The significance and related technologies of asteroid detection

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Abstract. Asteroid detection mission plays an important role in the field of deep space exploration, and it has multiple theoretical and practical guidance advantages for asteroid detection missions, and also promotes all critical technologies of deep space exploration. At present, many asteroid exploration missions have been carried out around the world, and China also plans to launch the "Tianwen-2" probe around 2025 to carry out an integrated exploration mission of fly-by, orbit detection, attachment control and sample-return mission for asteroid 2016HO3. In this paper, we discuss the significance of asteroid detection and several related critical technologies. The theoretical value of asteroid detection covers such as promoting theoretical research on the formation and evolution of the solar system, solar system material, geohazard early warning and early warning of spacecraft orbit. As for the key technologies involved in asteroid detection, this paper discusses the design of transfer trajectory and near-orbit operation, autonomous landing, optical navigation, laser communication and electric propulsion, and summarizes the research and application results of these technologies in the international deep space exploration field.

Keywords: Asteroid trajectory design, Autonomous landing, Laser communication, Electric propulsion technology.

1. Introduction

Asteroids, which are the celestial bodies in the solar system that are similar to planets and much smaller in size, involves main belt asteroids, near-Earth asteroids, planetary Trojan minor bodies, some exo-Neptunian bodies and some Centaurian asteroids. Asteroids poss the original information about the formation and evolution of the solar system, contain vast resources, and pose a real threat to the Earth.

With the development of deep space exploration, asteroid detection has become one of the important elements of deep space exploration in the 21st century. Asteroid detection not only helps to explore the mystery of the origin and evolution of the solar system and life, but also can promote the development of Earth protection, space science and space technology applications, and can verify the key technologies of deep space exploration, which is the current international hot spot of deep space exploration.

Recently, a worldwide asteroid exploration boom has been set off, and many countries and organizations have put forward development plans, attached importance to the formulation of deep space exploration strategies, and strategically and highly defined their respective development directions and priorities. As asteroid exploration, especially manned asteroid exploration, is technically difficult, and involves a wide range of fields, it not only relies on advanced technology level, but also needs strong economic strength to support it. At present, the countries and organizations that have successfully carried out or are implementing asteroid exploration missions include the United States, Europe and Japan.

China has already started the implementation of asteroid detection missions, and is preparing to implement the near-Earth asteroid 2016HO3 sample return and the main belt comet 311P orbit detection mission in the asteroid belt around 2025, to achieve the trajectory detection, landing and sample return of near-Earth asteroids, hoping to achieve three detection modes by detecting two types of targets in one launch.

In this paper, the significance of asteroid detection, the current status of international development and the mission objectives are achieved by China's asteroid detection mission and the adopted key technologies will be discussed.

2. The significance and development status of asteroid detection

2.1. Theoretical and practical implications of asteroid detection

The theoretical and practical significance of asteroid astrometry includes the study of solar system formation theory, material research, geohazard warning, spacecraft orbit warning, and many other aspects. At the same time, asteroid astrometry is different from other astrometric surveys.

2.1.1 Theoretical Value Implications

On the one hand, asteroids may bring devastating disasters. The impact of an asteroid may show great disasters or even induce biological extinction, and the asteroid impact theory is the most popular dinosaur extinction hypothesis. But so far, we still know very little about asteroids.

On the other hand, in a scientific view, asteroids may help us to explore the formation of our solar system. Since asteroids without atmosphere, craters and exotic elements on asteroids are better preserved and can be used to study the evolution of the solar system deeply. The water existing on Earth may also be found in asteroids, many of which have traces of water on their surfaces, those were perhaps brought by asteroids or comets billions of years ago.

2.1.2 Practical guidance significance

Asteroids are rich in mineral resources and are important targets for space mining. According to the spectral characteristics, asteroids can be classified into Class C (carbonaceous), Class S (rocky), and Class X asteroids. Among them, C-class asteroids are rich in carbon, hydrogen, oxygen, nitrogen and other elements, while many of S-class and X-class asteroids contain huge mineral resources, and some of them are very rich in metal elements. The largest M-type asteroid detected so far, Ling Shen Xing, is about 250 km in diameter and has a metallic composition of about 90%, mainly iron, nickel and pyroxene. 3554 is about 2.5 km in diameter and is estimated to contain platinum and metal deposits worth more than $20 trillion, which may be an important resource for future human survival.

In addition, asteroids have weak gravity, relatively low resource extraction difficulty, and easy to change their orbits themselves. With the continuous progress of human space technology, in the future, we can mine asteroid mineral resources and send them back to Earth, or capture smaller asteroids and send them to near-Earth orbit or near the Moon for exploitation, or directly process them in situ to produce energy and materials for space activities, which can significantly facilitate the launching from Earth and reduce the cost. The development of asteroid resources has become an important means for great powers in the space age to fight for strategic resources and expand new frontiers, and will also lead the development of the Earth-Moon economic circle, space manufacturing and other space economy industry chain, which has an incomparably broad prospect.

Asteroid detection plays an important technology-driven role. Compared with large ones, asteroids have the characteristics of "microgravity and uncertainty" [1]. "Microgravity" refers to the fact that the gravitational force on the surface of asteroids is extremely small and it is difficult to establish orbits around them, so its detection requires high precision and reliable autonomous navigation capabilities; "uncertainty" refers to the fact that there is little a priori knowledge about asteroids, and before the arrival of a probe, the rotation period, topography, surface physical properties, etc. can only be speculated by astronomical observations and theoretical assumptions. Due to the "microgravity", the probe cannot be attracted to land by the gravity of the asteroid, and requires precise control of the propulsion system to achieve an attached landing, and the low escape velocity of the asteroid makes it very easy for the probe to take off on the surface of the asteroid. Due to the distance, Earth observation can only obtain the basic orbital parameters and a small amount of information about the asteroid, and it is difficult to grasp its size, topography, motion characteristics, gravitational field and other physical characteristics, which makes the rendezvous and landing of the probe on the asteroid face more difficulties.

Therefore, asteroid detection has an irreplaceable role in the development of traction space technology, and needs to break through a number of new core technologies, including orbital precision measurement and control and autonomous navigation, small thrust transfer orbit, surface

sampling of weak gravitational objects, multi-mode long-life electric propulsion, etc. The development of these technologies will enhance human deep space exploration capabilities.

2.2. History and status of asteroid detection

With the development of space technology, human beings began to use spacecraft to make close observations of small objects in the 1970s. International small-object surveys have been conducted for more than 30 years, with the United States, Europe and Japan completing their own unique landmark missions. Table 1 and Table 2 shows some of the representative missions and the asteroid detection missions planned by the U.S., Europe and Japan in the 2020s[2-3].

Table 1 Some representative asteroid detection missions

Mission	Year	Country	Target
Hayabusa	2003	Japan	25143 Itokawa
Hayabusa2	2014	Japan	162173 Ryugu
Dawn	2007	America	Ceres, Vesta
OSIRIS-REx	2016	America	1999 Bennu

Table 2 Planed asteroids exploration missions in 20s

Mission	Country	Year	Target
Lucy	America	2021	Troy
DART	America	2021	Didymos
Psyche	America	2022	M-Psyche
Castalia	Europe	2028	133P
GAUSS	Europe	2029	Ceres

In terms of development history, asteroid detection has gone through close flybys (e.g. *Deep Space 1, Star- dust* and *Rosetta* missions), to orbiting asteroids (e.g. *NEAR* and *Dawn* missions), and then to attached detection (such as *Rosetta* mission), to the current asteroid surface sample return programs (e.g. *Hayabusa* and *Osiris* missions).

In terms of scientific results, the precise orbits, velocities, volumes, material compositions, and internal structures of target small bodies have been determined through different exploration missions. For example, the U.S. "Deep Space 1" mission flew over comet 19P/Borrelly, for detecting the size, shape, surface characteristics, brightness, mass, density of comets and asteroids, the state of rotation of comet nuclei, and studying the plasma characteristics of comet hair, the interaction between comet hair and solar wind, brightness, and the characteristics of dust and gas streams emitted from comet nuclei. The Japanese Hayabusa 1 mission analyzed organic compounds such as amino acids and polycyclic aromatic hydrocarbons in the ground laboratory, and the results proved that the organic compounds in Itokawa are abiogenic. These missions are focused on the scientific issues of the origin of the solar system and the life, which is good for deeply understanding of the origin of the solar system and the laws of planetary formation and evolution, and exploring the origin of life.[4]

2.2.1 U.S. continues intensive asteroid exploration

The United States, who has always pioneered exploring small bodies, and carried out the largest number of small body exploration missions, have launched several probes with asteroid detection as the main mission, and extended from near-Earth, main belt asteroids and comets to Kuiper belt asteroids.

In 1991 and 1993, the U.S. Galileo probe detected the asteroids Gaspra and Ida on its way to Jupiter, and the size, shape, and cratering characteristics of the two asteroids were detected at close ranges [5-6]. "In 1998, the Deep Space 1 asteroid probe was successfully launched as the first international technology validation asteroid detection mission, which provided a new technology demonstration and a new technology validation mission [7]. The successful launch of Deep Space 1

in 1998, explored an optimal way to combine the demonstration of new technologies with NEO exploration missions [8].

In the 21st century, NASA successfully launched the Dawn probe [9] in 2007, aiming at the asteroid belt between Mars and Jupiter to detect the two largest protoplanets, Vesta and Ceres. This was the first time that humans circled an object in the asteroid belt and the first visit to a dwarf planet. After a flight of about four years, Dawn entered Vesta's orbit and began a 14-month-long orbit of Vesta. Dawn then traveled to Ceres, where it arrived two and a half years later. On November 1, 2018, NASA confirmed that Dawn had run out of fuel, ending Dawn's exploration journey. Dawn was equipped with three science payloads, including the Fractional Camera (FC), Visible Infrared Imaging Spectrometer (VIR), and Gamma Ray and Neutron Detector (GRaND). Table 3 shows Dawn's science payloads and exploration missions.

Table 3 Names and Missions of Dawn's payloads

Name	Missions
FC	Determination of asteroid physical parameters;Orbital Navigation
VIR	Generate spectral images
GRaND	Measurement of elemental composition and abundance

NASA successfully launched Osiris in 2016 to the ancient asteroid Bennu [10-11], which is one of the small bodies with the potential to impact the Earth and is considered as a potential threat object, and mastering the physical properties of Bennu will be helpful for future asteroid impact avoidance missions. Four more years later, Osiris has successfully completed sampling in 2020 and is expected to return the samples to Earth in 2023. Osiris carries six science payloads, including the Camera Suite (OCAMS), Visible Infrared Spectrometer (OVIRS), Thermal Emission Spectrometer (OTES), Weathering Layer X-ray Imaging Spectrometer (REXIS), Laser Altimeter (OLA), and Sampling System (TAGSAM). The Table 4 shows the main science payloads carried by Osiris and the exploration missions.

Table 4 Names and Missions of OSIRIS'S payloads

Name	Missions
OCAMS	Record spin states of asteroids and identify dangerous zones
OVIRS	Identify mineral and organic materials
OTES	Measuring and mapping the surface of asteroids
REXIS	Provide X-ray spectra of asteroids
OLA	Measuring the shape and volume of asteroids
TAGSAM	Collection of asteroid samples

In 2017, NASA announced two newly selected discovery-class, low-cost detection missions, the Lucy and Psyche missions [12]. The Lucy mission, which was successfully launched on October 16, 2021, is scheduled to reach the asteroid belt in 2025 and to explore the Trojan group asteroids from 2027-2033. The mission includes one target in the asteroid belt and five Trojan group asteroids bound in orbit by Jupiter. "The Sage mission is scheduled to launch in October 2023 and will arrive at asteroid Psyche #16 in 2030, where the probe will conduct 20 months of exploration studies.

In 2022, NASA also successfully implemented a Double Asteroid Redirection Test (DART) mission to perform a pre-orbit validation of the Kinetic Impact defense technology [13]. The DART impactor was launched in 2021 and successfully impacted the target asteroid Dimorphos, which orbits a larger asteroid Didymos, in September 2022. This impact could significantly alter the trajectory of this binary asteroid system and test the ability of humans to deflect the course of other astronomical objects, such as asteroids, to protect the Earth, humans, and other species.

2.2.2 Japan's deep space exploration activities focus on asteroids

Japan started later in the field of asteroid exploration, but has made a major breakthrough with a unique idea and plan to carry out a mission aiming at a one-step asteroid sample return.

Japan successfully launched the Hayabusa asteroid probe in 2003 with the plan to collect samples from asteroid 25143 Itokawa and return the collected samples to Earth [14]. After more than two years of flight, Hayabusa reached its intended orbit of 20 km from Itokawa in 2005. In November of the same year, Hayabusa made 2 short landings on the Itoigawa asteroid and attempted to sample it. In 2007, Hayabusa embarked on a return voyage to Earth, and in 2010, Hayabusa re-entered the Earth's atmosphere, with the return capsule successfully landing in the desert near Woomera in southern Australia, while the main body of the probe burned up in the atmosphere. Hayabusa was equipped with four science payloads, including the Visible Spectral Imager (AMICA), the Near Infrared Spectrometer (NIRS), the Optical Radar (LIDAR) and the X-ray Spectrometer (XRS). The Table 5 shows the main science payloads and exploration missions carried by Hayabusa.

Table 5 Names and Missions of Hayabusa's payloads

Names	Missions
AMICA	Measuring the shape and surface characteristics of asteroids
NIRS	Measuring the distribution and abundance of minerals on the surface
LIDAR	Create high resolution terrain profiles
XRS	Detection of X-ray fluorescence of surface elements

After the successful completion of the Hayabusa exploration mission, JAXA launched the Hayabusa 2 program, which was successfully launched in 2014 to collect samples from asteroid 162173 Ryugu and return the collected samples to Earth. In 2020, the sample return capsule successfully landed at the Woomera test site in Australia and obtained a total sample weight of 5.4 g [15]. This is the first time that humans have successfully completed multiple landing samples on an asteroid and the first time that samples from the subsurface of an asteroid have been collected. Hayabusa 2 is scheduled to fly over asteroid 2001 CC21 in 2026 and reach the next target asteroid 1998 KY26 in 2031.In terms of remote sensing, the Hayabusa 2 probe body carries four science payloads (excluding those included in the lander, etc.), including the Near Infrared Spectrometer (NIRS3), Thermal Infrared Imager (TIR), Optical Navigation Camera (ONC) and the Laser Altimeter (LIDAR). The Table 6 shows the Hayabusa 2 intrinsic science payloads and exploration missions.

Table 6 Names and Missions of Hayabusa II's payloads

Names	Missions
NIRS3	Obtain reflection spectra
TIR	Measuring heat radiation on the surface
ONC	Navigation and Multi-band Mapping
LIDAR	Estimation of asteroid topography, gravity and surface reflectivity

In addition, JAXA plans to launch the Destiny+ probe in cooperation with Germany in 2024 and to reach the vicinity of the near-Earth asteroid Phaethon around 2026 to analyze the composition of dust around it and to observe the speed and direction of the dust [16]. Japanese experts believe that Hayabusa 1 and Hayabusa 2 are only the beginning of its deep space exploration program, and Japan will continue to explore the solar system and the origin and evolution of life systematically and systematically by adhering to the concept of independent development. This shows that Japan hopes to use the world-leading research results achieved in asteroid exploration as an opportunity to rank among the world's advanced in the field of deep space exploration.

2.2.3 Europe actively promotes asteroid detection missions

Although Europe as the leader in comet detection, has no experience in asteroid detection, relying mainly on international cooperation to actively promote the implementation of asteroid detection missions.

On March 2, 2004, ESA's Ro-Setta-Philae probe was successfully launched, successfully flying close to the target asteroid "Stans" and making a comprehensive observation of the asteroid [17]. The Rosetta probe used the planetary borrowing technique, accelerated by the gravity of Mars once and Earth three times, and flew for 10 years before Philae landed on the surface of the target comet on November 12, 2014, and carried out an in-situ exploration.

In 2015, several research institutions, including the Observatoire de Paris, the Open University, the Chinese Academy of Space Technology, and the Beijing Institute of Technology, proposed the MarcoPolo-2D project and applied for the ESA Cosmic Vision M4 mission to complete the 2011 SG286 asteroid sample return, which was not selected for various reasons. Recently, European scientists have also proposed the main belt comet 133P detection mission and Ceres sample return mission.

2.2.4 Current status of asteroid detection in China

In the early 1990s, China initiated basic research related to asteroid detection. The Astronomical Observatory of the Chinese Academy of Sciences has carried out continuous astronomical observations of asteroids in the solar system for several decades, and has a good foundation in asteroid observation, asteroid orbit mechanics, ephemeris prediction and other aspects, and has carried out theoretical research on asteroid detection orbit design, faint and weak object identification and tracking and other technologies.

At 16:30 on December 13, 2012, the Chinese "Chang'e-2" probe achieved a precise close flyby of the asteroid Toutatis/4179 at a distance of about 7 million km from the Earth, and successfully obtained a high-resolution optical image of this asteroid for the first time in the world [18], which laid the necessary engineering practice foundation for China to carry out in-depth asteroid exploration.

From the high-resolution images of asteroid 4179 obtained by Chang'e-2, Chinese scientists studied the physical properties, surface characteristics, internal structure and possible origin of the asteroid, and found that Toutatis has an irregular shape and an uneven surface. The analysis yielded some new features on the surface of Toutatis that were not found in previous ground-based radar observations: a giant basin about 800 m in diameter at the end of the "body" and more than 50 distinct craters of different sizes on its surface, including two that were created near the same location in succession. The "neck" connects the "head" and "body" at a near-vertical angle; more than 30 areas with boulder features are present on the surface; and even smaller size craters can be distinguished from the images. More than 30 areas with boulder features are present on the surface, and even smaller linear structures can be distinguished from the images [19]. From its structural features, it can be inferred that Toutatis is probably a Close Approach double asteroid with a rubble pile structure, which may be formed by the slow approach of two independent small bodies, or as a result of the YORP effect, or caused by a massive impact.

In addition, China has started the implementation of an asteroid detection mission and is preparing to implement the NEO 2016HO3 sample return and the main belt comet 311P orbit detection project in the asteroid belt around 2025 to achieve orbital detection, attachment and sample return of NEOs, hoping to achieve three detection modes by detecting two types of targets in one launch [20].

2.3. Characteristics and trends of asteroid detection missions

From the asteroid detection programs that have been carried out and the planning of each country, it can be seen that asteroid detection has shown the following characteristics and trends.

(1) Shifting from flyby and companion detection to soft landing and sample return detection

In the early stage of asteroid detection, due to technical reasons, it is not yet possible to complete the surface landing and return detection of asteroids, but only flyby and companion detection.

However, because soft landing and sample return exploration can achieve greater scientific exploration results, with the development of technology, surface soft landing and sample return have been gradually realized. In addition to Hayabusa, there are several asteroid exploration missions under planning that require sample return.

(2) Multiple targets in one mission

In order to maximize the value of the mission, asteroid exploration usually detects multiple target asteroids. Some carefully designed flight orbits allow the probe to detect multiple asteroids, or to detect one or more target asteroids en route to other detection missions.

(3) Trying and Validating new technologies

Asteroid detection provides a good platform for the validation of new technologies. Combined with the demonstration of new technologies, asteroid detection can take into account more technical objectives and lay the technical foundation for the subsequent deep space exploration. Therefore, both the United States, Japan and Europe focus on the validation of new technologies, even if some of the scientific exploration value is sacrificed in some cases.

(4) Scientific objectives with more highlights and advanced technology driven

Asteroids and comets and other small solar system objects are considered to be the remnants of the formation of the solar system at the beginning of the material, can provide important clues for the origin of the planets, the evolution of the solar system and the origin of life and other basic scientific research. Around small bodies, scientists have raised frontier scientific questions such as "the origin of organic matter, the distribution and origin of water, the formation and evolution of dynamics, and the threat of collision of near-Earth asteroids," and these scientific questions strongly attract scientists' enthusiasm for exploration.

3. Major mission objectives for asteroid astrometry

Asteroid astrometry has multifaceted mission objectives. "The goal of small object detection is to break through the key technologies of surface sampling of weak gravitational objects, high precision and high autonomous navigation and control, small thrust transfer orbit, light and small ultra-high speed re-entry and return, multi-mode long-life electric propulsion, etc.; while achieving near-Earth asteroid proximity detection, sample return and main belt comet proximity detection, for asteroid and solar system origin and evolution, etc. provide detection data and real samples for frontier scientific research." Peijian Ye, technical advisor of the Fifth Academy of China Aerospace Science and Technology Group and academician of the Chinese Academy of Sciences, introduced [21].

3.1. Scientific Objectives

Small-object detection usually conducts multi-target detection in order to maximize mission value. China's planned Tianqian II asteroid detection mission has selected two small extraterrestrial object targets, 2016HO3 near-Earth asteroid and the main belt comet 311P, the former being the main target object for the sample return mission and the latter can be considered as an extended mission.

2016HO3 is an Earth co-orbital object with a diameter of 40-100 m and flexible launch and return windows, suitable for sample return and analysis of celestial sources. While the 311P comet nucleus is 320-580 m, the hot spots of research on it are focused on the main belt comet formation and evolution, and gas activity mechanism. At the same time, it is an Apollo-type near-Earth asteroid that will stay on Earth for the next 100 years, and is considered as a quasi-satellite of the Earth due to its unique orbit around the Sun that looks like it is also orbiting the Earth, with an average distance of about 20 million km from the Earth [22].

The selection of 2016HO3 as the sample return target for the 2016HO3 asteroid orbit schematic is further evidence of the high technological starting point of SkyQuest II. This is the smallest target object that humans have approached so far, with an estimated maximum diameter of only ~100 m, while the actual diameter may be only ~30 m. The smaller size of the object implies a more complex mission state. The 2016HO3 asteroid will rotate faster, which in turn leads to faster light changes and

a smaller sampling area available, requiring the probe to have the ability to reach with meter-level accuracy. The detection of asteroid 2016HO3 can further enhance the reach capability of complex objects, which can be more comfortable for other small object detection missions in the future; the determination of surface parameters of asteroids and the analysis of chemical composition of soil samples will further advance the theoretical research on the formation and evolution of asteroids and the solar system.

3.2. Project Objectives

For example, the SkyQuest II probe will carry a total of eight scientific payloads, including a medium-field color camera, a thermal radiation spectrometer, a visible infrared imaging spectrometer, a multispectral camera, a detection radar, a magnetometer, a charged and neutral particle analyzer, and a dust analyzer, to obtain global high-resolution images of the asteroid, its shape, surface topography, surface thermal radiation spectral images, visible to infrared spectral images The scientific data, such as asteroid surface level surface radar echoes, asteroid magnetic field, etc., are obtained [23].

The asteroid detection data obtained by the probe can be used to invert the topography, soil structure, thermal inertia, and other detailed data, and select the sampling area for sampling accordingly. After completing the sampling, the probe will perform sample transfer on the surface of the asteroid, that is, transfer the samples collected by the sampler to the sample storage container of the return module, after which it will fly away from the surface of the asteroid and then wait for the arrival of the return window to Earth.

The whole cycle of the asteroid detection mission can be divided into 13 phases, in order: 1. launch segment; 2. asteroid transfer segment; 3. asteroid approach segment; 4. asteroid rendezvous segment; 5. asteroid proximity segment; 6. asteroid sampling segment; 7. return waiting segment; 8. return transfer segment; 9. re-entry recovery segment; 10. main belt comet transfer segment; 11. main belt comet approach segment; 12. Main belt comet rendezvous segment; 13. Main belt comet close detection segment.

In the whole mission process, the implementation of each link compared to previous space exploration missions have put forward higher requirements for the maturity of the relevant technology, through the asteroid detection mission can verify the orbit design, autonomous sampling, measurement and control communications, autonomous navigation and control and other aspects of deep space exploration key technologies, through a mission to achieve a comprehensive breakthrough in the field of detection and core technology. The key technologies involved in asteroid exploration will be introduced in the next section.

4. Key technologies for asteroid detection

The "micro-gravity, uncertain" environmental characteristics of asteroids make the key technical requirements of asteroid detection missions different from those of Earth satellites and lunar probes, with higher level requirements and greater difficulty. The technical challenges facing asteroid detection are mainly reflected in the following.

4.1. Trajectory design

The orbits of asteroid probes can be divided into orbital, companion and transfer orbits. Due to the small mass of the target asteroid, even if the approach distance of the probe is small enough, it is difficult to be captured by the asteroid, and the asteroid is in a "companion" orbiting together. For the target asteroids with slightly larger mass, most of them have irregular coarse shape, weak gravitational force and uneven gravitational field distribution, fast rotation speed and irregular rotation axis, which make the orbit dynamics of the orbiting probe strongly nonlinear and make the design and analysis of the orbiting orbit very difficult. The design and optimization of the transfer orbit is undoubtedly also an important technology, and the optimal control problem is one of the

difficult points. For multi-target exploration, the orbit design requires even more repeated analysis and optimization.

In asteroid exploration missions, the search problem of launch opportunities is one of the key issues in mission design and planning. Interplanetary exploration missions usually require the completion of scientific exploration while minimizing the research cost and development time of the project. Based on these constraints and requirements, it is particularly critical technical difficulty to develop corresponding constraints (e.g., launch energy, launch time period, required velocity increment after launch, total velocity increment required for the mission, etc.) and to select the appropriate or optimal launch opportunity based on these constraints [24].

As more and more asteroid detection, flyby, orbiting, soft landing and sampling missions and objectives are successfully achieved, humans have gained more and more valuable information about asteroids, and the orbital design problems of long-range asteroid detection missions and the orbital dynamics and control of near-asteroid spacecraft have started to attract extensive attention from scholars in various countries. Among them, the problems of low energy interplanetary transfer based on the borrowed flight technology and the design of orbit and hover orbits based on the asteroid gravitational field modeling are very representative.

The following is an overview of the important research progress and results in both optimal launch opportunity search and transfer orbit and near-orbit design.

4.1.1 Optimal launch opportunity search

Selecting the optimal launch opportunity based on the constraints is the core problem of launch opportunity search for asteroid detection. To address this problem, several scholars have conducted studies. Sergeyevsky and Yin proposed a method to search for launch opportunities by plotting Pork-Chop diagrams of launch and arrival energies for direct transfer orbits [25], which is a classical method to find launch opportunities. Breakwell and Perko demonstrated the rationality of using the conic curve stitching method to calculate the design of interplanetary transfer orbits [26]. Battin [27] used the conic curve stitching principle to improve the computational model for plotting Pork-Chop diagrams.

Multi-body rendezvous lending orbits have many special advantages, such as: requiring less launch energy and enabling multiple missions in a single launch. Therefore, it has been intensively studied by many space agencies, in particular, researchers at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech) developed a tool for multi-body rendezvous orbit design and launch opportunity search using the conic curve stitching method, and used it to search for launch opportunities for missions such as Galileo and Voyager [28-32]. williams and Longuski proposed a method for designing multi-body rendezvous borrowing flight orbits [33], where the time period and target object for the initial launch are given, and a 3C match (i.e., an energy match between the fly-out and fly-in borrowing objects) is automatically searched for to find launch opportunities that satisfy the conditions. Subsequently, Moonish and Longuski proposed a launch opportunity search method for designing borrowed flight orbits with deep-space maneuvers [34], which is able to find all existing orbital solutions and launch opportunities with deep-space maneuvers by which the deep-space maneuver point will be designed such that the energy of the flight segment between the two gravitating bodies is minimized. The energy optimization problem for the whole orbit can be solved by the global optimization method proposed by D'Amario et al. [35-36]

4.1.2 Transfer orbit and near-orbit design

In the design of transfer orbits, the borrowed-force flight technology, which takes energy saving as a starting point, has attracted the interest of scientists. Up to now, the research results of the borrowed flight have focused on the discussion of the performance of various borrowed flight schemes and the analysis of the simple characteristics of the borrowed flight. Among them, the most representative one is the proposed technique of Earth-borrowed flight with deep space maneuver (ΔV-EGA). This technique states that the hyperbolic escape velocity at a planet can be changed in an interplanetary orbital design by a relatively small deep-space maneuver in a heliocentric large elliptical orbit. It was first proposed by Hollenbeck [37], while later Williams applied this method to

three Venus borrowing flights when performing orbit design for detecting Saturn [38]. Sims and Longuski [39-41] summarized the concept of ΔV-EGA and analyzed the properties of ΔV-EGA orbits, and finally, for reaching asteroids and Venus orbits with low emission energy are designed and analyzed.

In the field of asteroid spacecraft near-orbit dynamics, a wealth of research results has also emerged. The extensive application of the polyhedral modeling method in modeling the gravitational field of asteroids has enabled scientists to study more precisely the orbital dynamics of spacecraft in the vicinity of asteroids. Scheeres and Hudson et al. studied the orbital dynamics in the vicinity of the irregularly shaped asteroids 4769 Castalia and 4179 Toutatis as examples, respectively [42-43]. For the first time, the orbital characteristics of a spacecraft in the vicinity of an asteroid were analyzed in a more accurate model of the asteroid gravitational field, and the orbital dynamics of a spacecraft in the vicinity of a double asteroid system were studied by D. J. Scheeres et al [44-46], and the orbital characteristics of a spacecraft in a double asteroid system were analyzed in depth. For asteroids with uniform rotation, Sawai and Scheeres et al. analyzed the dynamics of the hovering orbit of a spacecraft in its gravity field [47-49]. For the control design problem and transfer orbit problem of the vehicle hovering orbit near the asteroid, Broschart et al. analyzed the design problem of the hovering orbit near the Itokawa asteroid by simulation [50-51]. Scheeres et al. further investigated the orbital control of the vehicle during the landing of the asteroid, using the Muses-C mission as an example [52-53].

Cui et al. analyzed the orbital characteristics and studied the stability of the orbit by using the Lagrangian equations of motion for the orbit near the asteroid [54]. Hu et al. analyzed the dynamics of the spacecraft near the asteroid and its effect on the orbit by using the NEAR and Muses-C missions as examples [55]. studied the constant thrust control method for asteroid companion flight and validated it with the simulation of the double asteroid system 1996FG3 [56]. Li and Qiao et al. designed the capture and escape orbits of the double asteroid system 1996FG3 by using a two-sphere model with a near-arch point Poincaré mapping [57]. case, the effect of various regenerative forces on its orbit was studied [58].

4.2. Autonomous sampling

The probe must be attached to or fixed relative to the surface of the asteroid when sampling. However, the surface gravity of the asteroid is very small, and if the probe is rigidly attached to the surface of the asteroid, the impact force generated during sampling will have an adverse effect on the probe, and if a flexible connection is used, the sampling equipment will be tested. At the same time, the sampling mechanism must be adapted to the working conditions of microgravity, and the sampling process must prevent contamination. In addition, the unknown composition of the asteroid makes drilling more difficult. Therefore, traditional methods such as drilling and excavation sampling are difficult to be applied in the sampling robot, and a sampling system with strong autonomy needs to be developed. Therefore, the asteroid explorer autonomous sampling mission mainly faces the following three difficulties.

(1) Complicated on-orbital conditions

The irregular shape, uneven gravitational field, and unstable rotation of asteroids make the dynamical environment in the vicinity of small objects extremely complex, which makes the probe orbit design and motion control difficult. Asteroids with diameters above 10 km are generally able to form orbits around them, but the orbits may become unstable within a short period of time due to irregular gravity and space uptake. It has been shown [59] that even similar initial states may produce three types of orbits: stable, escape, and collision with small bodies. For smaller sized asteroids, the effect of regressive forces such as solar photopressure is more pronounced, and even stable orbits cannot be formed. In addition, in a weak gravitational environment, there is no strict boundary between asteroid surface motion and orbital motion, and the probe may produce coupling of orbital motion with surface bouncing, sliding, and rolling during attachment. These complex dynamical environment effects put higher requirements on the navigation and control of asteroid attachment process.

(2) Lack of a priori physical information and unknown mechanism

Asteroid detection is not possible to accumulate target object data through multiple detection campaigns compared to planetary and lunar detection because of the wide variety of asteroids and their individual differences. Before the implementation of the detection mission, the physical properties of the target star can only be obtained through ground-based observations with large uncertainties, and the shape and gravitational field, orbit and other information obtained through observations may have large deviations from the actual situation.

The lack of a priori information imposes special requirements on the asteroid detection mission: on the one hand, the probe needs to observe the target star for a long time before attachment to continuously optimize the shape, gravitational field model, surface topography and other characteristic data; on the other hand, the uncertainty of the environment requires good robustness of the probe's navigation and guidance control algorithms to reduce the impact of inaccurate physical characteristics on the navigation and control accuracy. The impact of inaccurate physical parameters on navigation and control accuracy is reduced. At the same time, the autonomous sampling mission needs to develop a complete safety strategy for the threat of uncertainties such as small-body dynamics and surface topography.

(3) High landing-accuracy requirements

The precision requirements of asteroid attachment sampling missions are significantly higher than those of planetary landing missions. This is mainly due to its small and irregular size, lack of large flat area, and small attachment area. The weak gravitational field characteristic makes the escape velocity of asteroid small, so too large attachment velocity makes the probe easily bounce or even escape from the asteroid surface. In addition, for the attachment mission in the form of TAG, strict attitude control accuracy is also required because the attitude error of the detector during attachment will generate additional torque, which will lead to sampling failure.

To address the difficulties of complex dynamical environment, lack of a priori information and strict accuracy requirements, key technologies in the fields of modeling and characterization of dynamics near asteroids and autonomous intelligent attachment safety strategies for spacecraft need to be addressed. The following is an overview of the research results and progress in these two areas.

4.2.1 Asteroid dynamics modeling and motion characterization

The complex dynamical environment of asteroids poses special challenges to the autonomous attachment control of the probe, and it is necessary to model the dynamics and characterize the motion of asteroids.

4.2.1.1 Modeling the gravitational field of an asteroid

Gravitational field modeling is the core problem in modeling the dynamics near asteroids, and its methods mainly include two categories: the level approximation method and the 3D model approximation method [60]. The level approximation method uses an infinite number of levels to approximate the gravitational potential of the central object, and the most commonly used one is the spherical harmonic function model, which is simple and easy to express analytically, but is not applicable in some regions close to the surface of the asteroid. The ellipsoidal harmonic function model increases the convergence domain near the surface of the asteroid significantly by establishing the triaxial ellipsoidal envelope of the central object and describing its irregular shape by ellipsoidal harmonic coefficients [61]; the "internal gravitational field" modeling method proposed by Takahashi et al. [62] can solve the convergence problem, which is also in the form of spherical Herrera-Sucarrat et al. [63] expanded the gravitational potential of a non-spherical object in the form of spherical harmonic functions and spherical Bessel functions, and the choice of the expansion coefficients has a certain degree of freedom and can be determined in conjunction with the needs of dynamical analysis.

The three-dimensional model approximation method is a numerical method that uses a simplified three-dimensional model to approximate the irregular celestial shape and approximates the irregular celestial gravitational potential by numerical integration, and the commonly used models are the

triaxial ellipsoidal model and the polyhedral model. The triaxial ellipsoidal model treats the central object as a triaxial ellipsoid with uniform mass, and only the basic dimensional information of the central object is required, which is easy to calculate but less accurate. Werner et al [64] established a more accurate polyhedral model using polyhedra to approximate arbitrary irregular shapes with high accuracy and no convergence problem, which is suitable for accurate gravitational field modeling of arbitrarily shaped asteroids, but it is computationally intensive and does not give an analytical expression of the potential function. In practical applications, a suitable model or a combination of different methods should be chosen according to specific needs.

4.2.1.2 Analysis dynamical model near asteroids

The analysis of motion characteristics near asteroids includes both orbital motion and surface motion analysis.

Scheeres et al. [65-66] first studied the periodic orbit around an asteroid and its stability in a triaxial ellipsoid model, and then studied the periodic orbit in a uniform spin gravitational field based on a second-order quadratic model and gave stability criteria; Liu et al. [67-68] proposed a homogeneous rotating cube model, analyzed the position and stability of the dynamical equilibrium point based on this model, and derived the orbit around the period; Yu et al. [69] studied the dynamical equilibrium point and its period orbit family near the Kleopatra asteroid based on the polyhedral model; Li et al. [70] abstracted the Kleopatra asteroid as a dumbbell-shaped body and studied the dynamical equilibrium point and the period orbit under this model.

In the study of the surface motion of asteroids, Scheere et al. [71] performed a detailed analysis of the dynamical environment of the surface and nearby orbits of the Itokawa asteroid based on the data obtained from the Hayabusa mission and gave the surface escape velocity distribution, Guibout et al. [72] studied the surface motion characteristics of rotating ellipsoids and gave the equilibrium points of their surfaces and performed stability analysis; Liu et al. Liu et al. [73] studied the surface motion of a rotating cube, and gave the equilibrium point and the periodic orbit around the equilibrium point in the case of neglecting friction, and the condition that the mass does not escape from the surface in the presence of friction. These studies have deepened the understanding of the surface and orbital complex motion of asteroids.

4.2.2 Detector autonomous intelligent attachment security policy

Safety is a prerequisite for successful asteroid attachment detection. Rocks, pits, slopes and other obstacles on the asteroid surface need to be continuously detected and effectively avoided during the descent process; for special cases such as obstacles that cannot be avoided or actuator failure, a complete safety strategy needs to be developed. Among them, autonomous obstacle detection and avoidance and autonomous mission planning are the two key technologies to realize the autonomous intelligent attachment safety strategy.

4.2.2.1 Autonomous collision avoidance and evasion maneuner

The asteroid-attached autonomous obstacle detection methods can be divided into three types of detection methods based on passive sensors, active sensors, and multi-sensors information fusion according to the type of sensors used. The passive sensor-based obstacle detection method identifies obstacles by processing grayscale images acquired by optical cameras, which is generally simple in algorithm and fast in calculation, but only for a specific type or types of obstacles; the active sensor-based detection method identifies obstacles by processing altitude information (digital elevation map) acquired by radar or LiDAR, which is suitable for various types of obstacles and has high accuracy and fast in calculation, but The multi-sensors based obstacle detection method uses multiple sensors to detect obstacles separately, and then evaluates the target area comprehensively by information fusion method, which makes full use of the characteristics and advantages of different types of sensors, and can improve the tolerance to the conditions such as light and sensor failure. With the miniaturization of sensitizers and the improvement of on-board computer performance, the obstacle detection method based on multi-sensitive information fusion will be more developed and applied.

After the detector detects the obstacle during the descent and reselects the attachment zone, it needs to plan the avoidance trajectory according to the new target point and guide it to attach safely to the new target zone. The commonly used methods for obstacle avoidance guidance include classical polynomial methods and potential function methods. Among them, the potential function method characterizes the distribution of desired and undesired states by constructing a scalar potential function, and then derives the guidance law based on Lyapunov stability theory, which can integrate the obstacle threat and detector state, transfer energy and other factors, and can achieve better avoidance effect and fuel consumption performance.

4.2.2.2 Autonomous mission planning and task scheduling technology

Due to the complex environment and long mission duration, the asteroid probe actuators and other components are prone to failure; combined with resource constraints and control biases, the probe may not be able to effectively avoid obstacles after detection. In this case, the probe needs to terminate the current mission and re-plan in time; reconfigure with valid components or system redundancy to form a new execution capability in case of actuator failure; and enter the safe mode autonomously if necessary and wait for the ground upload command. Autonomous mission planning technology can automatically generate a safe sequence of activities to meet the mission objectives based on real-time environmental information and the detector's own state, and can reprogram the detector to move or remain in a safe area autonomously when a new threat emerges, thus greatly improving the detector's survivability.

Chien et al.[74] studied a spacecraft activity time sequencing and constraint processing method based on the timeline knowledge representation method, elaborated the common features of various timeline-based scheduling systems, and pointed out its reuse advantages at the algorithm and software levels; Cui et al. [75] proposed a domain-independent heuristic planning method based on the planning activity correlation, which effectively reduced the number of planning steps and backtracking steps and improve the planning efficiency. With further maturation of the technology, autonomous mission planning techniques will play a more critical role in future autonomous intelligent attachment missions of asteroids.

4.3. Navigation and Control

Due to the long distance, there is a time delay in communication between the asteroid probes and the Earth, and if they encounter occlusion from other stars, they may not be able to contact the ground for a longer period of time. Especially when the probe reaches the detection target, the mission time is short and the real-time requirement is higher. The response time based on ground measurement and control navigation is extended slowly, which is not conducive to the handling of unexpected emergencies. In addition, many parameters of the asteroid are unknown or the accuracy of ground determination is low, including inertial attitude, rotation rate and inertial tensor and other information need to be determined in orbit; the irregular shape of the asteroid, the non-uniform mass distribution and weak gravitational field will also have a strong uptake on the orbit of the approaching asteroid. Therefore, asteroid probes must have navigation and control systems with high autonomy, accuracy and robustness, and require more autonomy in the navigation system than lunar probes. In the following, the research results are outlined for both autonomous navigation techniques for irregular faint targets and guidance and control techniques in weak gravitational environments.

4.3.1 Autonomous Navigation Technology for Irregular Faint Targets

Navigation methods that rely solely on ground stations cannot meet the accuracy and real-time requirements of asteroid detection. However, the characteristics of asteroid irregularity and low albedo bring technical difficulties to autonomous optical navigation. Therefore, the autonomous navigation technology for irregular faint targets is a key technology in the navigation control of the probe, which mainly consists of the following two aspects.

4.3.1.1 Autonomous navigation technology for asteroid attachment

When the detector is far from the target star, it is difficult to obtain relative distance information and relies mainly on optical cameras for autonomous navigation. The U.S. Stardust mission developed a faint target center autonomous tracking technique to determine the relative state of the probe by extracting the target star centroid in the image [76]; Cui et al. [77] proposed a sequential image-based asteroid 3D model reconstruction and probe attitude measurement method, which synchronizes the target Zhu et al. [78] studied an autonomous navigation method for asteroid orbiting and attachment using terrain features as navigation landmarks, and analyzed the influence of the spatial distribution of landmarks on the navigation accuracy based on observable metrics, and gave the optimal navigation landmark selection The optimal observation scheme is given.

In the final attachment stage, the range information relative to the target surface is available, and the optical image combined with the range information can effectively improve the navigation accuracy. Johnson et al. [79] proposed a computer vision-based autonomous navigation method for small object attachment, using stereo vision and feature matching methods, combined with laser rangefinder range information to estimate the detector state, while obtaining a 3D topographic map of the target star surface. Shao et al. [80] proposed a feature matching method combined with inertial guidance information to create a virtual map using stitched images to determine the position of the probe in the coordinate system of the landing site even when the target landing site cannot be observed; Tian et al. [81] estimated the motion state of the probe by tracking the feature points in the sequence image and combining the distance information to the surface of the asteroid. method does not require the exact location of the feature points, thus improving the applicability of the method.

4.3.1.2 Self-attached navigation filtering technology

In addition, autonomous navigation techniques for irregular dark and weak targets include autonomous attached navigation filtering techniques. Navigation filtering algorithms can be classified into two categories according to the processing of the observation data: batch algorithms and recursive algorithms. Batch algorithms process a batch of observations acquired over a period of time to derive the optimal estimate for that period of time, such as the least squares method; recursive algorithms update the previous state based on real-time measurement data to obtain the latest state estimate, which is usually used for real-time processing in orbit, and commonly used algorithms include Kalman filter, extended Kalman filter, and traceless Kalman filter.

The dynamical model near the asteroid is strongly nonlinear and uncertain, which has a large impact on the accuracy and stability of the algorithm; the actual measurement data is also difficult to meet the white noise assumption, and when there are nonlinear influences on the measurement, the least squares method is no longer the unbiased optimal linear estimate, which will reduce the orbit determination accuracy. Pan et al. [82] proposed a batch orbit determination method based on a semi-parametric regression model, which can separate and eliminate the nonlinear influences in the observed data, thus achieving better orbit determination accuracy than the classical batch method; to address the problem of possible systematic or non-Gaussian errors in the observed information, Khutorovsky et al.[83] proposed a non-statistical orbit determination method with limited measurement error method, which can effectively reduce the effect of colored noise on the orbit determination filter. These improved methods provide important references for the filtering design of autonomous navigation for asteroid attachment.

4.3.2 Guidance control technology in weak gravitational environment

The gravitational coefficients of asteroids vary greatly, and for different types of asteroids, a targeted attachment scheme needs to be designed according to the environmental characteristics of the target star. The guidance control of hovering, descent and attachment process in weak gravitational environment is one of the key technologies.

4.3.2.1 Autonomous hover motion control

The weak gravitational properties of asteroids make their nearby natural orbits unstable and require active control to maintain stability; at the same time, they also allow detectors to obtain richer motion patterns under active control, and hovering motion is a unique form of motion in the weak gravitational environment of asteroids.

Sawai et al. [84] studied the hover control problem of an asteroid detector and proposed a closed-loop control strategy for the hovering motion of a uniformly spinning small object based on the altitude measurement, and analyzed the hovering points near a non-uniformly spinning asteroid; Broschart et al. [85] designed a hovering motion control law in the inertial system and the asteroid solid joint coordinate system to realize the hovering motion control at a given altitude and region. Zeng [86] analyzed the feasibility of applying a solar sail for hovering detection of dumbbell-type asteroids, and gave a feasible hovering detection area. The solar sail relies only on the solar pressure effect to generate control force, which can maintain the orbit stability for a long time without fuel consumption and has a unique advantage in asteroid hover control.

4.3.2.2 Autonomous descent guidance control

Considering the differences in gravitational coefficients, different control methods should be used for the attachment of different types of asteroids. In terms of impulse maneuver control, Cui et al [87] proposed a closed-loop impulse maneuver control method for autonomous asteroid attachment; Cui et al [88] proposed an impulse maneuver guidance law based on the analysis of the trajectory shape of small object attachment based on the guidance variables.

Lantoine et al. [89] proposed a combination of direct and indirect methods to ensure the accuracy and reduce the solution time; Gao et al. [90] improved the overall performance of the navigation control system by optimizing the landing trajectory to ensure the observability of the system state; Hu et al. [91-92] proposed a small object attachment trajectory anti-difference optimization method to reduce the trajectory tracking error while optimizing the fuel consumption; Ren et al. [93] improved the reliability of the optimization results by considering the uncertainty of the small object mass distribution in the attachment trajectory optimization problem based on the reliability theory. In terms of explicit feedback guidance, Hawkins et al. [94] designed an autonomous asteroid attachment feedback guidance method based on zero-controlled displacement deviation/zero-controlled velocity deviation with reference to Earth re-entry guidance; Furfaro et al. [95] proposed a multi-slip mode surface descent guidance method based on higher-order sliding mode control theory with good robustness to bounded unmodeled upturns.

4.3.2.3 Autonomous attachment dynamics control

Due to the weak gravitational pull of asteroids, probes are prone to bounce when attached. Some missions have designed TAG attachment methods that allow the probe to make brief contact with the surface of the asteroid and to ascend and depart immediately after sampling. For long-stay attachment methods, anchoring mechanisms are generally required to secure the probe to the surface of the target star. And once the probe bounces, achieving safe attachment through active control is a feasible solution, which requires the study of the mechanism of probe bouncing motion on the surface of the asteroid and its control method.

Sawai et al. [96] analyzed the dropping dynamics of artificial beacons for the Hayabusa mission and simulated the bouncing process of beacons on the surface of asteroids; Bellerose et al. [97] studied the dynamics mechanism and control method of jumping rovers on the surface of asteroids, gave the estimation method of the bouncing motion time and distance of rovers, and designed the corresponding sliding mode control law; Yu et al. [98] analyzed the surface dynamics of the asteroid based on the polyhedral model, and studied the relationship between the descent trajectory of the surface rover and the release altitude.

4.4. Propulsion Technologies

In the asteroiddeep space exploration mission represented, propulsion technology is an important factor limiting capability of spacecraft. Deep-space exploration missions have pulled the development of multiple propulsion technologies, and the advancement of propulsion technologies has provided more options for the expansion of deep-space exploration missions. The requirements for spacecraft and propulsion systems vary greatly from one exploration mode to another, and the requirements for propulsion systems in asteroid exploration missions can be summarized in the following aspects.

First, the propulsion system is required a high specific impulse. Deep space exploration missions need to get rid of the gravitational force of various types of stars, which requires the probe to have a high velocity increment, and this velocity increment is obtained from two sources: one is provided by the interplanetary borrowing flight, and the other is provided by the spacecraft's own propulsion system. The former requires many constraints to be met, often at the cost of more time spent; the latter requires the propulsion system to have a higher total impulse, which can only be achieved by a higher specific impulse when the launch weight is limited and the propellant carrying capacity is constrained.

Second, the propulsion system is required to provide suitable thrust. For the need for rapid orbit adjustment, rapid braking, controlled landing on the probe object, or the need for sampling after takeoff and return and other types of missions, the spacecraft is required to provide a large enough thrust to meet the probe mission requirements mentioned above, the specific thrust required to determine the size of the mission characteristics and gravitational conditions.

Again, the propulsion system is required to have a certain adaptability to energy. Many deep space exploration missions in the entire detection cycle, the spacecraft and the sun's distance will change dynamically, for the propulsion system relying on external energy, especially solar electric propulsion system, must have the ability to adapt to changes in energy, so that the engine can work properly in different power ranges.

In order to meet the above needs, deep space exploration class spacecraft propulsion systems are often a combination of multiple types, in different stages of work, the use of different propulsion technologies, so that they can play the maximum advantage. The following is an introduction to the application and research progress of two typical propulsion technologies, electric and nuclear propulsion technologies.

4.4.1 Electric propulsion technology

The vigorous development of deep space exploration missions cannot be carried out without the support of space propulsion technology. In the process of deep space exploration mission, chemical propulsion technology has made great progress, and its main feature is that it can provide large thrust in a relatively short period of time, and it is the most widely used and mature space propulsion technology. However, with the continuous development of deep space exploration, the main shortcomings of traditional chemical propulsion gradually revealed, including small engine specific impulse, low fuel utilization efficiency, etc. Due to the low energy density of chemical propulsion itself, the current jet speed is close to its limit, and there is little room for improvement. Future deep space exploration missions require more payloads and higher propulsion speeds to allow multi-target exploration of a wider space. This requires the study of new propulsion technologies to supplement and replace traditional chemical propulsion technologies.

Electric propulsion is a propulsion technology that uses electrical energy to heat, ionize, and accelerate propellants to form high-speed jets to generate thrust, and its specific impulse is generally one order of magnitude higher than chemical propulsion. Due to its unique advantage of high specific impulse, a high total impulse can be obtained by using a limited amount of propellant, so it has been widely used in deep space exploration missions. The current application of electric propulsion system, usually by solar energy to provide energy, with the change in the detection distance, the size of the energy provided by solar energy is also changing, which requires such electric propulsion system should have the ability to adapt to changes in energy.

Compared with conventional chemical propulsion systems, electric propulsion systems have some significant features, mainly including:

(1) small thrust, generally in the order of tens to hundreds of m N, and therefore generally longer reorbiting time.

(2) high specific impulse, generally thousands of seconds, an order of magnitude higher than chemical propulsion, which can effectively reduce the consumption of work material.

(3) long service life, generally thousands of hours of normal operation, with a high degree of reliability.

(4) maneuvering several times, thus realizing multiple track changes and intermittent track changes.

(5) Low vibration caused, and low vibration interference to the detector during ignition operation.

Electric propulsion technology has been successfully applied in the past deep space exploration missions. For example, the electric propulsion system of the Dawn probe is an ion electric propulsion system with three diameter ion thrusters for orbit transfer [99]; the electric propulsion system of the Hayabusa probe is a microwave ion electric propulsion system with four microwave ion thrusters, which can adapt to solar power variations [100]; Deep-space1 uses a variable power ion propulsion system as the main propulsion to verify a number of new technologies, including electric propulsion technology [101].

In summary, electric propulsion is suitable for the main propulsion task of deep-space exploration because of its outstanding advantages of high specific impulse, which can greatly reduce spacecraft fuel consumption and increase the load carrying capacity. The current electric propulsion for deep space exploration applications mainly relies on solar energy to provide energy, and ion and Hall electric propulsion technologies are the most widely used and adapted to different mission requirements, each with its own advantages. Due to the special needs of deep space exploration, solar electric propulsion should be able to adapt to the characteristics of the solar sail output power changes, and can work reliably under different power.

4.4.2 Nuclear Power Propulsion Technology

The most common way of energy supply for deep space probes is solar cell array power generation, and with the increase of power demand and the growth of distance to the sun, the effectiveness of solar power generation is significantly reduced and is no longer applicable for high-power missions above 100kW. Nuclear energy is the inevitable development direction of future space energy, and countries have also conducted long-term and in-depth exploration of nuclear power in space, in this context, the research on space nuclear propulsion technology was generated.

Nuclear electric propulsion system to nuclear fission, nuclear fusion, radioisotope decay, antimatter annihilation and other processes to produce thermal energy into electrical energy and provide electric propulsion system, relative to the nuclear thermal or chemical type of high thrust low efficiency propulsion, nuclear electric propulsion for low thrust high specific impulse propulsion, nuclear reactors, radioisotope generator of high power density characteristics and electric propulsion of high efficiency characteristics of the combination, can make the spacecraft free from the The combination of the high power density characteristics of nuclear reactors, radioisotope generators and the high efficiency characteristics of electric propulsion can free spacecraft from dependence on solar energy and can generate several orders of magnitude higher thrust than solar electric propulsion. Space nuclear electric propulsion technology has wide application prospects in the field of long-range deep space exploration.

In recent years, major space powers have been vigorously conducting research in this technology area. In 2003, NASA launched the "Prometheus" research program, which planned to develop a space nuclear propulsion system and use it first for the "Jupiter Icy Satellite Orbiter" (JIMO) mission. [102]. In 2009, Russia officially approved the development of a spacecraft with a MWe class nuclear propulsion system [103]. In 2015, EAS proposed the DiPoP (Disruptive Space Power and Propulsion Technology) project and the MEGAHIT (Megawatt Efficient Space Power System) program to implement its vast deep space exploration program [104-105].

The space nuclear propulsion system consists of five major subsystems: space nuclear reactor subsystem, thermoelectric conversion subsystem, high-power space thermal emission subsystem, power management and distribution subsystem, and high-power electric propulsion subsystem, among which the space nuclear reactor subsystem and high-power electric propulsion subsystem are the most critical. In space nuclear reactors, the United States has implemented several R&D programs and formed a strong technical reserve [106-108]. Russia (including the former Soviet phase) has developed a variety of power supply models and launched a total of 37 space nuclear reactor power supplies into space [109]. In terms of high-power electric propulsion technology, there are various technological routes, including power ion, high-power Hall, magnetic plasma thruster (MPDT), and variable specific impulse magnetic plasma thruster (VASIMR).

In summary, space nuclear propulsion is the best choice for human to carry out long-range and large-scale deep space exploration missions due to its advantages of high power, high specific impulse and large thrust, which can achieve rapid detection of astronomical objects in the solar system and is also suitable for future exoplanet exploration. The space powers represented by the U.S. and Russia have been conducting space nuclear propulsion research for many years, and have carried out substantial research in the design of nuclear propulsion systems, space nuclear reactors and high-power electric propulsion and other key subsystems, and have proposed future development plans. Nuclear electric propulsion technology will be widely used in future deep space exploration missions such as asteroid detection.

5. Summary

With the development of deep space exploration technology, asteroid detection has become one of the important contents of deep space exploration in the 21st century. Asteroid detection missions have multiple theoretical and practical perspectives, including solar system formation theory research, material research, Earth disaster warning, spacecraft orbit warning, etc. Until now, major spacefaring countries such as the United States, the European Union, China and Japan have successfully carried out several asteroid detection missions and achieved remarkable results, providing important references for the implementation of future asteroid detection missions. Asteroid detection missions will be carried out around two levels of science and engineering objectives, the former is mainly the study of asteroid and solar system formation and evolution, while the latter includes the verification of some key technologies in the field of deep space exploration.

These key technologies are embodied in various fields such as orbit design, autonomous sampling, navigation control and propulsion technology. In orbit design, the design of transfer trajectory, approach orbit and companion orbit will be the key to make the asteroid reach the mission target in the most time- and energy-efficient way; in autonomous sampling, the dynamics modeling and motion characterization of small objects and the design of autonomous intelligent attachment safety strategy of the probe will determine whether the sampling can be successfully carried out; in navigation control, the autonomous navigation technology for irregular and faint targets and the navigation control technology for weak gravitational environment will determine whether the sampling can be successfully carried out. In navigation control, autonomous navigation technology for irregular and faint targets and guidance control technology in weak gravitational environment will affect the normal operation of the probe in deep space; in propulsion technology, electric propulsion technology is widely used in deep space exploration, while nuclear propulsion technology is a new field born to meet the more demanding needs of deep space exploration. The key technologies in these fields will be further validated and applied in future asteroid exploration missions, bringing better returns for human deep space exploration.

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