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A Survey of Several Common Navigation Methods for Spacecrafts

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Abstract: Spacecraft work beyond the earth’s atmosphere. With the development of aerospace industry, missions of spacecrafts are becoming more and more complex. So spacecrafts need more efficient and accurate navigation system to help their works. Every navigation system has its advantages and disadvantages. This paper summarizes several common navigation methods and their characteristics, and the application of different navigation methods, as well as their trend of future development.

Keywords: Aerospace navigation, Inertial system, Celestial navigation.

1. Introduction

Navigation for the spacecraft is an important step for a successful flight. It is almost impossible for spacecrafts to complete their missions when their position, velocity, attitude are not clear. There are two main functions of aerospace navigation. The first is to determine the information of the spacecraft like its position, velocity vector, attitude etc. The second is to make plans for the flight[1].

With the increasing speed of spacecrafts, the more complex missions, the increasing distance from the earth and complexity of spacecrafts themselves, the navigation systems become more demanding, especially for the deep space spacecrafts. Nowadays we still face several problems. The first is the matching of the advantage of the navigation modes with the requirements of spacecrafts’ missions. The second is more combined ways of integrated navigation and how to make integrated navigation achieve the best results. Third, the further development of new navigation methods and navigation methods for particular conditions. The fourth is the update and optimization of navigation systems’ algorithm. Fifth, the continuous optimizing of the hardware equipment.

This paper summarizes some common domestic and foreign space navigation technologies and looks forward to the future development.

2. Several Navigation Methods and Their Development Tendency

2.1. Inertial Navigation

2.1.1. A Brief Introduction to the Principles of Inertial Navigation

Inertial navigation is a relatively mature navigation method, which is widely used. It uses the gyroscope and the acceleration senor to obtain the three axis angular acceleration and linear acceleration of the system to calculate the position, velocity, attitude of the spacecraft. According to whether the system needs the external devices and human’s information sources, the navigation system can be divided into two types, the autonomous navigation or not. The inertial navigation is an autonomous navigation system. The advantages of inertial system are its high data update rate, high short-term accuracy. Also it won’t be influenced by the electromagnetic interference. The disadvantage is that, because the information is obtained by integration, the error will also accumulate, which makes its long-term accuracy low[2].

The accuracy of the inertial navigation is closely related to its gyroscope. This paper mainly introduces the optical gyroscopes and the hemispherical resonance gyroscope.

2.1.2. Optical Gyroscope

Optical gyroscope includes ring laser gyroscope and fiber optic gyroscope[2].

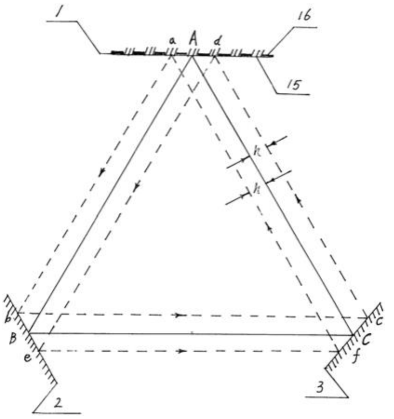

Figure 1. Ring Laser Gyroscope Model[4]

Figure 1 shows a simple model of a triangular ring laser gyroscope. Ring laser gyroscope has high precision, good stability and long service life. The main advantage of ring laser gyroscope is that it has no rotor moving parts. The research on ring laser gyroscope abroad mainly focus on improving its accuracy. The development interests can be divided into two directions. One is miniaturized and low accuracy ring laser gyroscope. The other is large size and ultra-high accuracy ring laser gyroscope. In 2021, Y.Broslavets et al. From the Moscow Institute of Physics and Technology studied the multi frequency solid-state ring laser gyroscope based on YAG: Cr4+, and determine the laser parameters to ensure the maximum accuracy of angle measurements[5]. G.Barantsev et al. from Lomonosov Moscow State University analyzed the effect of the dynamic elastic torsion on attitude accuracy of the navigation system caused by mechanical dithering device of ring laser gyroscope, and proposed a method to calibrate this parameters by compensating attitude integral[6]. For ring laser gyroscope, the commercial undersea precision inspector of Kawasaki Heavy Industries was equipped with SPRINT-Nav 700, which uses Honeywell's ring laser gyroscope and accelerometer for navigation[2].

For fiber optic gyroscope, the research mainly focuses on using a variety of optical modulation and process optimization methods to improve the comprehensive performance of fiber optic gyroscope, so as to improve its accuracy and reduce its cost. Researchers from Universidade Estadual de Campinas proposed a method to improve the linearity of open-loop fiber optic gyroscope based on mean demodulation scheme. This method can improve the linearity of sensor output by 65 times, and the nonlinear error is better than 2.3×10-4[7]. For the fiber optic gyroscope inertial systems, Advanced Navigation Company from Australia launch the digital fiber optic gyroscope inertial navigation system Boreas D90, which can provide 0.01(°)/h strategic bias stability, 0.005°roll/pitch accuracy and 0.01°heading accuracy on the basis of significantly reducing costs[2]. For applications, the Norwegian Coast Guard's P6615 Jan Mayen class warship was equipped with a strapdown fiber optic gyroscope navigation system provided by the French iXblue company in January 2021. Russian Optolink Company installed an fiber optical gyroscope on Soyuz MS-7 spacecraft to help it complete its landing mission[2].

2.1.3. Hemispherical Resonator Gyroscope

Hemispheric resonator gyroscope is a kind of Coriolis vibratory gyroscope. Compared with optical gyroscope, it has the advantage of miniaturization. It has a board application prospect in the aerospace field and is a trend of the future gyroscope. The research on hemispheric resonator gyroscope has been carried both abroad and at home.

The United States is the first country to study hemispheric resonator gyroscope, and its gyroscope's accuracy can reach 0.0008(°)/h. In about 1986, many hemispheric resonator gyroscope products had come out, including HRG158 (which can work under harsh conditions), HRG130 (which is used to intercept strategic missiles), etc[8][9]. In 1994, Delco Company invested more resources in the hemispheric resonator gyroscope. The HRG130R was improved on the basis of HRG130 to make it able to withstand a worse working environment. Another improved design, HRG130P, eliminated the problem of nitrogen leakage. Within the measurement range of ±12(°)/h, its accuracy can reach 0.0005(°)/h. It has accumulated more than 50 million flight hours in various space missions, and is currently the main product.

Since the 1980s, with the research of hemispheric resonator gyroscope in the United States, the former Soviet Union has also carried out research. Russia has developed a rate integral hemispheric resonator gyroscope with an accuracy of 10^{-4}(°)/h[10]. The hemispheric resonator gyroscope HRG-30ig developed by Russian Medicon Company has developed a special leveling technology, with a dynamic range of >600(°)/s, bias stability of <0.01(°)/h[11], which has been applied in the aerospace field to some extent. In resent years, Russia has further deepened its research on hemispheric resonator gyroscope and made some progress. Russian inertial navigation system is equipped with a large number of hemispheric resonator gyroscope systems. In addition to the United States and Russia, other countries, such as France, have also carried out research on hemispheric resonator gyroscope. This pater will not introduce it specifically.

China has also carried out research on hemispheric resonator gyroscope, and has made some progress. In 2002, CET-26 developed the first hemispheric resonator gyroscope system and after that, it continued to solve many key technical problems. In 2018, a hemispheric resonator gyroscope system developed by the Shanghai Academy of Spaceflight Technology completed its first flight on a communication technology experimental satellite. The hemispheric resonator gyroscope system in China is still in the experimental stage, and its accuracy can only meet the low dynamic requirements in the aerospace field[12]. It is still far from being widely used and still has a certain gap with foreign countries, so further research is needed[13].

2.2. Satellite Navigation

2.2.1. A Brief Introduction to the Principles of Satellite Navigation

Satellite navigation is a technology that uses satellites to locate users in space. Satellites interacts with the users through radio waves, and users calculates its own position through the radio messages of several satellites[14]. GPS, GALILEO, GLONASS use the principle of side-surveying intersection positioning. That is, to measure the distance between the target to be measured and several known points. Then, through several satellites, the position of the target can be calculated.

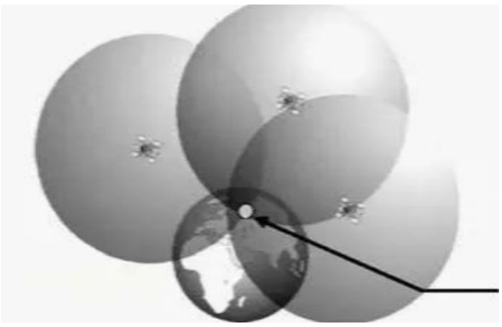

Figure 2. Principle of the Side-surveying Intersection[14]

Since conventional satellite navigation is only applicable when the target is lower than the satellites' orbit, satellite navigation is mainly applicable to low earth orbit spacecraft and spacecraft at launch phase. For satellite navigation of high orbit spacecraft, more research is needed. The research of satellite navigation is mainly focus on improving its accuracy, improving its algorithm, expanding the application scope of satellite navigation, deploying more satellites and so on. Due to the limitation of satellite navigation for spacecraft, more development direction lies in how to better combine with other navigation methods like inertial navigation for integrated navigation.

2.2.2. Measurement and Control of Low and High Orbit Spacecraft

At present, the research of satellite navigation system in low and medium orbit has been relatively mature, such as China's BeiDou navigation satellite has the ability to provide the measurement and control service for spacecraft[16]. In March 2010, the Remote Sensing 9 satellite carried the BeiDou-1 subscriber computer, verifying the BeiDou space-based TT&C (Tracking, Telemetry and Command) technology[17]. With the successful global network of BeiDou-3 satellites, the BeiDou communication system can solve the problem of all-day TT&C of low earth orbit spacecraft. The global message system carried by BeiDou-3 satellite can achieve global real-time coverage, and the service scope covers the global surface and 1000km above[18][19].

The research on satellite navigation for high orbit spacecraft is still not enough. In 2018, Jiaxin Chai et al. Studied the strength of receiving navigation signals and the multi constellation joint navigation mode[20]. In 2020, Meng Wang et al. Conducted a comparative analysis of low orbit spacecraft and high orbit spacecraft, and gave a detailed assessment[21]. Navigation of high orbit spacecraft are facing with the problems like weak navigation signals received and few high orbit satellites. Navigation of high orbit spacecraft using satellite navigation is currently a hot topic at home and abroad[22].

Figure 3. BeiDou-3 Satellite[23]

2.3. Celestial Navigation

Celestial navigation is an autonomous navigation method. The advantage of celestial navigation are high reliability, simple and mature, not interfered by electromagnetic, and the error does not drift with time[24].

Celestial navigation can be divided into near-earth celestial navigation and deep space celestial navigation. Deep space celestial navigation can be classified according to angle measurement navigation, velocity measurement navigation and range measurement navigation. The angle measurement navigation method uses optical sensors to obtain images of astronomical objects, and obtains the orientation information of the detector relative to the target object through image processing. By using multiple orientation information, spacecrafts calculate its position and attitude. Celestial angle measurement navigation is a relatively mature navigation method at present[25], and the error of it for deep space navigation is about 10-250km[26][27]. Ranging navigation mainly refers to X-ray pulsar navigation, which will be introduced separately in the following paper. Velocity measurement navigation obtains the velocity vector of the detector relative to the astronomical target by observing the spectral frequency shift caused by the motion of the detector relative to the astronomical target.

2.3.1. Some Applications, Problems and Research Interests of Celestial Navigation

Since the 1980s, more and more spacecrafts have been using celestial navigation to complete their tasks, and the relevant navigation methods have also been improved. The Deep Space 1 launched by NASA in 1998 completed its autonomous navigation in the cruise phase only by means of celestial angle measurement navigation. The Surveyor Probe launched in 2005 also used celestial navigation methods. Celestial angle measurement navigation has been applied in many deep space exploration missions, but its accuracy is affected by the distance between spacecrafts and astronomical targets[28]. In 1960, Franklin of the United States proposed the idea of using Doppler phenomena to measure the velocity of spacecrafts. He believed that the solar spectrum could be used as an information source for celestial velocity measurement navigation[29]. Since then, the theory of celestial velocity navigation has been developing at home and abroad, but until now, there is still a lack of a corresponding complete engineering system. And the celestial velocity navigation is still in the engineering verification stage. In addition, many countries in the world have made a lot of research on the star sensors, which is the core device of celestial navigation. Ball Aerospace Company of the United States has developed the CT-633 star tracker, which can be used as an attitude sensor and can be applied to many occasions, including space stations, Earth orbit satellites, etc. ASTRO series star trackers developed by Germany Jena Company were successfully applied to MIR space station[30]. The research and development of star sensors in China started in the 1980s, a little later than that in foreign countries. However, after decades of research, related technologies have also achieved certain progress to some extent.

At present, there are still some technical and theoretical problems as well as engineering practice problems in celestial navigation in the aerospace field. For example: space-time issue. That is the time used by the atomic clock in deep space spacecraft is different from the time used for Coordinated Universal Time and planetary calendar. The error caused by conversion between different spatio-temporal datum will have a greater impact on high-speed deep space spacecraft[25].

3. Some Other Navigation Methods

3.1. X-ray Pulsar-based Navigation

X-ray pulsar-based navigation is a kind of celestial ranging navigation. The principle of X-ray pulsar-based navigation is to measure the time when the detector receives the X-ray photon of the pulsar, and the time when the pulse arrives at the reference point (usually the center of mass of the solar system). The difference between the time data multiple the speed of light, that is the projection of the distance from the spacecraft to the reference point on the line between the pulsar and the reference point.

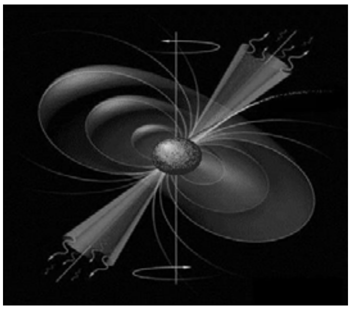

Figure 4. X-ray Pulsar Radiation[31]

In 1974, the the Jet Propulsion Laboratory (JPL) first proposed an autonomous orbit determination method based on radio pulsars, which treated each pulsar as a beacon. In 1981, the American Institute of Communication Systems proposed to use the X-ray pulse signal instead of the radio pulse signal as the observation measurement, because the X-ray pulse concentrated most of the energy of the pulsar[32].

In 2004, the Defense Advanced Research Projects Agency of the US proposed the autonomous navigation and positioning verification based on X-ray source[33], planing to apply pulsar navigation to the solar system. In addition, Europe and Japan have also planned or carried out relevant theoretical and experimental research on X-ray pulsar-based navigation[34][35]. For engineering, in2004, both the European Space Agency (ESA) and the United States Department of Defense proposed the plan for X-ray pulsar-based navigation of deep space spacecraft. In 2007, NASA took over the relevant plans of the U.S. Department of Defense, and completed the space verification of X-ray pulsar navigation for the first time in 2017. The highest positioning accuracy is about 4.8km[36]. China's research on pulsar-based navigation started relatively late. In 2007, Ping Shuai studied the principle, engineering application and feasibility of pulsar navigation[37]. In 2016, the Institute of High Energy Physics of the Chinese Academy of Sciences used the Crab pulsars to determine the orbit of Tiangong 2, with an error of about 20km[38]. In 2019, the Institute of High Energy Physics of the Chinese Academy of Sciences used China's first X-ray astronomical satellite "Insight" to carry out X-ray pulsar navigation test, with an error of about 10km[39].

X-ray pulsar-based navigation has the advantages of strong autonomy, high accuracy, stable signal source, strong anti-interference ability, etc. At present, the research on X-ray pulsar navigation is not mature enough. Future research interests on X-ray pulsar-based navigation include: data measurement and processing technology, error correction technology, X-ray detector, navigation algorithm, etc[37].

3.2. ΔDOR Deep Space Navigation

ΔDOR deep space navigation and positioning technology is based on VLBI (very long baseline interferometry). The accuracy of its angle measurement can reach the class of milliangle per meter[40]. The principle of ΔDOR navigation is that the spacecraft transmits signals from deep space to multiple ground stations. The ground station uses the radio power in deep space to correct the errors caused by the spacecraft's transmission. Use the data from multiple ground stations, the position, attitude can be calculated.

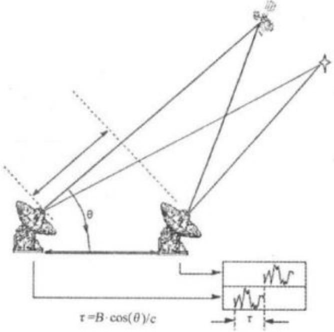

Figure 5. Principle of VIBL[40]

NASA first applied ΔDOR technology on Voyager 1 after years of research. Since then, HASA hasn't stopped studying the ΔDOR technology. The European Space Agency and the Japan Aerospace Exploration Agency have also work on this technology. The European Space Agency used the ΔDOR navigation on the Ulysses detector in 1992. Japan Aerospace Research and Development Agency has used ΔDOR navigation on NOIOMI, in order to ensure the successful orbit change. In 1998, the VIBL station in Shanghai participated successfully in the differential VLBI positioning observation organized by NASA. First application of ΔDOR navigation in China was in 2004 to measure the "Probe 1" satellite[40]. The VLBI stations were in Shanghai, Urumqi and Kunming. The average orbit determination error was 2km, and the speed error was 5cm/s. In 2007, Chang'e-1 lunar exploration satellite also used ΔDOR technology[40].

Although China has basically mastered the key technology of VLBI. But still lots of observation and experiments are needed for better application of ΔDOR navigation. ΔDOR system has many development directions, including spacecraft transmitter, data transmission channel, weak signal reception, finding more suitable pulsars, and related algorithms for data processing.

Table 1. Comparison of different navigation methods

Navigation Methods	Inertial Navigation	Satellite Navigation	Celestial Angle Navigation	Celestial Velocity Navigation	X-ray Pulsar-based Navigation	With the Help of Ground Station (ΔDOR)
Autonomous Navigation	Yes	No	Yes	Yes	Yes	No
Core Devices	Gyroscope, Accelerometer	Satellite, Satellite Receiver	Star Sensor	Spectral Velocity Sensor	X-ray Receiver	Ground Station Receiver
Measuring Target	Self Acceleration, Angular Acceleration	Distance From Spacecraft to Satellite	Angular Between Spacecraft and Target	Spectral Frequency Shift	Pulse Arrival Time	Time Difference Between Ground Stations Received
Principle	Integration of Acceleration	Side-surveying Intersection Positioning	Geometric Calculate	Doppler Shift	Constancy of Light Velocity	VIBL
Properties	Highest Short-term Accuracy; Low Long-term Accuracy; Mature; High Data Update Rate	High Accuracy; Mature for Middle and Low Orbit; Poor Performance for High Orbit	Simple and Mature; Accuracy Decrease as Distance Between Probe and Target Increase; Better For Low Orbit	Suitable for Deep Space; Good Real-time Performance; Have Velocity Integration Error; Still in Engineering Test Stage	Suitable for Deep Space; High Accuracy; Still in Engineering Test Stage	Suitable for Deep Space; Have a Lot of Related Technologies; Need More Engineering Test

4. Conclusion

Table 1 is a direct comparison of these navigation methods. Different navigation methods have different advantages. So it’s important to find the suitable navigation method and use the proper integrated navigation for particular flight mission. It is predicted that autonomous navigation will become a important research interest in the future. At the same time, we will continue to develop special navigation methods and more integrated navigation methods for various scenarios.

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