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Dayi Wang · Maodeng Li · Xiangyu Huang · Xiaowen Zhang

Spacecraft Autonomous Navigation Technologies Based on Multi-source Information Fusion

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Dayi Wang
Beijing Institute of Spacecraft System Engineering
CAST
Beijing, China

Xiangyu Huang
Science and Technology on Space Intelligent Control Laboratory
Beijing Institute of Control Engineering
CAST
Beijing, China

Maodeng Li
Science and Technology on Space Intelligent Control Laboratory
Beijing Institute of Control Engineering
CAST
Beijing, China

Xiaowen Zhang
Science and Technology on Space Intelligent Control Laboratory
Beijing Institute of Control Engineering
CAST
Beijing, China

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Series Editor's Preface

China's space technology and science research have earned a place in the world, but have not been compiled into a series of systematic publications yet. In 2018, the series *Space Science and Technology* edited mainly by me and co-authored by the leading figures in China's space industry was published in China, when China Academy of Space Technology was celebrating the 50th anniversary of its founding. This collection contains 23 volumes in Chinese, only 10 of which have been selected, recreated, and translated into English. In addition, each English volume has been recreated at the suggestion of the Springer, by deleting the contents similar to Springer's existing publications and adding the contents that are internationally advanced and even leading, and bear both Chinese characteristics and worldwide universality. This series fully reflects the knowledge and engineering experience recently accumulated by Chinese scientists and engineers in space technology and science research.

As Editor in Chief of this series, I always insist that this collection must be of high quality, either in Chinese version or in English version. First, the contents of this series must be condensed and sublimated based on the combination of theory and practice, so as to provide both a theoretical value and engineering guidance. Second, the relationships between past knowledge and state-of-the-art and between other people's work and our own new findings should be properly balanced in the book contents to ensure the knowledge systematicness and continuity and to highlight new achievements and insights. Each volume intends to introduce the readers something new. Third, the English version should be customized for international exposure and play a solid supporting role for China to contribute to the world's space field.

This collection consists of 10 volumes, including *Spacecraft Thermal Control Technologies, Spacecraft Power System Technologies, Spacecraft Electromagnetic Compatibility Technologies, Technologies for Spacecraft Antennas Engineering Design, Satellite Navigation Systems and Technologies, Satellite Remote Sensing Technologies, Spacecraft Autonomous Navigation Technologies Based on Multi-source Information Fusion, Technologies for Deep-Space Exploration, Space Robotics, and Manned Spacecraft Technologies.*

Spacecraft Autonomous Navigation Technologies Based on Multi-source Information Fusion takes deep-space spacecraft as application object and focuses on the method of multi-source information fusion and its application to autonomous navigation in the deep-space explorations. This volume focuses on estimation theory, fusion algorithm, performance analysis, autonomous navigation technique based on information fusion, and ground simulation test technique.

This volume is the fruit of the author's painstaking efforts and wisdom borne in his working practice. He has long been committed to the research of autonomous navigation technology of deep-space spacecrafts. He participated in the design of autonomous navigation scheme of Chang'e lunar exploration project. He has solved a series of key technical problems and made a number of breakthroughs. The autonomous navigation scheme for lunar exploration based on the research results of this volume has been successfully applied to the exploration missions of Chang'e series and will be applied to subsequent lunar and Mars exploration missions. Therefore, high practical value is one of the features of this volume.

Another feature of this volume pays close attention to the organic integration and later application of estimation theory, fusion theory, and autonomous navigation technology. The book follows the principles of integration and simplicity, gradually unveils the theory of estimation fusion, and builds a bridge between theory and engineering technology to help readers embark on the road leading to spacecraft autonomous navigation.

The publication of this series adds a new member to the international family of space technology and science publications, and intends to play an important role in promoting academic exchanges and space business cooperation. It provides comprehensive, authentic, and rich information for international space scientists and engineers, enterprises and institutions as well as government sectors to have a deeper understanding of China's space industry. Of course, I believe that this series will also be of great reference value to the researchers, engineers, graduate students, and university students in the related fields.

Peijian Ye
Academician
Chinese Academy of Sciences
Beijing, China

Preface

Spacecraft autonomous navigation refers to the technology of determining the spacecraft's position and velocity in real time using onboard equipment without relying on the ground support. Autonomous navigation based on multi-source information fusion is an autonomous navigation method that fuses multiple information sources (multiple observation targets, multi-sensors, prior knowledge, etc.). Autonomous navigation technology based on multi-source information fusion has great application prospects in the field of deep-space exploration. Compared with a single sensor and a single observation source, it can enhance information redundancy, extended time, and space coverage, and reduce information acquisition costs. This book focuses on the theory and methods of multi-source information fusion and its application in autonomous navigation for deep-space exploration. The content involves estimation theory, fusion algorithms, performance analysis, information fusion autonomous navigation technology, ground simulation test technology, etc.

The book is divided into four parts that consist of 12 chapters. The first part (Chap. 1) introduces basic concepts of autonomous navigation and summarizes main autonomous navigation methods for deep-space spacecraft. The second part (Chaps. 2–4) consists of estimation theory, fusion algorithm, and performance analysis. These chapters constitute the theoretical basis of multi-source information fusion autonomous navigation technology. The third part (Chaps. 5–11) presents time and coordinate systems, dynamic models and environment models, inertial navigation technology, optical autonomous navigation technology, optical/pulsar integrated autonomous navigation technology, altimeter- and velocimeter-/optical-aided inertial navigation technology, and simulation testing techniques of the autonomous navigation based on multi-source information fusion. Chapter 12 is the fourth part, which is the summary of the whole book and the prospect of technological development trends.

The main features of this book are as follows: (1) The basic estimation and fusion theory are emphasized in this book. Its main procedure is to consider a general situation first and then derive solutions for some then specific situations, which is easy for grasping the problem. In addition, when describing the basic theory of information fusion, this book will give as many different forms as possible, which will help researchers to consult and establish different forms of conceptual connections. (2) The autonomous navigation technology of the spacecraft involved in this book emphasizes practical application, some of which have been applied to actual flight missions such as Chang'e 3 and Chang'e 4 soft landing missions and will also be applied to subsequent Chinese planetary landing missions. (3) This book focuses on the combination of estimation, fusion theory, and autonomous navigation technology. Therefore, when narrating the application of the technology, a brief review of related theoretical methods will be made to facilitate the reader to establish the connection between theory and application.

Beijing, China Dayi Wang

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About the Authors

Dayi Wang Dr. Wang Dayi, a Professor and doctoral supervisor, born in November 1973, is currently the deputy director and commander in field of space science and exploration of Beijing Institute of Spacecraft System Engineering. He is a winner of the National Science Fund for Distinguished Young Scholar and National Defense Fund for Outstanding Young Scholar. He is also selected by National Ten Thousand Talent Program, and serves as the Chief Technology Expert of 973 Project. He won the China Association for Science and Technology Qiu Shi Outstanding Young Scholar Award, was honored with the Prize for Scientific and Technological Innovation of Ho Leung Ho Lee Foundation, and was selected by National Million Talent Project, in 2015, 2016, and 2017, respectively. He is a national outstanding mid-aged expert entitled to the special government allowance of the State Council.

Dr. Dayi Wang has carried out innovative research works and solved a series of key technical problems in the field of spacecraft autonomous navigation and autonomous diagnosis and reconfiguration technology, making contributions to the successful flight test of Chang'e lunar probes and other spacecrafts.

Maodeng Li received the B.S. and Ph.D. degrees in aerospace engineering from Harbin Institute of Technology, Harbin, P.R. China, in 2006 and 2011, respectively. From September 2011 to August 2013, he was a postdoctoral research associate in Beijing Institute of Control Engineering (BICE). Since August 2013, he has been with Science and Technology on Space Intelligent Control Laboratory of BICE as a senior engineer. His current research areas include spacecraft autonomous navigation and GNC design for planetary landing missions.

Xiangyu Huang received the B.S. and Ph.D. degrees in aerospace engineering from Harbin Institute of Technology, Harbin, P.R. China, in 1999 and 2005, respectively. Since August 2005, he has been with Science and Technology on Space Intelligent Control Laboratory of Beijing Institute of Control Engineering (BICE), where he is currently Professor and Senior Research Specialist. He was GNC Engineer of the Chang'e-3 lunar landing mission, and his current research area is the GNC design for planetary landing missions. He won one National Technological Innovation prize (second class) and three ministerial-level prizes (first class).

Xiaowen Zhang received his B.S. degree from Harbin Engineering University, Harbin, China, in 2005, and his M.S. degree in control theory and control engineering from China Academy of Space Technology, Beijing, China, in 2009. He is currently Senior Engineer at Beijing Institute of Control Engineering. His research interest covers GNC system design of deep-space exploration missions and spacecraft autonomous navigation and guidance technology. He won one first-class ministerial-level prize.

Acronyms

APSR	Accretion-Powered Pulsars
ASG	Air Suspension Gyroscope
AXP	Anomalous X-ray Pulsar
BCRS	Barycentric Celestial Reference System
BLS	Batch Least Square
BLUE	Best Linear Unbiased Estimation
CDF	Cumulative Distribution Function
CF	Centralized Fusion
CGRO	Compton Gamma Ray Observatory
CI	Covariance Intersection
CKF	Cubature Kalman Filter
DARPA	Defense Advanced Research Projects Agency
DPS	Deep-Space Positioning System
DR	Dead Reckoning
DTG	Dynamically Tuned Gyroscope
EKF	Extended Kalman Filter
ESG	Electrostatically Suspended Gyroscope
ET	Ephemeris Time
FDIR	Fault Detection Isolation Recovery
FOG	Fiber Optical Gyroscope
FOM	Figure of Merit
GDOP	Geometric Dilution of Precision
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
HMXB	High-Mass X-ray Binary
HRG	Hemispherical Resonator Gyroscope
HRSC	High-Resolution Stereo Camera
HXMT	Hard X-ray Modulation Telescope
ICRF	International Celestial Reference Frame
IMM	Interacting Multiple Model

IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ISAS	Institute of Space and Astronautical Science
ITS	Impactor Targeting Sensor
JD	Julian Date
JDL	Joint Directors of Laboratory
JPL	Jet Propulsion Laboratory
KF	Kalman Filter
LEC	Linear Equality Constraint
LFG	Liquid Floated Gyroscope
LIDAR	Light Detection and Ranging
LMMSE	Linear MMSE
LMXB	Low-Mass X-ray Binary
MAP	Maximum A Posteriori
MAPS	Multi-autonomous Positioning System
MDL	Minimum Description Length
MEMS	Microelectromechanical System
MF	Measurement Fusion
MICAS	Miniature Integrated Camera and Spectrometer
MJD	Modified Julian Date
ML	Maximum Likelihood
MMAE	Multiple Model Adaptive Estimation
MMSE	Minimum Mean Square Error
MOEMS	Microoptoelectromechanical Systems
MOLA	Mars Orbiter Laser Altimeter
MRI	Medium-Resolution Imager
MRO	Mars Reconnaissance Orbiter
MSE	Mean Square Error
MSL	Mars Science Laboratory
MSP	Millisecond Pulsar
NASA	National Aeronautics and Space Administration
NICER	Neutron star Interior Composition Explorer
NRL	Naval Research Laboratory
PDF	Probability Density Function
PDOP	Position Dilution of Precision
PF	Particle Filter
PINS	Platform Inertial Navigation System
PMF	Probability Mass Function
PSR	Pulsating Source of Radio
QEC	Quadratic Equality Constraint
RLG	Ring Laser Gyroscope
RPSR	Rotation-Powered Pulsar
SAW	Surface Acoustic Wave
SEXTANT	Station Explorer for X-ray Timing and Navigation Technology
SINS	Strapdown Inertial Navigation System

SSB	Solar System Barycenter
ST	Sidereal Time
STK	Systems Tool Kit
TAI	International Atomic Time
TCB	Barycentric Coordinate Time
TCG	Geocentric Coordinate Time
TCP/IP	Transmission Control Protocol/Internet Protocol
TDB	Barycentric Dynamical Time
TDOA	Time Difference of Arrival
TDOP	Time Dilution of Precision
TDT	Terrestrial Dynamical Time
TOA	Time of Arrival
TT	Terrestrial Time
UKF	Unscented Kalman Filter
USA	Unconventional Stellar Aspect
UT	Universal Time
UTC	Coordinated Universal Time
VSMM	Variable Structure Multiple Model
WLS	Weighted Least Square
XNAV	X-ray Pulsar-Based Navigation

Chapter 1
Introduction

Navigation generally refers to the determination of the orbit (position and velocity) and attitude parameters of a vehicle (or a moving body) relative to a coordinate system at a given time. In general, spacecraft navigation refers only to the determination of orbit parameters. In general, the navigation relying on only the onboard measuring and computing devices rather than ground support is referred to as spacecraft autonomous navigation, while the spacecraft autonomous navigation realized by the fusion processing of multiple information sources (multiple observed objects, multi-sensor measurements, priori knowledge, etc.) is called multi-source information fusion-based autonomous navigation.

Autonomous navigation is the core technology of autonomous spacecraft operation and is the premise for a spacecraft to autonomously control its orbital attitude and perform its space missions such as lunar soft landing and in-orbit services. Autonomous navigation can not only reduce the dependence of a spacecraft on ground control and improve its independent survivability, but also relieve the restriction on the layout of ground telemetry, track, and command (TT&C) stations posed by the limited land area and enhance the spacecraft capability of completing a task outside the TT&C area.

Compared with the autonomous navigation based on a single sensor and a single observed object, the autonomous navigation based on multi-source information fusion is an important development direction in the aerospace field, which can provide better time and space spreadability and more information redundancy, and enhance the autonomous capability of the system. A deep-space exploration spacecraft (hereinafter referred to as "probe" or "deep-space probe") generally flies a long distance and a long time in an almost unknown environment, with a particularly urgent need for a high degree of navigation autonomy. Taking deep-space exploration missions as the background, this book focuses on the theories, methods, and technical issues related to the autonomous navigation based on multi-source information fusion.

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1.1 Autonomous Navigation Technology

Spacecraft navigation can be divided into absolute navigation and relative navigation depending on the choice of the selected reference coordinate system. In general, the determination of motion parameters relative to the fixed coordinate system of a space target is called relative navigation, while the determination of motion parameters relative to an inertial system is called absolute navigation. Therefore, spacecraft autonomous navigation can also be divided into autonomous absolute navigation and autonomous relative navigation. It is in the research domain of relative navigation to determine the position and velocity of the tracking spacecraft relative to the target spacecraft in an in-orbit service for such a target. From the perspective of measurement principle, spacecraft autonomous navigation can be mainly divided into inertial navigation, autonomous optical navigation, autonomous navigation based on pulsars, and the navigation based on artificial beacons (global satellite navigation system, inter-satellite measurement, etc.). Strictly speaking, the navigation based on artificial beacon is not totally autonomous navigation and will not be discussed here. Next, only inertial, optical, and autonomous navigation based on pulsars will be introduced.

1.1.1 Inertial Navigation

Inertial navigation system (INS) is an autonomous navigation system based on dead reckoning (DR), which consists of a set of inertial devices and a navigation processor. Inertial devices, also called inertial measurement unit (IMU), mainly include three orthogonal gyroscopes and three orthogonal accelerometers. The gyroscopes are used for measuring the inertial angular velocity of a vehicle, and the accelerometers are used for measuring the specific force acting on the vehicle (also known as "non-gravitational acceleration"). In addition, through the numerical integration of IMU measurements, spacecraft position, velocity, and attitude can be determined.

Neither relying on external information nor radiating energy to the outside, INS has many advantages, such as high short-time accuracy, high bandwidth, complete navigation information, good concealment, and strong insusceptibility to disturbance. INS is not only used in spacecrafts, but also widely used in other moving vehicles. It is the most important navigation in aerospace, aviation, and sailing. However, the only weakness of INS is that its navigation accuracy will decrease over time.

1.1.1.1 Gyroscope

Gyroscope ("gyro" for short) is a device that uses the conservation of momentum to sense the direction. According to their working principle, the existing gyros fall into two categories [1]: those based on classical mechanics, such as mechanical gyros and vibratory gyros; and those based on modern physics, such as laser gyros and fiber-optic gyros.

1.1.1.2 Accelerometer

Accelerometers can be divided into mechanical accelerometers and solid-state accelerometers. Among them, the basic principle of a mechanical accelerometer is to connect the detected mass block with its shell through a spring. Under the steady state, the force acting on the mass block will balance with the spring tension, and the net elongation of the spring can be used to measure the received force proportional to the acceleration. Solid-state accelerometers include [2] surface acoustic wave (SAW) accelerometers, silicon accelerometers, quartz accelerometers, etc. With the development of MEMS technology, MEMS accelerometer emerged. There are two types of MEMS accelerometers: one works in the same way as mechanical accelerometers and the other is based on the principle of solid-state accelerometers. Like MEMS gyroscope, MEMS accelerometer is also small in size, light in weight, low in power consumption and cost, and fast in start-up, but poor in accuracy.

1.1.1.3 Inertial Navigation System

According to the different ways of installation of inertial devices in the vehicle, inertial navigation systems fall into two types, e.g., platform inertial navigation system (PINS) and strapdown inertial navigation system (SINS). The inertial devices of PINS are mounted on the platform and thus isolated from the external rotation. By installing universal joints, the platform can be aligned with the navigation coordinate system. The gyro on the platform detects the rotation signals, which are transmitted to the torque motor that rotates the universal joints to compensate the external rotation, thus keeping the platform in alignment with the navigation coordinate system. Once the included angle between universal joints is obtained, the information on vehicle attitude can be acquired. After compensating for the gravitational acceleration, the accelerometer signals can be integrated to obtain the velocity value and integrated again to obtain the position information.

The SINS system has no physical platform, with gyro and accelerometer directly mounted on the vehicle. Compared with PINS, this system is much smaller in size, weight, and cost. However, its inertial device has lower measurement accuracy due to the fixation on the vehicle, whose vibration and shock directly affect the component and the bad working environment. In addition, the accelerometer outputs in the SINS are the components in the vehicle coordinate system, which need to be converted into navigation coordinate system. As a result, the calculation becomes more complicated. However, with the rapid development of inertial devices and electronic computer technology, the above problems no longer restrict the development of SINS and this system has been widely used in the navigation field. Unless specially specified, all the inertial navigation systems in this book are SINS.

1.1.2 Autonomous Optical Navigation

As early as in the 1960s, institutes began to study the autonomous navigation technology for deep-space exploration, and gradually tested and applied it in missions. With continuous improvement in the performance and reliability of onboard computers, sensors, and actuators, the technology of autonomous navigation has been successfully applied to more and more deep-space missions, providing an important guarantee for improving the survivability of deep-space spacecrafts. So far, deep-space exploration relies mainly on autonomous optical navigation. The working principle of autonomous optical navigation is to identify the targeted celestial bodies with known ephemeris as navigation beacons, and then plan and process the observed optical images of the beacon, and finally derive the position, velocity, and attitude of the spacecraft from the known information [3, 4]. Key technologies of autonomous optical navigation include [3] the selection and planning of navigation beacons, the technology of optical navigation sensor, the technology of navigation information acquisition and processing, the navigation filtering algorithm, and other technologies. The main factors affecting the accuracy of autonomous optical navigation include state priori knowledge, unmodeled acceleration, sensor pointing error, measurement frequency, ephemeris errors of navigation beacons, random noise in measurement, and other systematic errors.

1.1.2.1 Deep-Space Autonomous Optical Navigation

The first application of autonomous optical navigation in deep-space dates back to 1960s. Battin et al. [5] proposed the autonomous navigation theory of interstellar spacecrafts, that is, to calculate the spacecraft position by measuring the angle between line of sight (LOS) of the known celestial body (such as the sun, earth, moon) and the star in distance, and using the ephemeris of that celestial body. The Apollo 8, launched in 1968, applied this theory and used sextant as the optical sensor of autonomous navigation system, so as to verify the feasibility of spacecraft autonomous navigation for the first time. The sextant on Apollo 8 was a dual-line narrow-field device used to measure the angle of LOS between the earth or the moon and a star. According to the geometric relationship, the spacecraft position in the space could be determined. Due to the technology restrictions at that time, the accuracy of position calculation obtained solely by angular measurement was not high enough. Therefore, autonomous navigation was only used as a supplement to ground TT&C to confirm the orbit safety and provide support for a spacecraft to return to earth when the navigation support from the ground was unavailable. In a later series of manned Apollo missions, autonomous celestial navigation was used as a backup of terrestrial navigation at the earth-moon transfer stage, and autonomous navigation and control was adopted at the lunar landing and ascending rendezvous stages.

The Mariner 9, the first Mars probe launched by the USA in May 1971, used photos of the natural satellites of Mars (Phobos and Deimos) with a star background taken by onboard optical system for autonomous navigation. Subsequent flight evaluations showed that the Mariner 9's optical observations were more accurate than previously expected and could have been used for navigation in the Mars orbiting phase without any other help [6].

In January 1994, the "Clementine" lunar probe launched by the USA used two star trackers to determine its own attitude and demonstrated the function of autonomous operation. It was originally intended to use the earth/moon images and inertial attitude information acquired by the imaging sensor for the earth-moon transfer and circum-lunar autonomous navigation. But due to the probe fault, navigation calculation based on the image data was only conducted on the ground [7].

On October 24, 1998, the "Deep Space 1" probe launched by the USA successfully demonstrated the onboard autonomous deep-space navigation and control system for the first time. At the cruise stage, the autonomous navigation based on the images of asteroids and background stars taken by the navigation camera was demonstrated with the positioning accuracy of about 250 km and the velocity accuracy of about 0.5 m/s, which are high enough to meet the requirements for cruising navigation accuracy. When approaching and flying over the asteroids or comets, the probe used the autonomous navigation technique based on the images of target asteroids or comets. Its autonomous navigation and control system can autonomously complete the photographing sequencing, image processing and analysis, orbit determination, ephemeris correction, orbit correction, and attitude maneuver [8, 9].

In January 2004, the "Stardust" probe launched by the USA in February 1999 flew by the "Wild-2" comet with the aid of autonomous optical navigation, and completed the mission of comet sampling. In 2006, it returned to the earth. The Stardust's closest approach to the "Wild-2" comet during its fly by the comet was expected to be 120–150 km, and the flyby time only lasted a few minutes. Because of the long distance from the earth, it could not rely on the ground-based navigation. Therefore, in the flyby process, the Stardust processed the comet images through center extraction, obtained the center of the comet, and with the help of attitude determination system and filtering technology, completed real-time autonomous navigation. [10]. The Stardust also used autonomous optical navigation during its flyby the "Tempel 1" comet on February 14, 2011.

In May 2003, the Hayabusa probe launched by Japan completed the first sample return from an asteroid. During the rendezvous and landing phases, it successfully accomplished autonomous attachment by using an optical navigation sensor, a radar rangefinder and a laser rangefinder, and communicating with pre-dropped navigation landmarks [11].

In September 2003, the ESA launched "SMART-1" to conduct an autonomous navigation experiment for future deep-space missions, and to return the in-orbit observations of autonomous navigation system to the ground for processing. In the experiment, a navigation camera was used to take photos of the identified navigation beacon. Those photos, combined with the image data and the probe attitude information, could determine the line-of-sight direction of the navigation beacon, which then was input to the navigation filter to estimate the orbit for the probe [12].

In March 2004, the “Rosetta” launched by ESA and the lander it carried adopted the autonomous control technique. Its autonomous control software could make autonomous decisions and controls far away from the earth (with a communication delay of 0.5 h) to ensure its correct operation. In order to ensure the probe safety, autonomous guidance, navigation, and control was implemented when landing on the comet nucleus. The orbit where the probe was located was determined by processing the measurements taken by a camera, a radar, and the orbit control was accomplished autonomously.

In January 2005, the “Deep Impact” launched by the USA completed its mission of rendezvous and impact with a comet and demonstrated autonomous navigation and control in the collision. Partially inheriting and developing the autonomous navigation and control system of Deep Space 1, an impactor can realize autonomous navigation and control within two hours before the impact with the target comet by using the images and attitude information of the comet taken by a navigation sensor [13].

In August 2005, when approaching the Mars, the “Mars Global Surveyor” launched by National Aeronautics and Space Administration (NASA) and equipped with an experimental navigation camera took pictures for two natural satellites of the Mars, and relied on their images and ephemeris information to realize autonomous navigation at an accuracy higher than that of ground TT&C, and demonstrated high-precision navigation necessary for future Mars-landing missions.

1.1.2.2 Analysis of Autonomous Optical Navigation at Different Flight Stages

The optical navigation sensors, image processing algorithms, and navigation methods selected for various probes at different mission stages will vary with the distance between the probe and the targeted celestial body, the position of the probe relative to a larger celestial body such as the sun or the earth, and the distribution of smaller celestial bodies around.

1. Autonomous Optical Navigation at the Stage of Free Flight

At the stage of free flight, the probe cannot be observed since it is far away from the targeted celestial body. Therefore, the navigation beacons for this stage are usually the celestial bodies with known ephemeris and near the flight orbit. Through continuous observation of the navigation beacon for a period of time, the orbit (and attitude) information of the probe can be estimated based on the ephemeris information of the navigation beacon. The Deep Space 1 relied on the optical measurements and ephemeris of asteroids and background stars to determine its own position and velocity. The “Clementine” probe extracted the direction vectors of the earth’s center and the moon’s center from the images of the earth and moon taken by the navigation sensor at the earth-moon transfer stage, and by combining the direction vectors with the attitude information and the earth/moon ephemeris information, estimated the orbit for the probe with the Kalman filter (KF) method. Due to the fault in the probe, its autonomous navigation experiment was not completed [14]. But this autonomous navigation method based on optical imaging was demonstrated by the "SMART-1" of ESA through a ground test.

2. Autonomous optical navigation at the approaching stage

When being approached by the probe, the size and brightness of targeted celestial body shall ensure that the navigation sensor of the probe is sensitive enough to image the target body on its focal plane. In this case, the targeted celestial body can be selected as the navigation beacon. By using the navigation sensor to continuously image the targeted celestial body and extracting its center vector information in combination with its inertial attitude and ephemeris, the orbit and attitude of the probe relative to the targeted celestial body can be determined. The center point extraction technique of a targeted celestial body was demonstrated when the Voyager probe launched by the USA encountered Neptune and Uranus. Thanks to this technique, optical navigation has been applied to the Stardust's approach to the comet [10]. This technique has also been used by Deep Space 1.

3. Autonomous optical navigation at the orbiting stage

When flying around the targeted celestial body, the probe is closer to it and thus obtaining its clear images by using the navigation camera. The navigation system uses the image processing algorithm to extract the edge image of the target and then calculates its apparent radius and center pointing vector as specially required for flying around spherical celestial bodies such as large planets. For an irregular small celestial body, its feature points are first identified by matching its edge image with its pre-processed model and then combined with the attitude information to determine the orbit of the probe through the filtering algorithm. The "Clementine" probe relied just on the optical navigation when flying around the moon. The apparent radius and centroid vector of the moon were extracted from the moon images acquired by the sensor and then combined with the attitude information to determine the orbit of the probe through the filtering algorithm.

To meet the need for autonomous navigation at the stage of flying around small celestial bodies, the JPL laboratory in the USA has developed an autonomous navigation method based on optical imaging [15]. In this method, the edge image of a small celestial body (the target) obtained by the wide-field camera is matched with the pre-processed target model, and then the position of the probe relative to the target center is determined in real time by using the weighted least-square (WLS) method, and at last, the position information is input into the navigation filter to calculate the orbit parameters of the probe.

4. Autonomous optical navigation at the landing or attachment stage

During autonomous landing or attachment, the probe is closer to the target. In order to accurately identify the surface conditions of the target, a safe landing site shall be selected, and the optical navigation camera shall have a small field of view and high resolution. The Institute of Space and Astronautical Science (ISAS) in Japan has developed a technique of autonomous navigation and guidance for asteroid landing [16]. To land on the asteroids where the state of the landing site is not known in detail, the institute proposed a method of autonomous landing navigation using a navigation camera and a laser rangefinder. According to that method, the navigation camera takes pictures of the landing target, the laser rangefinder measures the distance from the probe to the target surface, and then the filter acquires the information on probe position and velocity. Misu et al. in Japan invented an autonomous asteroid-landing navigation algorithm that determined the position and attitude of the probe relative to the target asteroid by extracting and tracking feature points [16]. Johnson et al. working in the JPL proposed an autonomous asteroid-landing navigation algorithm based on computer vision [17].

Through the above analysis, it is easy to see that, in the deep-space exploration, the method and technical means of autonomous control based on optical imaging navigation vary with stage and mission. At different operating stages, the different targets tracked by imaging navigation sensor have a different size, distance, brightness, and background stray light influence. This makes it very difficult to design the navigation sensor and operate the image processing algorithm. As a result, the research of optical sensor technology, navigation filtering algorithm, and image processing algorithm has become critical to the autonomous navigation of deep-space exploration spacecrafts. Table 1.1 summarizes the candidate solutions of autonomous navigation in deep-space exploration.

1.1.3 Autonomous Pulsar-Based Navigation

The autonomous navigation of deep-space probe based on X-ray pulsar is to determine the position unit vector of the pulsars in the barycentric celestial reference system (BCRS) and the standard arrival time of X-ray pulse through very-long-baseline interferometry (VLBI), to compare them with the pulsar LOS direction and actual arrival time measured by the X-ray detector installed on the deep-space probe, and to obtain the navigation information such as the position, velocity, and time of spacecraft through an appropriate filtering algorithm. Attitude determination can also be achieved through the navigation based on X-ray pulsar, in a way similar to the attitude determination based on optical camera. By imaging the pulsar, its coordinates in the probe coordinate system are obtained, so that the azimuth of LOS vector relative to the probe can be estimated.

Table 1.1 Candidate solutions of autonomous navigation in deep-space exploration [3]

Deep-space mission phase	Autonomous navigation task	Autonomous navigation scheme	Navigation sensors configuration	Navigation algorithm
Heliocentric transfer phase	Determine the heliocentric orbit	Based on the images of multiple asteroids and background stars	IMU, star sensor and high-precision NFOV navigation camera	Navigation asteroids selection and planning, image processing, navigation filtering, and celestial ephemeris calculation
Earth-moon transfer phase	Determine the geocentric orbit	Based on earth and moon images	IMU, star sensor and navigation camera	Image processing, navigation filtering, and celestial ephemeris calculation
Approach phase	Determine the attitude and orbit of the probe relative to the target body	Based on images of the target body (its center/edge/feature)	IMU, star sensor and navigation camera	Image processing, navigation filtering, and celestial ephemeris calculation
Impact phase	Determine the attitude and orbit of the probe relative to the target body, and the impact point information.	Autonomous navigation and predictive guidance scheme based on images of the target body (its center/surface feature)	IMU, High-precision WFOV navigation camera, star sensor and	Image processing, navigation filtering, celestial ephemeris calculation, and maneuvering guidance calculation
Orbiting phase	Determine the attitude and orbit of the probe relative to the orbited body	For a large orbited body, autonomous navigation scheme is based on the image/other optical information of the target body to acquire its orientation and apparent radius; for a small orbited body, autonomous navigation scheme is based on images of the target body (its center/edge/feature)	WFOV navigation camera, or other optical sensor, star sensor and IMU	Sensor data processing (image processing) and autonomous navigation filtering algorithm

(continued)