WHITE PAPER

CELESTIAL AUGMENTATION OF INERTIAL NAVIGATION SYSTEMS: A ROBUST NAVIGATION ALTERNATIVE

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Summary: This White Paper discusses the addition of automated celestial observation capability to inertial navigation systems. Although such astro-inertial systems are now in limited operational use, with good success, the automated star trackers they contain are based on outdated, gimbaled technology. New strapdown star tracker systems with silicon array detectors, currently used in space applications, would provide a cheaper, more reliable navigation system with a significantly reduced footprint. With reduced costs and enhanced reliability, such systems may be practical on many platforms not previously considered, including surface ships and a variety of aircraft.

Background

For many years, celestial navigation was the primary means for navigating surface ships and aircraft. The dawn of modern radionavigation systems gradually relegated celestial navigation to a minor, backup role — a role it retains to this day. Yet, in certain respects, the general concept of celestial navigation is more important today than it was ten years ago. The great success and widespread use of the Global Positioning System (GPS) have resulted in termination of, or uncertain futures for, older alternative electronic navigation systems. Furthermore, vulnerabilities of the GPS system are widely acknowledged. Prudent navigation practice (and Navy policy[1]) requires both a primary and a secondary means of navigation, with the secondary independent of the primary. Celestial navigation remains one of the few independent alternatives to GPS.

Celestial navigation is often overlooked as an alternative to GPS because of the drawbacks of its traditional practice. However, celestial navigation can encompass any method that utilizes observations of astronomical bodies — bodies with known positions in a standard celestial reference frame — to determine the position of a platform in a standard terrestrial reference frame. The various methods for performing celestial navigation can be grouped into three general categories. Traditional, manual methods require use of a handheld sextant, coupled with manual sight planning and reduction procedures (i.e., printed almanacs and forms). Traditional, computer-based methods also require use of the sextant, but sight planning and reduction are performed using software, such as the U.S. Naval Observatory's STELLA program[2,3]. Finally, fully automated methods use some type of automatic electronic sextant or star tracker to make observations, which are then fed to software that performs the sight reduction. Star tracker data can also be sent directly to inertial navigation systems and incorporated into the INS solution.

It is usually stated that a fix obtained by traditional means (i.e. through use of a sextant) is accurate to about 1-2 nautical miles. This is because altitude observations of stars made with handheld marine sextants ("sights") are no more accurate than about 1-2 arcminutes. Most methods of sight reduction — both manual and computer-based — take advantage of the low accuracy of the observations by incorporating approximations and non-rigorous assumptions as a means to simplify the computations. An exception to this "rule" is STELLA. STELLA is based on an entirely new approach to sight reduction that retains one arcsecond angular precision throughout[4]. Thus, given perfect observations, STELLA is capable of producing fixes accurate to about 30 meters on the Earth's surface. In short, better fixes can be obtained with better observations.

Replacing the handheld sextant with an automated observing device — an electronic star tracker, for example — offers the possibility for greatly improving the quality of the observations. This is not a new idea. Over the years, star trackers have been used with great success on many spacecraft, missiles, and high-flying aircraft. The problem is that the known star trackers in operational use are based on old technologies. Without a doubt, these old technologies limit the effectiveness of the systems and are responsible for their high cost. The goal of this paper will be to demonstrate that star trackers based on newer, off-the-shelf technologies show promise for a wider range of applications at lower cost, and may provide an effective navigation alternative in situations where GPS is denied or unavailable.

Principles of Celestial Navigation

The sky provides the most fundamental and accurate inertial system available, in which each star is a well-defined benchmark. The cataloged positions and motions of the stars define the celestial reference frame.

From a moving vehicle, the measurement of the directions of two or more stars with respect to a vehicle-fixed coordinate system provides an instantaneous determination of the vehicle's attitude with respect to the celestial reference frame. If there is also a determination of the direction of the local vertical (gravity vector) with respect to the same coordinate system, the vehicle's attitude with respect to the local horizon system (including absolute azimuth) can be obtained. The determination of the local vertical is not trivial for a moving vehicle (see below) and in general will require corrections for coriolis forces and geophysical deflection.

The local vertical provides the direction orthogonal to the geoid and, appropriately corrected, toward the center of the Earth. To obtain latitude and longitude, we need a time reference. The correct time essentially provides, through well-known formulas (and daily astronomical measurements), the orientation of the Earth's latitude/longitude grid in the celestial reference frame. Since we have already determined the direction from the vehicle to the center of the Earth in the celestial frame, we now know the latitude and longitude of the point beneath the vehicle. For celestial navigation, the time reference is actually not needed to high precision, because the Earth's angular rate of rotation is relatively slow: a hundredth of a second uncertainty in time translates to only 5 meters on the surface of the Earth.

Celestial observations provide virtually no information on a vehicle's height. Given a large number of celestial observations, we could in principle determine barometric height above sea level to very low precision from the effects of atmospheric refraction on the observations, but there are, of course, better ways of obtaining this information.

An essential element in celestial navigation is the determination of the exact direction of the local gravity vector. In traditional, marine-sextant celestial navigation, the observed horizon is assumed to be a circle orthogonal to the local vertical. For a fixed location there are more direct alternatives: modern tiltmeters or accelerometers are sensitive to the direction of gravity to arcsecond (or better) precision. If we could construct a hypothetical vehicle that moves completely smoothly across the surface of the Earth, the (uncorrected) gravity vector could be measured directly with these instruments.

Of course, our hypothetical smoothly moving vehicle does not exist. In real-world conditions, a moving vehicle is subject to a variety of accelerations from both internal and external sources. These accelerations cannot in principle be separated from that due to the Earth's gravity, so that any instantaneous measurement of the local gravity vector from inboard devices, such as tiltmeters or accelerometers, is highly contaminated. That is why, for the user of a marine sextant, the sea horizon works better than a direct measurement of the local vertical: the horizon is not subject to the accelerations of the ship.

The problem of determining the true local vertical from a moving vehicle leads us to inertial navigation systems. These units can be thought of as an automated form of very precise dead reckoning. Each system combines a set of gyros, a set of accelerometers, and a computer. The unit must be initialized when the vehicle is at a known location. Using a continuous, rapid series of gyro and accelerometer measurements, the INS can compute the vehicle's instantaneous position and velocity at any later time. As part of its navigation calculation, an inertial navigation system must *infer* the direction of the local vertical at each computation step. Essentially, the INS serves as a plumb bob. Due to gyro drift and other errors, its vertical inference may not be as accurate as we would like (errors may accumulate at a rate of an arcsecond to an arcminute per hour), but it is likely to be better than any alternative. Thus, in open loop mode, an INS can provide a usable, although not ideal, reference direction for astronomical measurements.

However, the astronomical measurements can be used to help correct certain INS errors ¾ the star observations provide a link to the celestial reference system that can be used to constrain the INS gyro drift. (The Kalman filter in the INS computer directly uses the star tracker data.) Both orientation and position determinations are significantly improved. And, the INS will continue to provide navigation data (although of lesser accuracy) even if stars cannot be observed because of cloud cover. This kind of tightly coupled celestial-INS system has been used on a small number of platforms with great success, as described in the next section. The closed-loop combination is not perfect, since it is insensitive to at least one INS error mode (the Schuler oscillation), but it is a proven technology with a substantial engineering foundation.

Automated Celestial Technology

Since the early days of the space age, automated celestial observing systems have been used on missiles, satellites, and planetary exploration spacecraft as an aid to navigation. Strategic missile systems such as Polaris, Poseidon, Trident, and MX have used compact star trackers in the powered phase of flight to determine the absolute orientation of the vehicle for the inertial guidance system. The more modern of these units achieve sub-arcsecond (<1 μrad) angular precision. The Space Shuttle has several star trackers in its nose. Automated star trackers have become off-the-shelf items for attitude determination for a large number of Earth-orbiting satellites; Lockheed Martin and Ball Aerospace are two of the contractors involved. NASA deep space missions use star or Sun sensors en route for attitude determination, and science camera images of the target body against the star background as part of the terminal navigation program. Star trackers have evolved from single-star to multi-star capability. Thus, space systems provide an extensive technological base in the automated measurement of stellar angles.

Automated celestial observing systems have also been combined with INS on a small number of aircraft, including the SR-71, RC-135, and B-2. The RC-135 system is a Litton LN-20 gimbaled star tracker dating back about two decades. The LN-20 uses a short Cassegrain telescope with a small field of view (6 arcminutes) which executes a specific observing program involving 57 bright stars. The unit obtains a star fix about every 110 seconds. The star tracker angle encoders have a 1.2 arcsecond (6 μrad) resolution. The B-2 system is also old technology, based on Northrup legacy systems from the Snark missile, U-2, and SR-71. Like the RC-135 system, it is a gimbaled Cassegrain system with a small field of view (0.7 arcminute) that executes a specific observing program on a small catalog of stars. It obtains several star fixes per minute, reporting both altitude and azimuth (accuracy classified) back to the INS (which also takes in radar and GPS data). The B-2 system sits in the left wing and observes through a 7-inch window on the top surface. These systems all have many moving parts and tend to be large, heavy, and expensive. Nevertheless, users report that they are quite reliable and, according to at least one B-2 crewmember, make GPS virtually superfluous.

New technology developed for space systems within the last decade has not yet been applied to operational surface and air navigation. The differences between the old and new technologies can be summarized as follows:

Old Technology	New Technology
Gimbaled	Strapdown (few or no moving parts)
Small field of view	Wide field of view
Single star observations	Multiple simultaneous star observations
Photomultiplier tube or similar detectors	CCD (silicon array) detectors
Programmed observation sequence	Automatic star pattern recognition

Compared to the old technology, the new star trackers are simpler, smaller, draw less power, and more reliable. With higher quantum efficiency detectors, many more stars (thousands rather than tens) can be observed, providing a substantially higher data rate. Potentially, these star trackers may also be significantly cheaper, although currently the small number of units produced and the requirements of space hardware qualification have kept costs artificially high.

An example of a state-of-the-art star tracker is Lockheed's AST-201 system.[5] Using what amounts to a standard camera lens with a charge coupled device (CCD) array in its focal plane, this unit can detect stars down to visual magnitude 7 (fainter than the human eye can see). The unit is designed to be mounted on a rotating satellite and has no moving parts. The star tracker has an 8.8° field and its electronics subsystem contains its own star catalog and star pattern recognition software. The unit operates as a "black box" that receives stellar photons as input and provides a continuous stream of digitized orientation angles as output. The orientation accuracy is several arcseconds about axes parallel to the focal plane. The unit is approximately 15 cm × 15 cm × 30 cm, including the lens shade, weighs about 4 kg, and is, of course, space qualified. The calculated MTBF is over 700,000 hours.

Would such an automated star tracker be practical for surface or air navigation? The latest technology has yet to be exploited for such uses. The most relevant R&D experience dates from the late 1980s, when Northrop designed a system called the Optical Wide-angle Lens Startracker (OWLS) that it packaged with an aircraft inertial navigation system.[6] Using a holographic lens that could simultaneously image three 3° fields of view, each with its own CCD detector array, the OWLS could deliver arcsecond-level orientation angles to the INS. The OWLS operated in the far red (R band, λ 0.6-0.8 μm) so that it could detect stars down to R magnitude 5 at sea level in daylight. Clearly Northrop thought its system had broad application: "…astro-inertial navigation offers a practical solution for high-precision, autonomous navigation for surface ships, commercial aircraft, cruise missiles, strategic aircraft, remote piloted vehicles, and hypersonic vehicles." Unfortunately, ten years ago, DoD's navigation strategy was highly focused on full deployment of GPS and OWLS was never deployed operationally.

Star tracker technology for space systems has continued to evolve. We believe that the latest technology in star trackers, exemplified by the Lockheed AST-201, provides an opportunity for the development of small, lightweight, inexpensive, reliable celestial systems that can be coupled to existing INS systems for aircraft and ships. A not unreasonable expectation for this technology is the acquisition of large numbers of star positions, day or night, at an accuracy of better than one arcsecond (less than 30 meters or 100 feet).

The Effects of Cloud Cover

Except in space applications, a fundamental obstacle to celestial observations is cloud cover. On the surface of the Earth, the average probability of a clear line of sight to a given star is approximately 50% (i.e., on average the Earth is about half cloud covered). With increasing height, the probability increases: to about 60% at 5,000 feet, 70% at 20,000 feet, and 95% at 40,000 feet.[6] It is possible to improve the situation by observing in certain bands in the far red or near infrared part of the spectrum where the atmosphere is somewhat more transparent (also, the sky is darker and there are more stars per magnitude interval), but the problem of clouds never completely disappears for celestial observations made at or near sea level. The wide variety of cloud types and distribution makes quantitative assessment difficult. For example, scattered cumulus, even if covering 50% of the sky, present little problem because each one blocks a given line of sight for such a short period of time. Similarly, the brighter stars and planets can be seen through cirrus. As mentioned above, many years of user experience with existing astro-inertial systems on aircraft have been quite positive. One of the strengths of such systems is that the INS serves as a bad-weather "flywheel" that essentially carries the stellar fix forward until new observations can be obtained.

Even for the surface fleet, where a run of bad weather can separate star sights by a day or more, astro-inertial systems can be valuable. Although a run of cloudiness will in general last longer than for aircraft, the time en route is correspondingly longer. Of course, until relatively recently in naval history, celestial navigation was the only method available for ships in the open ocean, and was used with considerable success.

Proposed Technical Concept and Approach

Inertial navigation systems, which are now common on Navy ships and aircraft, clearly have a major role to play in mitigating the effects of GPS denial. However, since these systems are really only a very accurate form of dead reckoning, they require periodic alignment to some sort of external reference system. That external system could be GPS, of course, and embedded GPS inertial (EGI) systems are now being manufactured by two vendors, Honeywell and Litton. A tri-service EGI program office at Wright-Patterson AFB is managing the deployment of EGI systems on a variety of platforms.

Of course, EGI does not really provide a secondary means of navigation that is "independent of the primary" so there is continuing interest in practical GPS alternatives. We propose that celestial navigation, in a new, highly automated form, can provide a truly independent input to EGI systems that would greatly enhance their robustness under hostile operating conditions. This idea builds on the success of existing, older-technology celestial-inertial DoD systems.

The Navy has pursued an even broader concept of blended navigation solutions in its Navigation Sensor System Interface (NAVSSI),[7] a real-time computer that provides the ship-board navigator with "one stop shopping" for position, velocity, and heading information from GPS, INS, fathometer, gyrocompass, radar, and other sources. NAVSSI is presently installed aboard 69 surface combatants and scheduled for 100 more. Each of these ships has some form of inertial navigation system requiring GPS data. SPAWARSYSCEN San Diego is the project manager for NAVSSI technology development, and has recently added the STELLA celestial navigation algorithms, developed at USNO, to the NAVSSI Block 3 software. Currently there is no program to add any type of star sensor that could provide the kind of data the system needs to fully exploit those algorithms, or to constrain the INS solution. Celestial-INS systems have not been used on ships, even though modern sensors in the far red or near infrared would allow significant numbers of star observations to be collected both night and day at sea level. SPAWARSYSCEN SD and USNO propose to pursue recent developments in star tracker hardware that could add to the reliability of NAVSSI on a day-to-day basis and allow for valid navigation solutions in the event of GPS denial. This represents a new application of state-of-the-art technology developed for space applications, with some risks to be addressed.

The expertise in GPS, inertial navigation, and electro-optics at SPAWARSYSCEN SD together with the expertise in celestial navigation, astronomical instrumentation, and precise time at USNO represents a unique combination of capabilities for pursuing this concept. Since SPAWARSYSCENT SD is already the NAVSSI technology manager, the development of new systems to alleviate the effects of possible GPS non-availability on fleet navigation is a natural extension of its current program responsibilities. Additional collaborations with groups at other commands may be useful and will be explored.

Conclusion

The combination of automated star trackers and inertial navigation systems is a synergistic match in the true sense of the word. Considered as stand-alone systems, inertial and celestial navigation have complementary characteristics. After initialization, INS is self-contained and has no coupling to an external reference system; celestial provides a direct link to the most fundamental inertial reference system available. INS units require initial alignment using positioning data from another source; celestial is completely autonomous. INS accuracy degrades with time from initial alignment; celestial fix accuracy is not time dependent. INS units are oblivious to the weather; celestial is sensitive to cloud conditions. Yet, despite their differences, both INS and celestial are passive, jam-proof, and in operational use are not dependent on shore or space components.

As our defense forces rely increasingly on GPS, it is important that this dependence does not become a single-point-failure risk for military operations. Independent alternatives to GPS are needed and are required by official policy. We propose that state-of-the-art star trackers designed for space applications can be profitably applied to surface and air navigation when used in combination with inertial navigation systems. Existing astro-inertial systems, built with older technology, have demonstrated accuracy and reliability on a limited number of platforms. New technology offers the possibility of significantly increased accuracy, reliability, and data rate with a smaller footprint and lower cost. Thus, these systems may become practical on many platforms not previously considered, including surface ships.

The 2000 Joint Chiefs of Staff master navigation plan[8] envisions a continuing DoD need for celestial navigation, both as traditionally practiced and in the form of automated, high-accuracy star trackers that augment inertial systems. With imaginative application of the latest technology, celestial navigation has as much of a role to play in the future as it has in the past in helping to provide safe passage for our military forces worldwide.

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