Review of Polar Integrated Navigation Algorithm

Tian Ming1,a
1National University of Defense and Technology, Hunan Changsha, China
a Corresponding Author’s Email: 2913463551@qq.com

Abstract: Developing the research of navigation and positioning in high latitude area has important political, economic and military value, and it is of great significance to realize the global navigation of inertial navigation system. In this paper, the basic algorithms suitable for polar navigation are summarized, various polar integrated navigation methods are compared, and the research of inertial / astronomical integrated navigation with small error, high accuracy, wide application is particularly introduced.

1. Introduction

As the global climate warms, the melting of Arctic sea ice accelerates further, even the area and thickness of winter sea ice have been drastically reduced [1]. According to the forecasts of experts at home and abroad, after 2020, the ice in the sea surface of the Northwest Passage will be reduced to the extent that merchant ships can basically sail safely. During 2060-2080, the sea ice of Arctic summer will melt completely, allowing merchant ships to sail unimpeded. Moreover, according to the calculations of the international shipping community, ships travel through the Arctic saves at least 40% less voyage than detouring the Suez or Panama Canal [2]. For example, the current route from Shanghai to London need to travel through the Panama Canal, the whole journey is about 13,000 nautical miles. If the Arctic route is adopted, the voyage will be shortened to 8850 nautical miles. Therefore, once the Arctic route is navigable, it can become the quickest route between North America, Northern Europe and Northeast China.

In addition, the Arctic region is rich in oil and gas resources [3-4]. According to statistics, about a quarter of the oil and gas resources that have not yet been discovered by human beings are distributed in the Arctic. The Arctic has 90 billion barrels of crude oil and more than 4.7 billion cubic meters of natural gas, according to the latest estimate by the U.S. Geological Survey. In addition, with the development of military science and technology and the variability of international political, economic and military situation, all the military powers have put forward higher demands on the fast strike capability and the global combat capability of the ships. That is to say, on the basis of higher speed, the voyage is required to be as short as possible, therefore, the ships are requested to be able to navigate around the world. If necessary, the ships can cross the Arctic. It is of great significance and urgency for ships to have the ability to navigate in the North Pole. The accumulation of Arctic navigation experience will lay an important foundation for China’s future trade with the Arctic waterway.

Therefore, for economic, scientific and military reasons, it is of great value to carry out research on inertial integrated navigation in polar regions. It provides a reference for exploring the navigation mode in high latitude area and plays an important role in ensuring the safe navigation and positioning of polar activities.
2. Research status of polar inertial navigation algorithm

The main difficulty of realizing the global navigation of inertial navigation system is that with the increase of latitude, the polar longitude converges rapidly and finally converges to a single point, which makes it difficult to establish the heading direction relative to the longitude, thus causing the error amplification and so on. Therefore, the traditional inertial navigation algorithm based on the pointing northern bit system is invalid in the polar region [5-7]. In order to solve the problem that the traditional navigation algorithm system faces in the polar region, inertial navigation algorithm which is suitable for the polar region is being developed step by step.

In the early years, the effective word length of the computer was relatively short. The mechanical arrangement of the Wander Azimuth Inertial Navigation system and the Freedom Azimuth Inertial Navigation system could be used for normal navigation in most areas of the earth. But the accuracy is not high, besides, also face the problem of calculation overflow and so on [8]. The mechanical arrangement of inertial navigation system based on the Inertial Reference Coordinate and the Earth-Centered Earth-Fixed Coordinate also has the ability of global navigation, but the output information is difficult to be understood directly by users [8].

In 1941, British Royal Air Force Lieutenant Colonel K. C. Maclure put forward the concept of grid inertial navigation system based on Greenwich meridian heading, which preliminarily solved the problem of no coordinate system in polar navigation [9]. After the grid inertial navigation system, several inertial navigation systems with different definitions have been gradually differentiated, such as the Universal Transverse Mercator (UTM), the Universal Polar Stereographic (UPS) and the Military Grid Reference System (MGRS) etc. [10].

In August 1958, the Nautilus, an American nuclear submarine, successfully crossed the Arctic pole, thus truly opening up the scientific exploration of high latitudes [11]. The N6A inertial navigation system of it is also one of the most advanced platform inertial navigation systems at that time. After entering the polar region, N6A will automatically switch to the inverse coordinate inertial navigation system. The inverse Mercator projection is used to make the chart. In inverse coordinate inertial navigation system, the latitude and longitude is approximately a grid at the pole, which avoids the problem of the traditional geographical longitude line converging on the pole. However, any navigation system has its own shortcomings. When the system is in some specific position, it will still have singular problems, and the limitation of error accumulation over time is still reflected in the system.

Nowadays, countries all over the world are making great efforts to explore and study the polar regions. The latest models of large commercial aircraft developed by Boeing and other large aircraft manufacturing companies can carry out missions around the world. Boeing took the lead to pioneer a polar commercial route between North America and Asia in 2001. In addition, several member countries of the Arctic Circle, including Russia, are quite mature in the field of polar chart drawing and polar navigation. Meanwhile, the United Kingdom and the United States are also developing AUV for polar exploration, such as the APOGEE and ALTEX series in the United States and the AUTOSUB series in the United Kingdom [12].

At present, some progress has been made in the study of inertial navigation in polar regions in China. In view of grid navigation, Zhou Qi and Yue Yazhou put forward an indirect grid navigation algorithm for polar regions with the moving azimuth inertial navigation arrangement as the core, and derived the directional cosine matrix between the wandering coordinate system and the grid coordinate system. In this way, the course and velocity of grid can be obtained indirectly. Meanwhile they replace the latitude and longitude high positioning parameters with Earth-Centered Earth-Fixed Coordinate, which solves the problem of navigation and positioning in the polar region [13]. Peng Wensheng, Sun Fuping and others put forward a method of using grid coordinate system to obtain grid heading directly and then optimize navigation performance of inertial navigation system [14]; By constructing the navigation equation and system error model based on grid coordinate system, they analyze the principle that inertial navigation system using grid coordinate system to solve the problem of orientation in polar region. The simulation results show that the errors of attitude, velocity and position are similar to those of traditional
inertial navigation system in low latitude. The inertial navigation system using grid coordinate system can meet the requirements of carrier navigation in polar region.

Aiming at the transverse coordinate system, the correction and damping of the transverse navigation algorithm are designed in the literature [15] and [16] to improve the accuracy of the long-term navigation and to suppress the periodic oscillation. The literature [17] and [18] optimize the transverse navigation algorithm under the ellipsoidal earth model. The results show that the lateral inertial navigation system can solve the polar navigation problem.

Finally, in the course of the development of polar inertial navigation technology, several relatively mature polar inertial navigation algorithms have been gradually formed. Some typical ones are: polar inertial navigation algorithm based on swimming azimuth coordinate system, polar inertial navigation algorithm based on horizontal coordinate system, polar inertial navigation algorithm based on grid coordinate system, etc., which solve the problems of polar navigation from different angles, and combine with rotating modulation or integrated navigation, etc. to improve the accuracy of navigation.

3. Research status of polar integrated navigation

However, when considering the global execution capability of inertial navigation systems, none of the commonly used mechanical arrangements can achieve global navigation alone. A great deal of researches have been done at home and abroad on various integrated navigation methods in middle and low latitudes. However, there are few researches on integrated navigation systems in polar regions.

In order to meet the needs of full autonomy, high precision and long voyage navigation, the means of correcting the accumulated errors of inertial navigation by means of astronomical navigation system have been attached great importance to by the military power all the time. They have been working on this area since the 1950 s.

Take the United States Air Force as an example, the NAS-26 inertial / astronomical integrated navigation system in the 1980s, the SAIN strapdown inertial / astronomical navigation system J6 in the 1990s, the LN-120G inertial / astronomical integrated navigation system at the beginning of this century. All of them are typical airborne inertial / astronomical integrated navigation products, which have the capability of global navigation, full autonomy, high precision and long voyage navigation. The LN-120G inertial / astronomical combination meets the requirement of high precision navigation information for strategic reconnaissance mission.

At present, some scholars have carried out a great deal of theoretical verification of polar integrated navigation. In reference [10], a method of integrated navigation solution for inertial navigation / astronomical navigation in grid coordinate system is proposed, which can solve the disadvantages of inertial navigation. Zhang Fubin, Mapeng [19] and others put forward a method of inertial navigation / Doppler polar integrated navigation based on lateral earth coordinate system. The results show that this method can effectively restrain the increase of azimuth misalignment angle, and all belong to autonomous navigation system. Liu Wenchao, Tan Zhiyang [20] and others proposed to solve the problem of navigation at high latitudes by using INS/GPS integrated navigation with moving azimuth. The results show that the integrated navigation can meet the needs of navigation in most high latitudes. It can effectively improve the accuracy of navigation parameter estimation.

Because of the special geographical and electromagnetic conditions in the polar region, all kinds of navigation methods cannot always work properly, thus, not every integrated scheme is effective for integrated navigation. Because of the snow and ice covering, the geomorphological features of the polar region are not obvious, so the combination scheme of terrain matching will not be ideal. The radio navigation integrated scheme needs to arrange the navigation station on the ground, if carries on the large-scale construction navigation station, it will be not very realistic; INS/passive gravity matching is a passive navigation method, but it also needs to make a good gravity gradient map in advance. For INS/GPS integrated system, GPS has the characteristics of global and high precision, but in polar region, it is easily disturbed by severe weather, such as aurora and magnetic storm, so it cannot provide effective navigation data at any time. INS/DVL integrated scheme and Doppler log belongs to autonomous acoustic navigation system, can work independently without external assistance. It is an ideal
combination scheme. The combination of the two can reduce the speed, improve the navigation attitude accuracy, but it cannot effectively restrain the divergence of position error.

4. Research status of inertial astronomical integrated navigation at home and abroad

The aircraft has a high requirement for battlefield environment autonomy when it has a strategic long voyage, so it can still work with high precision when there is no satellite navigation system. Therefore, the astronomical navigation system with high precision attitude measurement and the continuous autonomous laser gyro inertial navigation system are the best choice of navigation system design [21].

With the development of navigation technology, integrated navigation system based on astronomical navigation system and inertial navigation system has become a hot spot in the field of aerospace navigation.

In the 1960s, Leighton began to design Stellar/Inertial System. It produced the first product in 1961, LN-5, in 1962, LN-7A, in 1969, LN-16 system, also known as AN/ASN-59, and in 1974, LN-20 series, which were replaced by computer solid state memory.

The LN-20 Stellar/Inertial/Doppler System, uses a MIL-ST-1750 processor. In this newly upgraded system, the advanced computer command language Jovial (Jules Own Version of IAL), uses the MIL-STD-1553 data bus, as well as the GPS external interface, the upgraded optical electronic decoder. A multivariate linear, multi-page LED control and display unit with CCD array star sensor, ring laser gyro, triaxial accelerometer and missile information loading device is used. When there is no GPS signal, the position accuracy can reach 2400ft / 24h, the heading angle is better than 0.5 °, and the position precision is better than 50ft / 24h and the heading angle is better than 20 °when there is GPS signal.

In order to meet the higher requirements of the US military for the system which concludes high precision, high reliability, ease of use and low cost, Leighton has upgraded its new LN-20 system and divided the system modularization into four replaceable parts. It includes Control and Display Unit, teller/Inertial Reference Unit, Navigation Computer Unit and Battery Unit. The control and display unit module can control the inertial navigation system, observe the satellite / inertial navigation information and state, and control the autopilot mode. In 1983, Kalman filter was added into the system, the resolution could reach 1.2 °, and the field of view of the star sensor could reach 35 ~ 85 °.

NAS-26 is the fourth generation inertial / astronomical system in the United States. The system consists of two gyroscopes with two degrees of freedom and three accelerometers. It tracks three stars per minute, with a minimum brightness of 3.5. It can track 6 to 8 stars, and the observation accuracy is 3 °. The system weighs 184 pounds and has a volume of 3.9ft³. The average failure-free working time is 800 h.

In the 1980s, the first intercontinental missile SM-62 Snark used the NAS-26 system for the first time. Its position accuracy reaches 1000ft / 10h, velocity error is less than 0.5ftr / s, and attitude error is less than 25 °. The average failure-free interval is more than 800 hours. The computer stores 61 ephemeris and provides 24-hour all-weather navigation. The ephemeris is updated once a year.

In 2005, Northrop was selected by the United States Air Force to provide a LN-120G high-precision astronomical navigation system for the US RC-135 reconnaissance plane series. LN-120G uses modern hardware and software, such as zero-locked gyroscopes, advanced accelerometers and new astronomical telescope electronic technology. In the inertial / starlight combination mode, LN-120G’s heading accuracy is better than 20 °. The high positioning accuracy of LN-120G enables the reconnaissance plane to accurately detect enemy targets.

Later, the strapdown Inertial Astronomical Integrated Navigation system (SAIN), based on holographic wide-angle lens star sensor, was developed by Northrop Corporation in the United States. The position error of integrated navigation (CEP) is less than 6.22fh. It can replace the satellite navigation system. And it is called the system with high performance and autonomous navigation capability in the 21st century. In addition, Microcosm Company has developed a high-performance multi-view field system, which can achieve high precision attitude determination at mid-low altitude or even sea level.
The French M51 missile uses inertial astronomical integrated navigation technology. The range of the missile is from 8000km to 11000 km and its hit accuracy reaches 200m. The Russian SS2N28 and SS2N218 missiles both use inertial astronomical integrated navigation technology. The missile has a range of 9200 km2 and hits the highest precision of the 370m. RSM-54 submarine-launched strategic missile uses the PINS/CNS integrated navigation system assisted by GLONASS satellite navigation. The RSM-54 "Deep Blue" missile was test-launched in March 2010, with a range of 8000km and a circle probability error of 600m. After the separation of the second stage rocket, the attitude of the satellite inertial navigation correction was completed, and then the position of the satellite navigation velocity was corrected.

Tsinghua University has made rich research achievements in high precision centroid extraction, star map recognition, attitude resolution and ground calibration. Beijing University of Aeronautics and Astronautics has made great achievements in star sensor optical imaging system, star map processing chip, centroid following imaging system, etc. Star map recognition and attitude tracking have achieved some research results. Harbin University of Technology has made progress in optical design of star sensors and attitude determination algorithms [22].

At present, an inertial / astronomical integrated navigation system [23] has been installed in a certain type of air tanker in China, and good results have been obtained. In the aspect of ship platform, the astronomical navigation equipment of small field of view star tracker is used, among which the typical celestial guide periscope is equipped with submarine, and the space guide equipment of surface ship is equipped. The inertial / astronomical integrated navigation system installed by medium and long-range bombers and AWACS is in the experimental stage, and some key technologies need to be solved.

5. Concluding remarks
When navigating in polar regions, navigation methods are affected by the special magnetic field distribution, astronomical and meteorological conditions of the polar regions, navigation methods such as geomagnetic navigation, radio navigation, and satellite navigation cannot always work properly in polar regions. Therefore, inertial navigation system, which does not depend on external information, has become an important means of navigation for transpolar vehicles under the restriction of special geographical environment in polar regions. However, due to the harsh natural climate in the polar regions, there were few means of transportation in the past. Now, most of the modernistic inertial navigation devices now are only suitable for low and medium latitude navigation, not for high latitude areas. Moreover, the inertial navigation in polar regions is seldom studied in China. Therefore, to carry out research on polar navigation algorithm, compare and analyze the advantages and disadvantages of each integrated navigation scheme will lay a theoretical and technical foundation for the realization of global navigation of inertial navigation system and also play a great role in ensuring the safe navigation and positioning of polar activities. At the same time, it has great economic value and social significance.

Reference
[1] Stroeve J, Serreze M, Drobot S, et al. Arctic Sea Ice Extent Plummeted in 2007[J]. Eos Transactions American Geophysical Union, 2013, 89(2):13-14.
[2] Khon V C, Mokhov I I, Latif M, et al. Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century[J]. Climatic Change, 2010, 100(3-4):757-768.
[3] Anonymous, Russia opens Arctic oil shipping line [J]. World Shipping, 2010 (9): 53-53.
[4] Arctic Research Writing Group, Study of the Arctic problem [M]. Ocean Press, 2011.
[5] Li J, Song N, Yang G, et al. In-flight initial alignment scheme for radar-aided SINS in the arctic[J]. Iet Signal Processing, 2016, 10(8).
[6] Xu J, He H, Qin F, et al. A Novel Autonomous Initial Alignment Method for Strapdown Initial Navigation System[J]. IEEE Transactions on Instrumentation and Measurement, 2017, PP (99):1-9.
[7] Salychev, Applied Inertial Navigation:Problems and Solution, Moscow: BMSTU Press,2004.
[8] Qi Z, Yongyuan Q, Qiangwen F, et al. The principle of Polar Flight Grid Inertial Navigation
algorithm [J]. Journal of Northwest Polytechnic University, 2013,31 (2): 210-217.
[9] Feng W, Yongyuan Q. Airborne weapon transfer alignment algorithm [J]. Chinese Journal of Inertial Technology, 2013,21 (2): 142-146.
[10] Qi Z, Yongyuan Q, Gongmin Y. Study on Inertial / Astronomical Integrated Navigation algorithm for large aircraft Polar region [J]. Systems Engineering and Electronic Technology, 2013, 35.
[11] Shu Y, Hong C. The submarine navigated under the Arctic [J]. Ship navigation, 2003, 3.
[12] Jiangcheng Yu, Aiqun Zhang. The Development and the Challenges of Underwater Vehicles for Polar Expedition [J]. IEEE, 2004: 95-99.
[13] Qi Zhou, Yaxhou Yue, Xiaodong Zhang, et al. Polar Flight indirect Grid Inertial Navigation algorithm [J]. Chinese Journal of Inertial Technology, 2014,22 (1).
[14] Wensheng Pang, Fuping Sun, Tsin-ming Cai, et al. Performance analysis of polar grid inertial navigation [J]. Journal of Navigation and Positioning, 2017 (2): 38-43.
[15] Li Q, Ben Y, Yu F, et al. System reset of transversal strapdown INS for ship in polar region[J]. Measurement, 2014, 60:247-257.
[16] Li Q, Ben Y, Sun F, et al. Transversal strapdown INS and damping technology for marine in polar region[C]// 2014 IEEE/ION Position, Location and Navigation Symposium-PLANS 2014. 2014:1365-1370.
[17] Yao Y. Transverse Navigation under the Ellipsoidal Earth Model and its Performance in both Polar and Non-polar areas[J]. Journal of Navigation, 2015, -1(2):1-18.
[18] Li Q, Ben Y, Yu F, et al. Transverse strapdown INS based on Reference Ellipsoid for Vehicle in Region[J], IEEE Transaction on Vehicular Technology, 2016:1-1.
[19] Fubin Zhang, Peng Ma, Zhihui Wang. Strapdown Inertial Navigation system / Doppler Velocity instrument Polar Integrated Navigation algorithm based on Transverse coordinate system [J].
[20] Wenchao L, Zhiyang T, Hongwei B, et al. Application of wandering Azimuth INS/GPS Integrated Navigation in Polar region [J]. Firepower and Command Control, 2013HN 38 (2): 69-71.
[21] ScottW.Lewis.Stellar Inertial Navigation Growing With The Times Upgrading Of The LN-20 Integrated Inertial Navigation System[J].
[22] Debao Cheng. Review of Airborne Inertial / Astronomical Integrated Navigation Technology [J]. Optics and Optoelectronic Technology-2009 7 (3): 49-52.
[23] Jinliang Zhang. Research on Integrated Navigation algorithm of Strapdown Inertial Navigation and Satellite Tracker [J]. Journal of Aeronautics and Astronautics. 2013N 34 (8): 1078-1083.