21ST CENTURY CELESTIAL NAVIGATION SYSTEMS

Yuri Dachev, Ph.D., Associate professor

Avgust Panov, LLM

Nikola Vaptsarov Naval Academy, Varna 9026, Bulgaria

e-mail: avgust.panov@gmail.com

Abstract

Celestial navigation is the art and science of navigating by the stars, sun, moon, and planets, and it is one of the oldest of human arts. With the rise of electronic means of finding location, especially with the increasingly popular Global Positioning System (GPS), knowledge of celestial navigation has experienced a precipitous decline. Celestial navigation involves reducing celestial measurements taken with a sextant to lines of position on a chart using calculators or computer programs… But there is another approach - Celestial navigation enters powerfully 21st century as a highly sophisticated technology. Unfortunately, since much of the new hardware has been developed for space and aircraft systems, many of the technological advances have been invisible to those outside the aero-space engineering community. Authors of this paper believes that much of the work that has gone into star trackers for space applications can be brought down to Earth to serve in new generation sea navigation systems - in particular, combining automated star trackers with inertial navigation systems (INS) seems to be a synergistic match - they have complementary characteristics. Although such astro-inertial systems are now in limited operational use with good success, the automated star trackers they contain are based on outdated technology. New star tracker systems, currently used in space and aircraft applications, would provide a cheaper, more reliable navigation system. With reduced costs and enhanced reliability, such systems may be practical on many platforms not previously considered, including commercial and naval ships. Currently modern bridge navigation systems rely almost entirely on GPS, it is important that this dependence does not become a single-point-failure risk for safe navigation. Independent alternatives to GPS are needed and are required. Application of available technology can ensure that 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 ships worldwide.

Keywords: Celestial navigation, Inertial navigation systems, Star-trackers

Introduction

Celestial navigation was the primary means for navigating ships for centuries. The rapid development of technology has brought about significant changes in marine navigation and the equipment used to ensure the safety of navigation relegating celestial navigation to a backup role at best. The great success and widespread use of GPS have resulted in the termination of some of the other older means of electronic navigation systems. Celestial navigation is often overlooked as an alternative to GPS because of the drawbacks of its traditional practice of sextant, almanacs, and manual sight plan and reduction procedures involving laborious mathematical equations (Pappalardi, F. "et al", 2001, pp. 1452–1459)

Commercial GPS units are quickly inundating both civilian and military vessels plying the world's waterways and can be found in an increasingly wide variety of places. Commercial GPS units can now be found within satellite systems, navigations systems, data links, unmanned vehicles, ordnance, and optical sighting systems. As a result, the dependency on commercial GPS technology is also proliferating, increasing the possibility of Electromagnetic Interference (EMI) or damage to these units. In May 2000, United States Naval Sea Systems Command (NAVSEA) launched an investigation into GPS susceptibility to EMI damages after receiving United States Navy (USN) message traffic indicating a United States Naval Ship (USNS) had experienced commercial GPS damage during a routine boarding operation training exercise (Williams, S. 2006, pp. 26-35).

The electronic navigation equipment now used on all ships includes items such as receivers of satellite navigating systems GPS, GLONASS, RADARs, systems of Automatic Radar Plotting (ARPA), and Automatic Identification System equipment (AIS). Electronic Chart Display and Information System (ECDIS) is one direction for use on vessels. ECDIS is a computer system which satisfies the special requirements that allows navigators to use an electronic nautical chart instead of plotting on paper charts. Such status ECDIS is determined by rule V/19 of the convention of International Maritime Organization (IMO) on Safety of Life at Sea (SOLAS-74/88). According to this rule, all ships should have: nautical charts and nautical publications to plan and display the ship's route for intended voyage and to plan and monitor positions throughout the voyage an

Electronic Chart Display and Information System (ECDIS) can be accepted as meeting the chart carriage requirements of this subparagraph; back-up arrangements to meet the functional requirements of this subparagraph is partly or fully fulfilled by electronic means. The corresponding complete set of sea nautical charts it can be used as duplicating means for ECDIS (IMO,SOLAS, 2012). Many commercial shipping companies have had great success with real-time navigation situational awareness equipment.

Vulnerability and disruptions in GPS Service

Table 1-0. GPS Dependencies in Maritime Transportation

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Vessel	Infrastructure	System
Automatic Identification Systems (AIS)	X		X	X	X	X	X	X			X		X		X
Draft Information System (DIS)	X	X		X				X			X		X		X
Electronic Chart Display and Information System (ECDIS)	X	X	X	X	X	X	X	X			X		X		X
Emergency Position Indicating Radio Beacon (EPIRB)	X			X	X	X	X	X	X	X	X		X		
Global Maritime Distress and Safety System (GMDSS)	X		X	X	X	X	X	X			X		X		X
GPS Location Services for Cargo Terminal Equipment	X	X			X	X		X			X		X	X	X
Hydrographic survey systems	X			X	X	X	X	X			X		X	X	X
NOAA Vessel Monitoring System	X		X	X				X			X		X		X
Positioning Aids to Navigation (ATONs)	X			X	X	X	X	X			X			X	X
Tidal measurements	X			X	X	X	X	X			X			X	X
USACE River Information Services (RIS)	X	X		X	X	X	X	X			X		X	X	X
USACE Vessel Monitoring System	X		X	X	X	X		X			X		X	X	X
USCG Vessel Traffic Services	X	X		X				X			X		X	X	X
Voyage Data Recorders (VDR)	X		X	X				X			x		X		
Virtual and Synthetic Aids to Navigation	X			X	X	X	X	X			X			X	X

The maritime shipping community was one of the first to fully embrace GPS for positioning and navigation. Today, GPS receivers represent one of the core components of any vessel's suite of navigation and communications equipment (Eric Wallischeck, 2016, pp 17-21).

GPS disruptions can be described by a number of bivariate characteristics, which are described in Table 1-1:

Table 1-1: Characteristics of GPS Disruptions

Characteristic	Example
Unintentional vs. Intentional	Is the disruption caused by a piece of space debris that disabled a GPS satellite or is it due to an intentional act by a disgruntled employee or terrorist?
Predictable vs. Unpredictable	Was the disruption due to an anticipated increase in solar flare activity or the sudden activation of a jamming device?
Environmental vs. Manmade	Is the disruption due to increased solar weather activity or due to an improperly configured radio transmitter operating in an adjacent frequency band?
Crude vs. Sophisticated	Is the disruption caused by a $50 GPS jammer purchased on-line, or by a hacker precisely manipulating a GPS signal to deceive shipping or highway traffic?
Local vs. Widespread	Is the disruption a targeted spoofing attack against a single cargo terminal, or does it cover a large geographic area (e.g., due to a significant solar weather phenomenon)?

Table 1-2 maps the five general categories of GPS disruptions against the characteristics described above.

Table 1-2: GPS Disruptions vs. Characteristics

<table>
<tr><th></th><th>Spectrum Encroachment</th><th>Solar Weather</th><th>GPS Infrastructure</th><th>Jamming</th><th>Spoofing</th></tr>
<tr><td rowspan="2">Unintentional or Intentional</td><td colspan="3">UNINTENTIONAL</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">INTENTIONAL</td></tr>
<tr><td rowspan="2">Predictable or Unpredictable</td><td colspan="3">PREDICTABLE</td><td></td><td></td></tr>
<tr><td colspan="5">UNPREDICTABLE</td></tr>
<tr><td rowspan="2">Environmental or Manmade</td><td></td><td colspan="2">ENVIRONMENTAL</td><td></td><td></td></tr>
<tr><td>MANMADE</td><td></td><td colspan="3">MANMADE</td></tr>
<tr><td rowspan="2">Crude or Sophisticated</td><td colspan="4">CRUDE</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">SOPHISTICATED</td></tr>
<tr><td rowspan="2">Local or Widespread</td><td>LOCAL</td><td></td><td colspan="3">LOCAL</td></tr>
<tr><td colspan="4">WIDESPREAD</td><td></td></tr>
</table>

GPS has operational characteristics and vulnerabilities (see above) that may render it unusable or unreliable under certain conditions. Much work is being devoted to developing strategies for GPS outages. IMO required "all ships irrespective of size to have a receiver for a global navigation satellite system or a terrestrial radionavigation system, or other means, suitable for use at all times throughout the intended voyage to establish and update the ship's position by automatic means" (IMO, SOLAS, 2012).

Prudent navigation practice 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. The question what to do if GPS is not available is still unanswered firmly. Some kind of alternative to GPS is needed to provide redundancy for navigation systems. Inertial navigation systems are being viewed as the answer. However, there is a complication. These systems are really only a very accurate form of dead reckoning, and they require periodic alignment to some sort of external reference system. That external system could be GPS, of course, but such a mode of operation does not provide a secondary means of navigation that is "independent of the primary."

Celestial navigation as GPS alternative

Celestial navigation is often overlooked as an alternative to GPS (Chris Gregerson et al, 2000) 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;
- ***Fully auto- mated 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 accurate to about 1-2 arcminutes (0,017-0,033 degrees). 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.

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. When GPS and INS is still not ripe, Celestial Navigation System (CNS) was spread to aeronautics by US (B-52, B-1B, B-2A, C-141A, SR-71, F22 et al.) and Soviet Union (TU-16, TU-95, TU-160 et al.) (AnGuo, Wang. 2007, pp.2347–2353) . Then the star tracker (i.e. track one star or planet or angle between it) (Noack, Thomas Luther, 1963). has been used to determine the attitude of the spacecraft in help orient the Apollo spacecraft enroute to and from the Moon. Now the advanced star sensor (i.e. sense many star simultaneous) is developed for the application of optical CCD technique (AST-201 Star Tracker System Specifications, 1998).

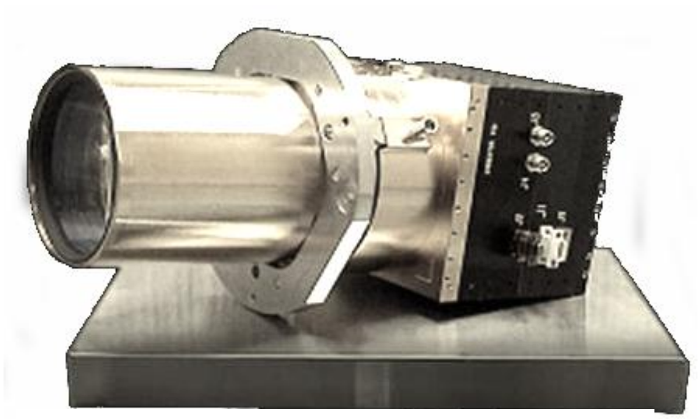
Over the years, star trackers have been used with great success on many spacecraft, missiles, and high-flying aircraft. The problem is that the known star trackers in operational use are based on old technologies and are very expensive. Without a doubt, these old technologies limit the effectiveness of the systems and are responsible for their high cost, but star trackers based on newer, off-the-shelf technologies show promise for a wider range of applications at significantly lower cost, and may provide an effective navigation alternative in situations where GPS is denied or unavailable.

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-arc second (< 0.000277778 degrees) angular precision. The Space Shuttle has several star trackers mounted in its nose. Automated star trackers have become off-the-shelf items for attitude determination for a large number of Earth-orbiting satellites; Compared to the old technology, the new star trackers are simpler, smaller, draw less power, and are 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 are also significantly cheaper, although currently the small number of units produced and the requirements of space hardware qualification have kept costs artificially high.

Would such an automated star tracker systems be practical for marine navigation?

Particular attention should be paid to the following two systems: Lockheed's ***AST-201(Autonomous Star Tracker) system*** developed in 1998 (AST-201 Star Tracker System Specifications, 1998) and Rockwell Collins ***CIPP (Celestial-Inertial Precision Pointing) System*** developed in 2015 (Celestial-Inertial Precision Pointing System Specifications, 2015).



AST-201(Autonomous Star Tracker) system

The AST-201 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 arc seconds about axes parallel to the focal plane. The unit is approximately 15 x 15 x 30 cm, including the lens shade, weighs about 4 kg, and is, of course, space qualified. The calculated MTBF is over 700,000 hours.

CIPP (Celestial-Inertial Precision Pointing) System

CIPP System is state-of-the-art high-performance sensor fusion unit for navigation. The system consists of two cameras, which convey the position of the sun or the stars to calculate orientation, working in conjunction with inertial sensors called micro-electromechanical systems (MEMS). The MEMS provide acceleration and angular-rate signals, like those used to enable a smartphone to know which way it's being tilted. Running on a dedicated processor, system software blends the information gathered by the cameras and the MEMS to give a best estimate of roll, pitch and heading angles continuously, sending out information 40 or 50 times per second. Using celestial object determination and inertial sensing, the device continuously calculates all three angles very accurately. Unit is 6.6 x 4.8 x 1.5 cm, weighs less than 100 g and is capable of pointing accuracies within a tenth of a degree. Peak power during celestial determination: < 2 W and standby power < 0.3 W! System can easily incorporate additional sensors such as a magnetometer (i.e. digital magnetic compass) into the solution.

Star tracker technology for space systems has continued to evolve. We believe that the latest technology in star trackers, exemplified by the above described systems, provides an opportunity for the development of small, lightweight, inexpensive, reliable celestial systems that can be coupled to existing INS systems for commercial and naval ships. A not unreasonable expectation for this technology is the acquisition of large numbers of star positions, day or night, providing an accuracy of better than one arc second (less than 30 meters).

Conclusion

The combination of automated star trackers and inertial navigation systems (INS) is a synergistic match. 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 nowadays ships navigation rely increasingly on GPS, it is important that this dependence does not become a single-point-failure risk for safety of navigation. Independent alternatives to GPS are needed: The state-of-the-art star trackers designed for space applications can be profitably applied to ships 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, data rate and lower cost. 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 ships worldwide.

References

PAPPALARDI, F., S.J. DUNHAM, M.E. LEBLANG, T.E. JONES, J. BANGERT AND G. KAPLAN. 2001. Alternatives to GPS. *Proc. MTS/IEEE Conference and Exhibition OCEANS. Vol. 3,* pp. 1452–1459.[online resource: http://ieeexplore.ieee.org/document/968047] Accessed April 2017.

WILLIAMS, S. 2006. RADAR'd GPS Vulnerable to High-Power Microwaves. *GPS World*, April 2006, pp. 26-35.

INTERNATIONAL MARITIME ORGANIZATION. 2012. *International Convention for the Safety of Life at Sea (SOLAS). Ch V, Regulation 19.*

ERIC WALLISCHECK ,"GPS Dependencies in the Transportation Sector", August 2016*, U.S. Department of Transportation ,Office of the Assistant Secretary for Research and Technology, John A Volpe National Transportation Systems Center,* pp 17-21.

INTERNATIONAL MARITIME ORGANIZATION, 2012, *International Convention for the Safety of Life at Sea, 1974 (SOLAS) ,CHAPTER V Regulation 19 , Para. 2.1.6.*

CHRIS GREGERSON, JOHN BANGERT AND FRED PAPPALARDI, 2000, "Celestial augmentation of Inertial Navigation Systems: A robust Navigation alternative", *U.S. Naval Observatory, Washington, DC (USNO) SPAWAR System Center, San Diego, CA (SPAWARSYSCEN SD).*

ANGUO, WANG. 2007. "Modern Celestial Navigation and the Key Techniques." *Acta Electronica Sinica* 35(12), pp.2347–2353

NOACK, THOMAS LUTHER, "An optimized celestial-inertial navigation system " (1963). *Retrospective Theses and Dissertations*. Paper 2943

"AST-201 STAR TRACKER SYSTEM SPECIFICATIONS, 1998, REV. D" LMMS-F426359-D, Lockheed Martin Missiles & Space Advanced Technology Center [online web resource:http://www.lockheedmartin.com/content/dam/lockheed/data/space/documents/ATC/ATC_Brochure.pdf], accessed April 2017.

CELESTIAL-INERTIAL PRECISION POINTING SYSTEM SPECIFICATIONS, 2015, Rockwell Collins Corp., [online resource: https://www.rockwellcollins.com/Products_and_Services/A_Z/C/Celestial_Inertial_Precision_Pointing_System.aspx], accessed April 2017.