysteresis error allowing effective thermal calibration and compensation. It is superior to spinning mass gyros in strapdown applications, and is an exceptional device for high-dynamic environments [Barbour et al., 2001]. High-speed turns, dives, and jinking maneuvers do not represent a real problem to a RLG. Unlike a conventional gyro that requires a finite time for wheels to spin up and bearings to come up to operating temperatures, the laser gyro is essentially ready instantaneously when turned on. Thus the laser gyroscope is more rugged than conventional gyros, offering the obvious advantages of much greater reliability and lower maintenance requirements. Although the RLG is an elegant angular rate sensor, it does have one significant problem; at low rates frequency locking between the two counter-propagating beams occurs which results in a null output [Volk et al., 1999]. This effect is referred to as lock-in. The phenomenon of lock-in is the most prominent error source in RLG and the most difficult to handle [Savage, 1984].

Lock-in occurs because scatter from the ring laser's reflecting surfaces couple the two counter-propagating laser beams. Although the introduction of dither allowed the RLG to achieve preeminent stature for navigation applications, it did result in some limitations. These include mechanical angle noise, acoustic noise, dither cross-coupling, as well as other detrimental system level effects. These dither induced vibration requires expensive damping mechanisms to limit the increase of acoustic signature in submarines. Moreover, the use of dither limits RLG performance to less than that theoretically possible. However the multi-oscillator ring laser gyroscope, as embodied in Litton's Zero-Lock Laser Gyro (ZLG), resolves the early problem encountered with applying optical bias and overcomes the disadvantages present in dithered ring laser gyroscopes. The ZLG is intended to fulfill the total range of applications possible for laser gyros including among others marine vehicles, aircraft, strategic missile, helicopter, ship, and land vehicle navigation, launch system guidance, flight control, motion compensation of other sensor systems, multi-function inertial systems, space related pointing and low noise applications. As opposed to the dithered RLG, the ZLG is a true strapdown angle sensor with no moving parts and no mechanical biasing [Barbour, 2010].

For the inertial sensor level redundancy management strapdown configuration is intrinsically appropriate. Normally 12 inertial sensors (6 gyros and 6 accelerometers) instead of 6 inertial sensors are installed in skewed configuration, allowing failure detection and isolation (FDI) up to two gyros or accelerometers for navigation as well as for flight control. The Boeing commercial 777 became the first aircraft to use a skewed redundant strapdown inertial sensor assembly, all sensors mounted to a common mounting block, the system provided by Honeywell in a skewed 6-sensor hexad configuration using GG1320 RLGs.

Fiber Optic Gyro (FOG)

In the mid-70s, RLG reached the status of the fully matured, producible and high performance sensor. Undoubtedly, the RLG has been the first unquestionable success of laser and electro-optics and entered the mass-production stage being incorporated, in all the new designed military and civilian aircrafts as the sensor of INS [López-Higuera et al., 2002]. The RLG at present is well established in the medium and high performance markets [Juang et al., 2009] and is decisively embedded in the 1nmph navigator business but it will come under cost and reliability pressure from FOG [Lawrence, 1993]. RLG are very expensive to manufacture, requires rigorous and skill involved processes with very specific components like ultra high precision mirrors, high quality glass cavities machined to close tolerances and its assembly in environment having stringent cleanliness requirements. Its production requires large and complex production base having highly trained human resource to ensure the quality and substantial yield of highly accurate product. The resonator assembly along with dither mechanism found in most RLGs unavoidably adds to their weight and size [Juang et al., 2009]. However miniaturization efforts are successful at the cost degraded reliability and accuracy. In addition there is shelf life issues associated with the RLG [Tooley et al., 2007]. The slow leakage of the gas media may degrade the performance over time. Also due to lasing and dither drive RLG consumes high power. Normally RLG consumes five to ten watts [Udd, 1985]. Due to high cost RLG market is mostly limited to navigation grade.

Fiber Optic Gyros (FOGs) use loops of fiber as the light path and are also based on the Sagnac effect. A FOG is composed of optical components like polarization-preserving fiber coil, semiconductor light source, LiNbO3 integrated circuit, fiber coupler, digital logic electronics and analog to digital convertor. The phase shift is proportional to the coil radius and the fiber length, as well as the input rotation rate. In true sense FOG is a solid state sensor and has zero mechanical noise in contrast to the dither noise in RLG and rotation noise in mechanical gyros [Valeri et al. 2001]. FOG manufacturing is offshoot of standard telecom-technology components and is competitive even with small production quantities [Napolitano, 2010]. As compared to RLG in FOG the light source does not require high voltage, the broadband light source prevents backscatter so there is no lock-in at low input rates and it has the potential for lower cost and lighter weight. An attractive element of the FOG is the ability to scale performance up and down by increasing or decreasing the fiber length accordingly [Barbour, 2010]. Most of FOGs are based on closed-loop signal processing approach having superior scale factor stability and linearity with operating the Sagnac interferometer at a null since open-loop techniques are sensitive to changes in optical power, modulation depth, changes in overall optical path loss, and electronic drifts. [Allen et al., 1994]

It is quite possible that FOG performance improvements will allow applications in strategic applications where the performance requirements exceed 0.001deg/h. In addition, FOG sensors have no gas or mirrors, do not require precision machining or alignment, and do not exhibit lock-in at low rate, which are inherent in RLGs and tend to keep RLG costs high. Therefore, in similar production quantities, FOG sensors should be an economical replacement for the RLG, especially in the lower-performance tactical and commercial applications. [Barbour, 1998]. Northrop Grumman has produced the inertial grade FOG in the mid-1980s and production of FOG based INSs started in 2001. The pure inertial performance better than 1 nmph is already achieved [Pavlath, 2006]. The first FOG based navigation system within the class of 1 nautical mile per day is already produced while the efforts are on its way to develop INS having pure inertial navigation accuracy of one nautical mile in a month [Paturel et al., 2014]. FOG has numerous advantages like small size, low power consumption, large dynamic range, long life, fast start-up and high-g bearing capability. However due to optical components such as fiber optic sensing coils, light sources and couplers the FOGs are very sensitive to temperature change. Due to high thermal gradients the split optical waves propagate in both directions of the fiber, each wave experiences an alternating refractive index. Their difference in propagation time results in a phase shift which can’t be separated from the phase shift due to the Sagnac Effect. Thus the thermal-induced non-reciprocity noise included in the FOG output effect the stability of constant compensateable bias and scale factor over the temperature range. FOG possesses very complex nonlinear temperature characteristic, which cannot be described by conventional methods such as linear polynomial fitting [Feng et al., 2006]. Extensive research has been conducted to model the temperature dependent drifts successfully [He et al., 2013].

In recent years FOG development has moved through the phase of initial production and entered the stage of mature production of the medium-precision class (5 to 0.05 deg/h), and it coexists along with high accuracy RLG ($\leq$ 0.001 deg/h) used for higher accuracy applications [Andronova et al., 2002]. Initially the FOG has comparatively poor scale factor accuracy over the temperature range. So its starts its voyage from marine applications and currently it is well penetrated in this market. Over the last decade there is a substantial improvement in FOG technology. Higher performance FOGs production is achieved by improvements in the quality of the components like modulators, beam splitters, polarizers and fiber coil. The effect of temperature dependent drift is also minimized by improving the temperature stability of these components.

Currently FOGs technology is covering applications in both lower and higher performing areas. It has now global coverage with respect to manufacturing as compared to RLG. Due to this global coverage lot of research work is ongoing all over the world to make it ultimately accurate inertial navigation sensor. In comparison to the previous generation of mechanical based gyro and RLG systems, the FOG based INS are significantly smaller size, much lower weight, lower power consumption, more reliable and increased shelf life.

Micro Electro Mechanical Systems (MEMS)

The past few years has seen the rapid maturity of the MEMS and its market has benefit of consecutive double-digit growth. The worldwide MEMS market is predicted to top 22 billion

US dollars by 2018 [Qu, 2016]. MEMS sensors have all of the advantages of reliable solid-state technology. MEMS gyroscopes have recently reached true tactical performance grade and MEMS inertial sensors are expected to enable many emerging military and commercial applications. MEMS technology offers many benefits such as batch production, cost reduction, low power consumption, reduced weight and size. Due to MEMS technology it is possible to fabricate 3-axis gyros, 3-axis accelerometers, 3-axis magnetometers and a bolometer on a single chip. Researchers are working on the development of more sensitive MEMS inertial sensors which are very stable over a long period of operational time. Although the aim of MEMS sensor developers community is to preserve all the benefits of MEMS: small size, weight, and power plus cost (SWaP+C) approach, however now the first results are available in literature demonstrating MEMS gyros with sub-degree/hour and MEMS accelerometers with sub mili-g in-run bias stability. In recent years these technologies will be a foundation for new companies producing a new generation of inertial sensors, and those it turn will enable new applications. The main beneficiaries of high-performance MEMS sensors in military applications are small-diameter missiles, underwater navigators, portable North-finders and UAV/UUV.

Recently MEMS has strong footing in navigation market due to its improved vibration rejection, error characteristics, robustness in extreme environment, larger bandwidth, and low cost. MEMS technology is making huge progress in tactical grade and is going to have a significant cost advantage over other technologies. INS manufacturers able to design compact systems with exceptional performance by employing proprietary algorithms and calibration process to commercial off-the-shelf sensors. MEMS will grow a lot and make inroads in tactical grade markets. The performance of MEMS is approaching FOG tactical grade accuracy levels. The INS market previously occupied by FOG is now dominated by MEMS. With steady advancement of MEMS technology, reasonable cost, and the aid of other sensors the replacement of FOG technology with MEMS may progress in the near future [Goodall et al., 2013].

INERTIAL NAVIGATION AIDS

The performance of an INS is characterized by time dependent drift in the accuracy of the position estimates it provides. The rate of error growth is governed largely by the accuracy of the INS initialization, imperfections in the inertial sensors and the dynamics of the course followed by the host vehicle. This divergence could be controlled by using similar navigation information provided by aiding sensors. Global Navigation Satellite System (GNSS), Terrain Contour Matching (TERCOM), Digital Scene Matching and Area Correlation (DSMAC), Celestial Navigation System (CNS), Doppler Velocity Log (DVL), Magnetometers etc. are few examples of aiding sensors. The selection of appropriate aiding sensor is dependent on the particular application. Due to adoption of these aiding techniques the requirement of very high accuracy inertial sensors of INS is minimized while maintaining system performance. The fusion of information from INS and aiding sensors is characterized as integrated navigation. The increasing availability of the embedded computational power allows the implementation of advanced fusion and complex sensor error modeling algorithms. Due to these advances the navigation capability of particular application is manageable by considering the two basic but conflicting requirements namely achieving high accuracy and low cost.

Today for the airborne, sea and ground applications Global Navigation Satellite Systems (GNSS) is one of the most lucrative and popular choice being adopted. The divergence of navigation errors of INS is prevented by using aiding information provided by the GNSS receiver. Mostly, the data fusion algorithm processes GNSS position and velocity information, which requires that signals from at least four satellites are available. With the advent of multi constellation and multi frequencies GNSS receivers the navigation solutions based on GNSS are now more accurate and reliable and less vulnerable to jamming and spoofing. In addition lot of research and development is in its full swing on the anti jamming antenna technology and anti spoofing algorithms. To achieve the accuracy for landing of autonomous vehicle GNSS receivers with differential corrections are being used. The GNSS receivers for the vehicles of high agility and dynamics are also in mature domain. GNSS provides a deterministic solution for both position and velocity, it has its own shortcomings of low data rate, susceptibility to jamming (even unintentional interference), and lack of precision attitude information [Schmidt et al., 2003]. Also for subsea applications where GNSS signal is not detectable, outputs of other underwater sensors such as DVL (Doppler Velocity Log), depth sensors and log speed sensors are fused with INS output.

Although GNSS should have been the best choice for its high positioning precision but with the advent of ECM (electromagnetic countermeasure), the application of GNSS is greatly influenced, particularly for the guided weapons. GNSS clean availability could not be assured during time of war. GNSS signals regional denial, jamming and spoofing are already being tested, pose a major threat to GNSS dependent systems. This means that in a battle against a capable opponent, the accurate inertial sensors in modern INS will be relied upon more than ever before. Celestial Navigation System (CNS) is a kind of autonomous navigation system based on celestial observations. In this case the errors also not accumulate over time. Thus it is suitable for vehicle navigation that requires high precision attitude determination for long duration autonomous operations. The limitations of CNS are its low update rate, vulnerable to weather conditions at low altitude and lack of position and velocity information. Celestial sensors include star sensor, sun sensor, earth sensor, moon sensor and planets sensitive sensors, etc. Among these sensors star sensors have been widely applied due to its high pointing accuracy. In addition to that CNS is immune to jamming and spoofing, currently star trackers of sub-arc-second attitude accuracies are available which can equally work at day and night.

In mid-1950s USA developed the U-2 high altitude reconnaissance airplane with the INS and CNS integrated navigation system. In the 1970s, the INS/CNS integrated navigation technology was utilized in America's "Trident 1 type" submarine launched ballistic missiles with the mission accuracy of less than 100 m over the range of 7500 km. In the former Soviet Union, the INS/CNS integration navigation technology has also been adopted in "Scalpel" and "Topol" intercontinental ballistic missiles. Other best examples are the American B-2A bombers, the Russian SS-N-23 ballistic missile and the French M51 Submarine Launch Ballistic Missile having range of 11,000 km. [Quan et al., 2015]

The Terrain Contour Matching (TERCOM) is also one aiding technique mostly used for low altitude flying objects. The main elements of this technique are radar altimeter, Air Data System (ADS) integrated with INS and a stored contour map of the area over which the vehicle is flying. With the help of measurements of height above ground obtained from radar altimeter, estimates of mean sea level height provided by the ADS and INS, the ground profile beneath the flight path is reconstructed in mission computer of the host vehicle. The resultant terrain profile is then compared with the stored map data to achieve a fix, from which the position of the vehicle may be identified. The TERCOM aiding is usually used for cruise missile. The drawback of this technique is that it is not functional when vehicle is flying on featureless terrain like sea and desert. The accuracies of few tens of meters could be achieved when the vehicle is flying on a well featured terrain.

Digital Scene Matching Area Correlation (DSMAC) is similar to the technique used by humans i.e. navigating with the help of remembered landmarks and ground features. When a fix is required a digital CCD camera acts as an 'eye' of DSMAC system acquire the image of the ground beneath the aerial vehicle. For the feature enhancement like bridges, road and railway junctions the captured scene is processed for noise removal so that appropriate navigation information could be acquired. The correlation techniques are used to search for recognizable patterns, which appear in a pre-stored satellite image of the same terrain. After successful matching between a feature in the scene and one in the database, geometrical calculations based on the aircraft's attitude and height above ground enable its position to be calculated at the time the scene was captured. To reduce the INS errors the position information normally latitude and longitude obtained from DSMAC system are integrated with pure inertial position information. However the registrations of the input images involve the challenges like images taken at different times, image acquisition with different sensors, images from different viewpoint etc. The DSMAC and INS integration is normally used for low altitude flying vehicles like cruise missiles. The precise position calculated with DSMAC is used to attack most of the targets effectively with a conventional warhead and to minimize collateral damage [Irani et al., 1994].

CONCLUSION

Many factors are shaping tomorrow's landscape of INS development: technology capabilities, inertial sensors maturity level, reliability, application vs. cost, and others. The strapdown INS has outdated the gimbaled INS due to better reliability, availability and serviceability. For gyros and accelerometers, the two largest errors are usually a bias instability which is measured in deg/hour for gyro bias drift, or milli-g for the accelerometer bias drift; and a scale-factor stability, which is usually measured in parts per million (ppm) of the sensed inertial quantity. The accuracy of the INS enhance with decreasing inertial sensor errors. [Schmidt, 2014]. The figure 2 depicts the drift of inertial sensors versus corresponding grade and type.

MEMS has made a lot of progress in the last few years and now accepted in more and more programs, including tactical applications. MEMS will grow a lot and make inroads in tactical grade. MEMS performance improvement to tactical grade and beyond will continue to dominate inertial sensor technology investment. Also in industrial markets, MEMS-based IMUs are enabling new applications. The MEMS based INS are more ruggedized, less expensive, having short readiness time and have comparable accuracy with mechanical inertial sensors like strapdown DTGs and flexure quartz accelerometers. The strapdown INS based on DTGs and quartz accelerometers mostly developed for performance and reliability hungry applications in the defense field like high dynamic strategic guided missions will be replaceable with INS having all MEMS. DTG and some other mechanical gyros are declining, mostly limited to retrofit business only. The MEMS technology is intrinsically cost effective and offers a rapidly expanding commercial business base to leverage and sustain accelerometers and gyros production and deployment in next generation guidance systems [Hopkins, 2001]. The quality of GNSS receivers has been improved through a long and incremental development cycle. Any discrepancy in navigation accuracy for more demanding applications will be covered by optimal fusion of pure inertial solution with high dynamic, multi frequencies and multi constellation GNSS receiver output.

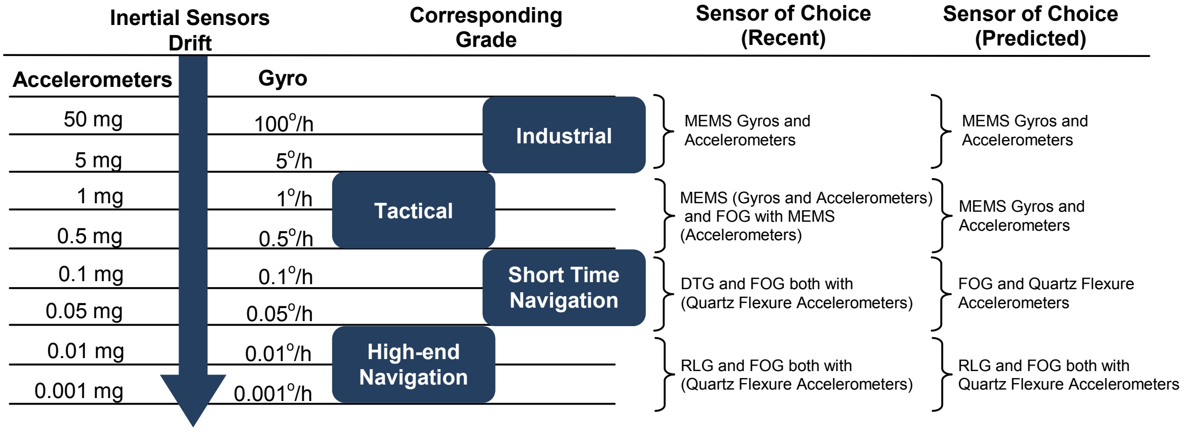

Figure 2: Inertial sensors drift vs. corresponding grade and type

RLG market is still very robust for high-end applications but the growth for new applications is now limited. But this is still the preferred technology for high end navigation. For long endurance, repetitive and highly expensive applications such as aircraft, spacecraft, naval vessels, unmanned combat aerial vehicles RLG will be remain on the top due to its ultimate maturity level. The FOG based INS is already proved its navigation grade accuracy however the FOG will not superseded the RLG largely due to the large existing RLG-based industrial infrastructure [Barbour, 2001]. RLG will remain a specialized instrument whose utility varies with the application and several factors limit its selection over modern mechanical system. The exacting cavity geometries and precision mirrors or prisms required for RLG manufacturing and the necessity of assembly under stringent clean room conditions drive its cost beyond economic application to low performance system. With the advent of better performance MEMS the medium grade FOGs will be soon replaced with MEMS. MEMS are also utilized in very wide range of non-inertial grade applications which were previously dominated by FOGs. However FOGs has potential to supersede RLG in accuracy and comparatively ease in manufacturing. Due to these facts FOG is not seen anymore as limited to medium grade, but on the contrary as the ultimate performance gyro that can surpass by at least one order of magnitude RLG technology subsequently [Lefevre, 2011]. FOG market is now has more focus on high performance applications ($< 0.1°/h$) with many competitors onboard. As compared to 20th century converging trends will prevail in INS design and development subsequently. The concentrating area in near future will be the accuracy enhancement of MEMS and FOG.

References

Allen, D., Bennett, S. M., Brunner J., Dyott, R. B. (1994): “A Low Cost Fiber Optic Gyro for Land Navigation, in Proc. SPIE Vol. 2292, pp. 203-217, 1994.

Andronova, I. A., Malykin, G. B. (2002): “Physical problems of fiber gyroscopy based on the Sagnac effect”, UFN, 172:8 (2002), 849–873; Phys. Usp., 45:8 (2002), 793–817

Barbour, N. M. (2001): “Inertial Components - Past, Present and Future”, Invited Paper, AIAA Guidance, Navigation and Control Conference, Montreal, Canada, August 2001.

Barbour, N. M. (2010): “Inertial Navigation Sensors”, NATO RTO Lecture. Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, 2010.

Barbour, N. M., Elwell, J. M., and Setterlund, R. H. (1992): “Inertial Instruments: Where to Now?”, in Proceedings of AIAA GNC Conference, Hilton Head, SC, 10–12 August, 1992, pp. 566–574.

Barbour, N. M., Schmidt, G. (2001): “Inertial Sensor Technology Trends”, IEEE Sensors Journal, Volume: 1, Issue: 4: 332-339, December 2001.

Chatfield, A. B. (1997): “Fundamentals of High Accuracy Inertial Navigation”, USA: American Institute of Aeronautics and Astronautics, Inc., 1997.

Feng, L. S., Nan, S. Z., Jin, J. (2006): “Research on Modeling and Compensation Technology for Temperature Errors of FOG”, Journal of Astronautics, vol.27, no.5, pp.939-941,1049., 2006.

Goodall, C., Carmichael, S., Scannell, B. (2013): “The Battle Between MEMS and FOGs for Precision Guidance”, Analog Devices, MS 2432, pp. 1-6. Accessed at 20 January 2015 via http://www.analog.com/en/index.html

Grigorie, T. L., Jula, N., Cepiscae., C., Răcuciu., C., Răducanu., D. (2008): "Evaluation Method of the Sensors Errors in an Inertial Navigation System”, WSEAS Transactions on Circuits and Systems Issue 12, Volume 7, December 2008.

He, Z., Liu G., Zhao X., Yao Z. (2013): "A Novel Comprehensive Compensation Approach for Fiber Optic Gyroscope Temperature Drift by Gaussian Process Regression", JCIT: Journal of Convergence Information Technology, Vol. 8, No. 1, pp. 134 ~ 142, 2013.

Hopkins, R., Borenstein, J., Antkowiak, B., Ward, P., Elliott, R., Weinberg, M., DePiero, M., and Miola, J., (2001): “The Silicon Oscillating Accelerometer: A MEMS Inertial

Instrument for Strategic Missile Guidance”, Draper Technology Digest, Draper Report No. R-2907, July 2001.
Irani, G. B., Christ J. P. (1994): “Image Processing for Tomahawk Scene Matching”, Johns Hopkins APL Technical Digest, Volume J 5, Number 3, 1994.
Juang, J.-N., Radharamanan, R. (2009): “Evaluation of Ring Laser and Fiber Optic Gyroscope Technology”, 9pp web paper. Accessed March 03, 2015 at: www.asee.org/documents/sections/middle-atlantic/fall-2009/01-Evaluation-Of-Ring-Laser-And-Fiber-Optic-Gyroscope-Technology.pdf
King, A. D. (1998): “Inertial Navigation-Forty Years of Evolution”, GEC Review, vol. 13, no.3, pp. 140-149, 1998.
Lawrence, A. (1993): “Modern Inertial Technology: Navigation and Control”, Springer-Verlag 1993.
Lefevre, H. C. (2011): “Ultimate-Performance Fiber Optic Gyroscope: A Reality”, Invited paper at OECC 2011, Taiwan, July 2011.
López-Higuera, J. M., Co-author and Editor (2002): “Handbook of Optical Fibre Sensing Technology”, 800 pages, Wiley & Sons, New York, 2002.
MacKenzie, D. (1993): “Inventing Accuracy”, Chapter 2, The MIT Press, 1993, Cambridge MA,London.
Minor, J. W. (1965): “Low-Cost Strapdown-Down Inertial Systems”, AIAA/ION Guidance and Control Conference, August 16-18, 1965.
Napolitano, F.,(2012): Fiber-Optic Gyroscope Key Technological Advanatges, IXSEA, 10/2012
Paturel Y., Honthaas J., Lefevre H., Napolitano F. (2014): “One Nautical Mile per Month FOG Based Strapdown Inertial Navigation System: A Dream Already within Reach?”, Gyroscopy and Navigation, 2014, vol. 5, no. 1, pp. 1–8.
Pavlath, G. A. (2006): “Fiber-Optic Gyros: The Vision Realized,” 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.
Quan, W., Li, J., Gong, X., Fang, J. (2015): “INS/CNS/GNSS Integrated Navigation Technology”, Springer, New York, 2015.
Qu, H. (2016): “CMOS MEMS Fabrication Technologies and Devices”, Micromachines 2016, 7, 14; doi:10.3390/mi7010014
Savage, P. G. (1984): "Advances In Strapdown Sensors", Advances In Strapdown Inertial Systems, AGARD Lecture Series No. 133, 14-15 May 1984.
Savage, P. G. (2013): “Blazing Gyros - The Evolution of Strapdown Inertial Navigation Technology for Aircraft”, Journal Of Guidance, Control, & Dynamics Volume 36, Number 3, May - June, 2013, Pages 637-655
Schmidt, G. T. (2014): “Navigation Sensors and Systems in GNSS Degraded and Denied Environments”, IEEE Aerospace and Electronic Systems Society, 2014.
Schmidt, G. T., Phillips, R. E. (2003): “INS/GPS Technology Trends” - The Charles Stark Draper Laboratory, 2003.
Skaloud, J., Bruton, A. M., Schwarz, K. P. (1999): “Detection and Filtering of Short Term Noise in Inertial Sensors”, Journal of The Institute of Navigation, Vol. 46, No. 2, Summer 1999, pp 97-107.
Titterton, D. H., Weston J. L. (2004): “Strapdown Inertial Navigation Technology”-2nd edition., The Institution of Electrical Engineers, Stevenage, U.K., 2004.
Tooley, M., Wyatt, D. (2007): “Aircraft Communication and Navigation Systems”, Butterworth-Heinemann Oxford, Woburn Massachusetts 2007.
Udd, E. (1985): Comparison of Ring Laser and Fiber Optic Gyro Technology, McDonnell Douglas Astronautics Company, 1985.
Valeri, R., Arnn, E., Humphery, I., Reynolds, C. (2001): “Development of a Small Precision FOG IMU, Proceedings of the 57th Annual Meeting of The Institute of Navigation, June 11 - 13, 2001, pp 609 - 613
Volk C. H., Gillespie S. C., Mark J. G. Tazartes D. A. (1999): “Multioscillator Ring Laser Gyroscopes and their Applications, AGARDograph RTO-AG-339, RTO/NATO, 1999.