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# Autonomous Navigation for Mars Exploration

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## Abstract

The autonomous navigation technology uses the multiple sensors to percept and estimate the spatial locations of the aerospace prober or the Mars rover and to guide their motions in the orbit or the Mars surface. In this chapter, the autonomous navigation methods for the Mars exploration are reviewed. First, the current development status of the autonomous navigation technology is summarized. The popular autonomous navigation methods, such as the inertial navigation, the celestial navigation, the visual navigation, and the integrated navigation, are introduced. Second, the application of the autonomous navigation technology for the Mars exploration is presented. The corresponding issues in the Entry Descent and Landing (EDL) phase and the Mars surface roving phase are mainly discussed. Third, some challenges and development trends of the autonomous navigation technology are also addressed.

**Keywords:** autonomous navigation, deep space exploration, inertial navigation, celestial navigation, visual navigation, integrated navigation

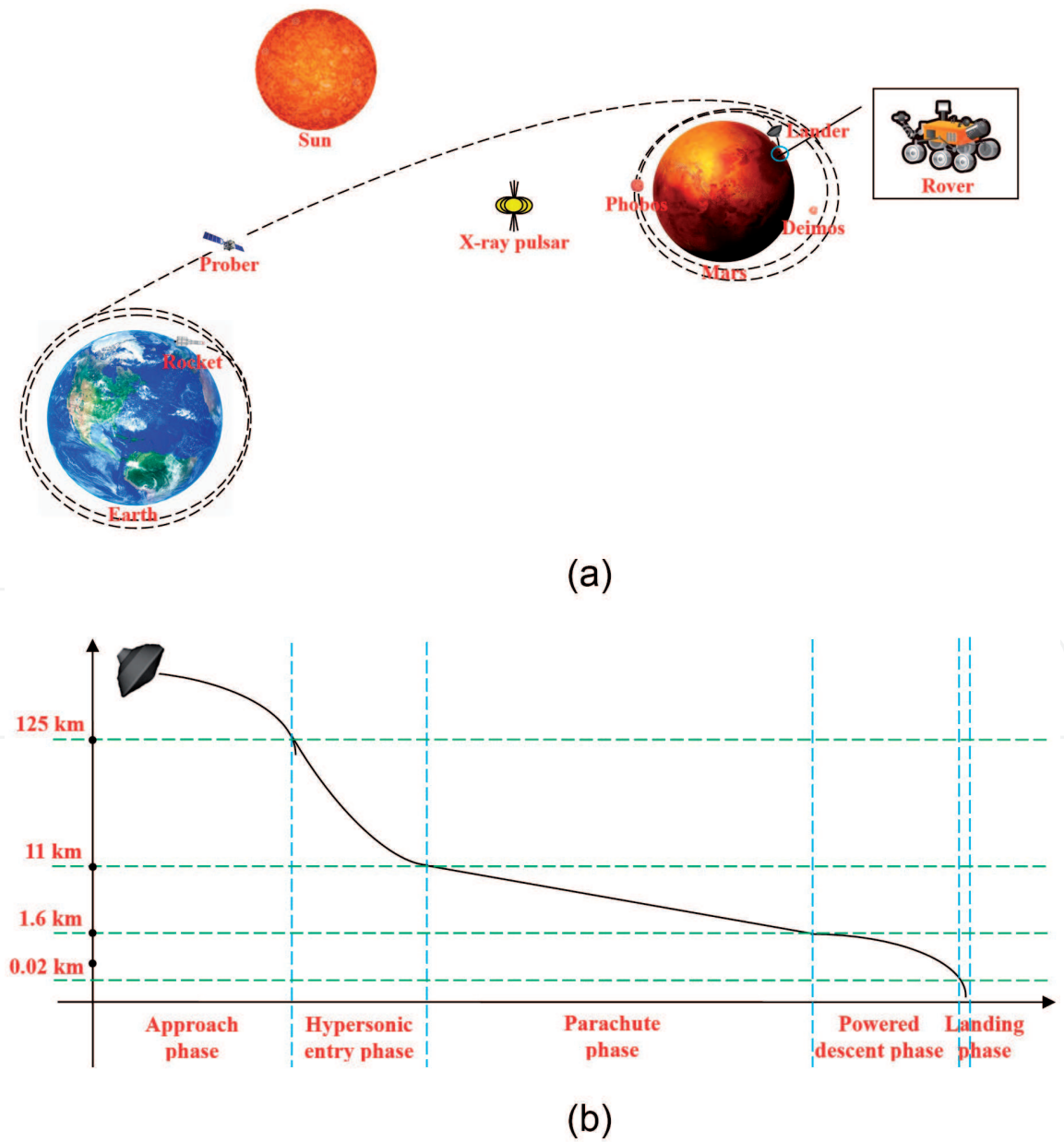
## 1. Introduction

The Mars is an attractive planet in the space, which looks red, faraway, and mysterious. It is believed that the Mars is the second planet, which is suitable for people to live [1]. After many years of probing, it has been found that the Mars has plenty of minerals, its average surface temperature is about  $-60^{\circ}\text{C}$ , it has thin atmosphere, and it even has water [2]. The scientific fiction is if we deploy some solar reflectors in Mars' orbit and build many greenhouse gas factories in its surface, the temperature there will increase gradually, and then the thick atmosphere [3] will be created, the ice in its polar and underground will melt, and finally, the primitive life may appear. Nowadays, to land that red planet and build new base, there is the competitive focus of aerospace technology for many countries. However, it is known that the distance between the Earth and the Mars is between  $5.5 \times 10^7$  and  $4 \times 10^8$  km, and it will cost us almost 7 months to reach that place. To reach that red planet in the vast and boundless universe safely, all the solutions point to the navigation technology [4].

In general, the flight mission of Mars exploration [5] can be divided into four phases. The first one is the launch phase. The rocket will send the Mars prober into the space and escape from the gravitational constraint of the Earth. The second one is the cruise flight phase. The prober will fly to the Mars by several times of orbit transfer [6]. The third one is the Entry, Descent, and Landing (EDL) phase [7]. This is the most dangerous flight stage in this mission because of the influences of the thin Mars atmosphere, the Mars gravitation, and its complex terrain. The last one is the roving phase. After a safe landing, the rover will walk on the surface of

Mars and look around here and there. Clearly, different navigation technologies should be employed in different flight phases. The satellite navigation [8], the inertial navigation [9], the celestial navigation [10], the visual navigation [11], and the integrated navigation [12] are the most popular navigation techniques in the aerospace engineering research field. **Figure 1** presents the sketch map and an example of Mars exploration. In **Figure 1**, (a) is the sketch map of Mars exploration flight mission, and (b) gives out a kind of landing method in the EDL phase.

Many research works have been done in the aerospace navigation research field. In [13], the authors proposed a new method, which could use the impulses in the solar light and the time difference of arrival method to improve the navigation accuracy. In [14], an inertial measurement unit and the orbits/aerostats beacons-based integrated navigation scheme were developed. The range and the Doppler information were integrated in the extended Kalman filter. In [15], a navigation method, which could use the inter-satellite link and the starlight angle, was simulated. The prober could determine its position by communicating with other space crafts and observing the stars. In [16], a norm-constrained unscented Kalman filter-based navigation scheme



**Figure 1.** The sketch map and an example of Mars exploration: (a) is the sketch map of the flight mission; (b) is a landing example in the EDL phase.

was proposed. This method could be used for the spacecraft attitude quaternion estimation during the Mars powered descent. After a comparable study of the popular navigation methods, it can be found that the navigation technique has the development trend of high accuracy, multi-function, mini-size, low power consumption, and long service life. In addition, the Artificial Intelligence (AI) technique [17] also has the potential application value in the navigation research field.

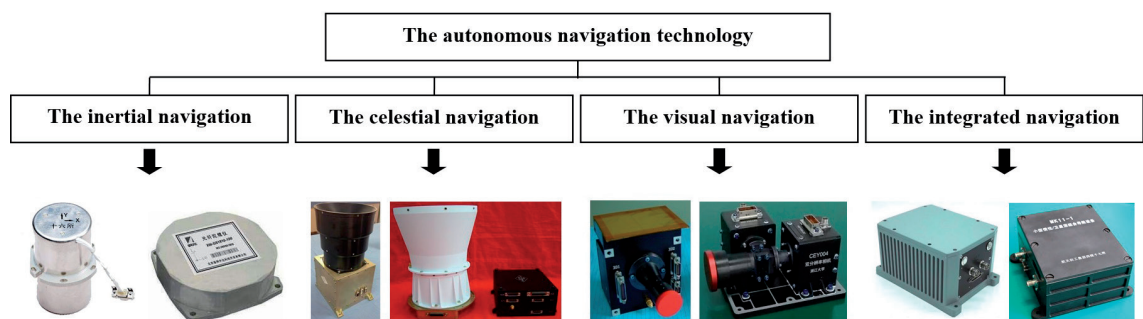
## 2. The key autonomous navigation techniques

Different from the traditional navigation techniques, the autonomous navigation [18] can realize the perception, the computation, and the decision making of the flight trajectory all by the aerospace prober itself. No exterior information is needed. Sometimes the autonomous navigation system can also emit some state information to the ground for the safety monitoring purpose. Many methods can be used to assist the autonomous navigation flight. The popular methods include the inertial navigation [19], the celestial navigation [20], the visual navigation, and the integrated navigation. **Figure 2** shows the sketch map of the popular autonomous navigation methods.

### 2.1 The inertial navigation

The inertial navigation can measure the acceleration of prober and use the integral computations to estimate its transient flight speed and spatial position. During that process, no energy will be radiated from the inertial navigation device, and no exterior auxiliary information is needed. The inertial navigation adopts the devices of the accelerometer [21] and the gyroscope [22] to realize the state estimation. The accelerometer [23] is a device, which can measure the acceleration of the carrier. In general, it can be classified into the linear accelerometer and the angular accelerometer. In the practical application, the linear accelerometer is commonly used because of its high precision and excellent stability. Many accelerometers have been designed, such as the piezoelectric accelerometer, the piezoresistive accelerometer, or the capacitive accelerometer. **Table 1** shows a kind of classification of the linear accelerometer. The gyroscope is a device, which can measure the rotation rate. **Table 2** illustrates some gyroscope products. They are the mechanical rotor gyroscope, the electrostatic suspended gyroscope, the vibratory gyroscope [24], the laser gyroscope, and the fiber optic gyroscope [25].

The inertial navigation is the most mature and popular method in the navigation research field. Comparing with other navigation techniques, the inertial navigation at least has three advantages. First, it is independent to the environment.



**Figure 2.**  
*The popular autonomous navigation methods.*

No.	The name	The basic principle	The application
1	The piezoelectric accelerometer	The principle of piezoelectric effect	The quartz crystal or the piezoelectric ceramics accelerometer
2	The vibrating string accelerometer	The relationship between the resonant frequency of string and the corresponding acceleration	The electromagnetic oscillator-based accelerometer with the string
3	The vibrating beam accelerometer	The relationship between the resonant frequency of beam and the corresponding acceleration	The electromagnetic oscillator-based accelerometer with the beam
4	The optical accelerometer	The principle of optical interference effect	The grating accelerometer, the fiber-optic accelerometer, or the polymer accelerometer
5	The pendulous accelerometer	The relationship between the rotation angle and the corresponding acceleration	The liquid-floated pendulous accelerometer, the flexure hinged pendulous accelerometer, and the pendulous integrating accelerometer

**Table 1.**  
*A kind of classification of the linear accelerometer.*

No.	The name	The basic principle	The application
1	The mechanical rotor gyroscope	The Newton's mechanics laws: the mechanical rotor can maintain its rotation orientation regardless of its base movement	The gas-floated mechanical rotor gyroscope, the liquid- floated mechanical rotor gyroscope, and the ordinary mechanical rotor gyroscope
2	The electrostatic suspended gyroscope	The ball rotor, which works in a vacuum electric field, can maintain its rotation orientation regardless of its shell movement	The electrostatic suspended gyroscope with a solid rotor, the electrostatic suspended gyroscope with a hollow rotor, and so on
3	The vibratory gyroscope	The Coriolis effect, which is observed from a vibrating structure	The tuning fork gyroscope, the hemispherical resonator gyroscope, and so on
4	The laser gyroscope	The Sagnac effect	The four-mode differential laser gyroscope, the mechanically dithered ring laser gyroscope, and so on
5	The fiber optic gyroscope	The Sagnac effect	The interferometric fiber optic gyroscope, the resonator fiber optic gyroscope, and the Brillouin fiber optic gyroscope

**Table 2.**  
*A kind of classification of the gyroscope.*

It can realize the all-weather and the all-time working modes in any places. Second, it can provide the position, the speed, the course, and the attitude information of carrier accurately. And its data updating ratio is also high. Third, it has the good performances in the anti-interference and the low system noise. Clearly, the inertial navigation also has some shortcomings. For example, according to its navigation principle, its navigation error will be accumulated. Another problem is that the inertial navigation also cannot give out the time information. Recently, the Micro Electro Mechanical Systems (MEMS) technology [26] has met its great development opportunity. The MEMS technology can realize the optoelectronics product



manufacturing in a microscopic degree. It has been used to improve the product performance of the vibratory gyroscope, the laser gyroscope, and the fiber optic gyroscope in recent years. In future, the miniaturization, the high precision, and the high reliability processes will be developed in the inertial navigation system.

## 2.2 The celestial navigation

The celestial navigation uses the space object, such as the sun, the moon, or the other stellar [27] as a reference to guide the flight direction and the flight attitude of the prober. Clearly, the star sensor [28] should be employed in this method. As a kind of optical measurement device, besides the visible light camera, the infrared camera, the ultraviolet camera, the X-ray camera, the  $\gamma$ -ray camera, and so on can all be used. Many methods have been designed for the celestial navigation, that is, the angle measurement-based navigation [29], the distance measurement-based navigation [30], and the speed measurement-based navigation [31]. The angle measurement-based navigation uses the angles among the sun, the other planets, the planet satellite, the asteroid, or the comet to carry out the autonomous navigation. The distance measurement-based navigation mainly employs the detection result of the arrival time difference between the X-ray pulsar and the standard pulse of the solar system center to estimate the navigation information and the time offset. In addition, the speed measurement-based navigation utilizes the optical Doppler effect [32] to implement the navigation. **Table 3** presents the popular methods of the celestial navigation.

The celestial navigation at least has three advantages. First, as a kind of optic measurement device, most of the celestial navigation systems are immune to the traditional electromagnetic interference problem [33]. Also, their working reliabilities are comparable high. Second, its navigation accuracy is good. Because the spatial distance between the celestial body and the prober is really large, the navigation precision can be very high if the star sensor performance and the corresponding data processing algorithm are proper. Third, most of the celestial navigation devices can work all-time long as long as the corresponding celestial bodies are visible. The celestial navigation also has some shortcomings. The biggest problem is that some devices cannot be used in the complex light environment. For example, the strong environment light or the cosmic rays will affect the application effect of these optic devices seriously. Another drawback is that some celestial navigation devices cannot give out the sequential output because of the target star occlusion problem. Comparing with the inertial navigation technique, the celestial navigation is still immature, and most techniques do not get the test of the practical flight mission. In future, the new modeling technique of the orbit function [34], the new measurement theory of the star, and the new estimation method of the navigation information can all be researched extensively to improve the application effect of the celestial navigation.

## 2.3 The visual navigation

The visual navigation uses the imaging sensors to accomplish the navigation task. In this chapter, the visual navigation means to use the visual sensors and the corresponding algorithms to the autonomous robot vehicle or the unmanned aerial vehicle for the navigation purpose. In many cases, the visual navigation is used as the direction guidance or the obstacle avoidance device. Without loss of generality, the imaging sensors in the visual navigation include the visible light camera, the infrared or the near-infrared camera, the multispectral camera, the laser imaging camera [35], and even the ghost imaging (i.e., the quantum imaging) camera [36].

The imaging system can be realized by the monocular vision system [37], the binocular vision system, the multi-sensor vision system, and the depth vision system [38]. In engineering, the narrow field camera, the wide field camera, and the panoramic camera can always be used. **Table 4** presents the popular visual navigation techniques. Different from the traditional navigation methods, the visual navigation can capture 2D image data; thus, the image processing and the pattern recognition techniques can be used for its navigation information analyses and estimations. For example, the region-based matching, the feature-based matching (point, line, or region feature), and the semantics-based matching can all be developed [39].

Clearly, the visual navigation has lots of application advantages. First, the imaging data have the abundant details, they are easy to be understood by people, and their processing results are also intuitive. Second, the imaging sensor can be used under a flexible working mode, such as the active mode or the passive mode. The active mode means the imaging sensor system will project some light to the observed target [40] to improve its visibility. The projected light can be the visible light, the infrared light, or even the laser in certain spectral bands. The passive mode indicates that the imaging sensor system will not project any light to the exterior environment. Third, the navigation accuracy is high. In many cases, the image-based navigation can realize the high precision navigation in centimeter degree or even more. This excellent performance can guarantee it to be used in some complex

No.	The name	The basic principle	The application
1	The sextant	The angle between any two typical objects can be used as a navigation reference	The celestial sextant
2	The celestial sensor	The spatial positions of some planets can be used as a navigation reference	The star sensors, such as the X-ray pulsar sensor, the asteroid sensor, the Mars sensor, the sun sensor, and the planetary photographic instrument
3	The horizon sensor	The horizons of some planets can be used as a navigation reference	The Earth horizon detection device, the Mars horizon detection device, and so on

**Table 3.**  
*A kind of classification of the celestial navigation technique.*

No.	The name	The basic principle	The application
1	The map-based navigation	The digital map construction and the feature matching	The navigation method in a known environment, it can be implemented by the absolute positioning and the relative positioning techniques, and so on
2	The optical flow-based navigation	The feature detection and the motion information estimation	The translation motion estimation method and the rotation motion estimation method
3	The appearance-based navigation	The image feature matching	The terrain matching and the landmark matching
4	The integrated visual navigation	The information fusion of different visual navigation techniques	The visual light camera and the infrared camera-based navigation, the visual light camera and the laser radar-based navigation, and the visual light camera and the depth camera-based navigation

**Table 4.**  
*A kind of classification of the visual navigation technique.*

terrain environments. Obviously, the visual navigation also has some drawbacks. For example, its data processing amount is very large. Comparing with the data processing of the inertial navigation, the computation of the image processing algorithm is really complex; as a result, the visual navigation needs its processing unit to contain the high data processing performance and the large power consumption. Another problem is that the visual sensor is sensitive to the environment light [41]. All kinds of atmosphere phenomena will create great negative influences on its processing result.

2.4 The integrated navigation

The integrated navigation uses the combination of two or more than two basic navigation methods above to realize the high precision direction guidance and the attitude estimation of carrier. Its key techniques include the computer-based feature extraction, the information fusion, and the time synchronization [42]. The integrated navigation can make up the disadvantage of the sole navigation method, realize the seamless navigation, and achieve the information redundancy designing of the navigation system [43]. Its system reliability and the navigation accuracy can be improved a lot. Currently, the most successful integrated navigation is the inertial plus the Global Positioning System (GPS)-based navigation method, that is, the combination of the inertial navigation and the satellite navigation. Regarding the autonomous navigation technique for the deep space exploration, **Table 5** presents the popular integrated navigation methods. From **Table 5**, any two basic navigation methods can be used for the integrated navigation application. The integrated navigation also has some drawbacks. For example, its complex system design, its big size, and its high power consumption are all the problems for the spacecraft application.

2.5 Some other autonomous navigation methods

Some other autonomous navigation methods can also be used for the Mars exploration. First, the radio-based navigation [44] is a choice. Traditionally, the radio-based navigation uses the satellites or the beacons on the ground to provide the prober some guidance information. Clearly, this method is not an autonomous technique. However, if we look both the satellite and the prober as a whole that means the Mars exploration prober system includes both the lander and the navigation satellites, the radio-based navigation can be considered. Second, the bionic navigation method [45] is another choice. The bionic navigation imitates the animals' sensory processing to accomplish the navigation. The stereoscopic vision, the auditory

No.	The integrated navigation method	The application
1	The inertial navigation and the celestial navigation	Three accelerometer, three gyroscope, and the star sensors (the observation from orbit)
2	The inertial navigation and the visual navigation	Three accelerometer, three gyroscope, the visible light camera, and the laser radar
3	The visual navigation and the celestial navigation	The visible light camera, the laser radar, and the star recognition sensor (the observation from ground)
4	The inertial navigation, the celestial navigation, and the visual navigation	Three accelerometers, three gyroscopes, the star sensors, and the celestial body feature recognition sensor

**Table 5.**  
*A kind of classification of the integrated navigation technique.*



sensation, the olfactory sensation, and the tactile sensation can all be utilized in this method. Lost of new sensors can be developed for this navigation technique. Third, the Mars atmosphere model-based navigation [46] can also be considered. For example, a kind of Mars flush air data system has been used to assist the estimations of the dynamic pressure, the Mach number, and the impact angle of Mars prober. By using all the new navigation theories and methods, the final navigation accuracy can be improved definitely.

### 3. The autonomous navigation for Mars exploration

#### 3.1 The autonomous and the nonautonomous navigations in Mars exploration

As we have stated, the Mars exploration mission can be divided into four phases, that is, the launch phase, the cruise flight phase, the EDL phase, and the roving phase. **Table 6** illustrates the comparisons between the autonomous navigation method and the nonautonomous navigation technique during four phases. In fact, both the autonomous navigation and the nonautonomous navigation methods are needed in the deep space exploration. In **Table 6**, regarding the nonautonomous navigation methods, the GPS, the Beidou satellite system, the GLONASS, and the Galileo system are the most famous satellite navigation systems in the world. The radio-based method can carry out the navigation by the means of the Deep Space Network (DSN)-based system [47] or its airborne radar equipment. The DSN is a land-based tracking, telemetry, and control network for the satellite navigation, control, and observation in the deep space. The giant radio emission equipment, the X-ray telescope, and some communication terminals are deployed in different sites on Earth or in orbit to assist the deep space navigation application.

The navigation in the EDL phase faces lots of challenges. First, the complex atmosphere and weather in Mars will create uncertainty to the navigation task. The attenuated atmosphere will cause the deficiency of the aerodynamic force [48]; no accurate environment model and aerodynamic model can be used; the gust and the sandstorm will always affect the land precision; and the descent speed is fast, and the blackout zone [49] still exists, which can affect the normal communication and so on. Second, the long-time space flight will rise changes and damages to the mechanical structure and the sensors [50] of prober. The cosmic ray, the extreme temperature, and the space debris will influence the health state of prober. Third, the time delay, which is larger than 10 minutes from Earth to Mars, also indicates that people cannot monitor its flight state in real time. To conquer these problems to some extent, the autonomous navigation can be used during the EDL phase. In the entry stage, both the inertial navigation and the celestial navigation can be used; in the descent stage, the inertial navigation can be considered; and in the landing stage, the inertial navigation and the visual navigation can all be employed.

The visual navigation in the roving phase also has some problems. First, since lots of optic devices are utilized, the complex environment light and the dust in air will influence their working states [51] seriously. Because the Mars surface has no liquid water and no vegetation, the wind with the sand can be commonly met. The lens of imaging sensor may be contaminated. Second, the low surface temperature in Mars also is a problem. Most of storage batteries cannot work under a normal state in that low temperature. The strength of materials will also be changed. Third, the poor performance of the imaging sensor can determine the limited computational effect of the image processing algorithm. To control the weight of launch load, the high performance camera with big size cannot be sent to Mars. Thus, how to use the images come from the low resolution imaging sensor for the data analysis

No.	The flight phase	The autonomous navigation methods	The nonautonomous navigation methods
1	The launch phase	The inertial navigation and the celestial navigation	The satellite navigation and the radio navigation
2	The cruise flight phase	The inertial navigation and the celestial navigation	The radio navigation, and so on
3	The EDL phase	The inertial navigation, the celestial navigation, and the visual navigation	The radio navigation, and so on
4	The roving phase	The inertial navigation, the celestial navigation, and the visual navigation	The radio navigation, and so on

**Table 6.**  
*The autonomous and the nonautonomous navigation methods in different flight phases of Mars exploration.*

purpose is a challenge. To conquer these problems above, on one hand, the special materials and process will be used to improve the performance of the imaging sensor; on the other hand, some typical workflows and data fusion algorithm [52] should be designed according to the environment characters in Mars.

### 3.2 The autonomous navigation algorithms

Many navigation algorithms have been developed for the autonomous navigation application. Regarding the inertial navigation, lots of time series data can be collected from the accelerometer and the gyroscope. Because of the electrical radiation, the impact and the vibration, and the temperature drift, their measurement data are always contaminated by the system noise or the exterior noise. As a result, the denoising computation and the trending prediction are necessary. In general, the classic Kalman filter, the Extended Kalman Filter (EKF), the Unscented Kalman Filter (UKF) [53], and the particle filter [54] can be used to improve the data quality. The Kalman filter belongs to a kind of sequential filter technique, which needs no complex iterative computation. Its processing speed is fast, while its need of the data storage capacity is small. In other cases, the least square filter [55] can also be considered to solve the denoising issue. The least square filter is a kind of batch processing algorithm, which needs no priori information of the state variable; it has been used to solve the orbit estimation issue currently.

The celestial navigation uses the imaging sensor to observe the typical celestial body. Lots of data processing methods for 2D data can be employed. For example, the dim target detection can be used to identify the Phobos and the Deimos of Mars in space; the image denoising [56] can be considered for the noise inhibition; the spectral analysis can be employed to assist the atmosphere component analysis; and the image quality evaluation can also be used for the celestial body recognition. The visual navigation also adopts the imaging sensor to percept the environment. Thus, the related image processing algorithms [57], such as the camera calibration, the image enhancement, the image restoration, the image denoising, the feature detection, the feature matching, the image mosaic, and the image segmentation, can all be utilized. Recently, the Simultaneous Localization and Mapping (SLAM) technique [58] begins to be used for the map navigation in the narrow area. Its familiar methods include the Lidar-based SLAM and the visual-based SLAM. This technique can be used for the visual navigation in the Mars roving phase in future.

The integrated navigation can get the multivariate data; thus, the data fusion technique should be applied for its data processing. The data fusion can improve the data processing precision and reliability by the measurement of information reasoning and integration. In general, the data fusion algorithm includes the linear

weighting-based method, the filtering with a Bayesian estimation-based method [59], the factor graph-based method [60], and the interactive multiple model fusion-based method. Among these methods, the linear weight-based method uses the sum of the weighted input data to carry out the fusion computation. The filtering with a Bayesian estimation-based method considers the prior information and the Bayesian statistical theory to implement the fusion calculation. The factor graph-based method employs the Bayesian network or the Markov model [61] to realize the data fusion. In addition, the interactive multiple model fusion-based technique uses two or more than two filters or the prediction model to accomplish data fusion. Clearly, the computation of data fusion can be realized by the parallel algorithm or the sequential algorithm.

3.3 The time service technique

The navigation system cannot leave the time service. The time service can provide a benchmark for the signal processing applications in the prober. Currently, the commonly used time service device in the satellite is the atomic clock [62]. In general, the atomic clock can include the cesium clock, the hydrogen clock, and the rubidium clock. Regarding the time service system, first, its time service precision should be high. For example, the time precision of some ground atomic clocks can reach  $10^{-18}$  s. Second, the integrated performance of atomic clock [63] should be good. The service life span, the mechanical performance, the temperature sensitivity, and the working stability should be calibrated and tested strictly before it is sent to the space. Third, the time synchronization ability of atomic clock should also be excellent. Although the autonomous navigation will not use any exterior information for its navigation; however, it needs to transmit some important state information to the ground sometimes. As a result, the clock synchronization issue should be another key technique for the atomic clock.

3.4 The practical navigation application for Mars exploration

In a practical application, although the autonomous navigation has many merits; however, because of the high maturity and the good reliability, the nonautonomous navigation technique will be used in the Mars exploration mission as long as it is possible. Regarding the Mars exploration mission, the nonautonomous navigation method can include the satellite navigation [64], the ground radio navigation [65], and the Doppler radar navigation [66]. Here, the ground radio navigation is a typical application of the radio-based navigation. Lots of ground radio equipment or beacons can be used to provide the navigation information for the prober. The

No.	The flight phase	The integrated navigation method
1	The launch phase	The inertial navigation, the celestial navigation, the satellite navigation, the ground radio navigation, and so on
2	The cruise flight phase	The inertial navigation, the celestial navigation, the ground radio navigation, and so on
3	The EDL phase	The inertial navigation, the celestial navigation the visual navigation, the ground radio navigation, the Doppler radar navigation, and so on
4	The roving phase	The inertial navigation, the celestial navigation, the visual navigation, the ground radio navigation, the Doppler radar navigation, and so on

**Table 7.**  
*The application of the autonomous navigation and the nonautonomous navigation for the Mars exploration mission.*

Doppler radar navigation also belongs to a typical application of the radio-based navigation. The Mars probe can use an active radar system to emit and receive signal to realize that navigation. Because of the extensive applications of these methods, both the ground radio navigation and the Doppler radar navigation are presented separately in this chapter. **Table 7** illustrates the integrated navigation method using both the autonomous navigation and the nonautonomous navigation for the Mars exploration. In fact, the nonautonomous navigation still plays a more important role in the flight mission than the autonomous navigation currently.

## 4. The challenges and the future works

### 4.1 The challenges

Although the explorations of the red planet have been performed for many years and lots of research plans have been proposed, many challenges still exist in the research field of autonomous navigation, including its accuracy, its reliability, and its service life of navigation system. **Table 8** shows some drawbacks of the autonomous navigation techniques. First, the accuracy issue can determine how precise when a navigation method is used for the Mars exploration task. Generally speaking, the accuracy of the integrated navigation is better than that of other sole navigation method. In the practical mission, both the autonomous navigation and the nonautonomous navigation should be used. Currently, the reported navigation accuracy of Mars landing mission is still not high. For example, the landing deviation of the curiosity rover (a Mars probe, which was launched by NASA in November 26, 2011) is about 10 km, while most of other landers could only reach the precisions from 100 to 300 km. The biggest uncertainty comes from the EDL phase. To improve the landing accuracy, the Mars atmosphere model, the orbit dynamics model, and the aerodynamics model should be researched elaborately in future.

Second, the reliability [67] is another problem. The reliability includes both the element reliability and the system reliability. The element reliability points to the probability of error free working state of each electronic or optic element. Also, the system reliability means the probability of error free working state of the whole navigation system. The redundancy designing degree of an aerospace system is also an evaluation index of the reliability. To improve the reliability, the environment experiments should be performed on ground to select the proper elements and test the robustness of the whole system. In general, the environment experiments include the temperature cycle experiment, the impact and the vibration experiment, the radiation experiment, the aging experiment, and the electromagnetic compatibility experiment. Third, the service life [68] of the Mars probe and its sensors also determine the result of the exploration mission. In many cases, the service life of a satellite can reach from several months to several years. The satellite healthy management is the new developed technique, which can extend the service life of satellite effectively. Its key techniques include the multiple sensors signal collection, the big data analyses, and the intelligent decision making and control.

### 4.2 The future works

Since the nature environment between the Earth and the Mars is similar, all the autonomous navigation methods developed in the Earth can be utilized in Mars. The first method should be the new-type inertial navigation techniques. The atom interferometric gyroscope [69], the nuclear magnetic resonance gyroscope [70],



No.	The autonomous navigation method	The shortcomings
1	The inertial navigation	The biggest problem is that the error can be accumulated. The navigation precision will be decreased with the time lapse.
2	The celestial navigation	The imaging sensor is easy damaged during the space flight. The practical application test of celestial navigation is still limited.
3	The visual navigation	The observation distance is small, and the environment light and the dust in air will affect the navigation accuracy seriously.
4	The integrated navigation	The system is complex and expensive, and its reliability is comparable low.

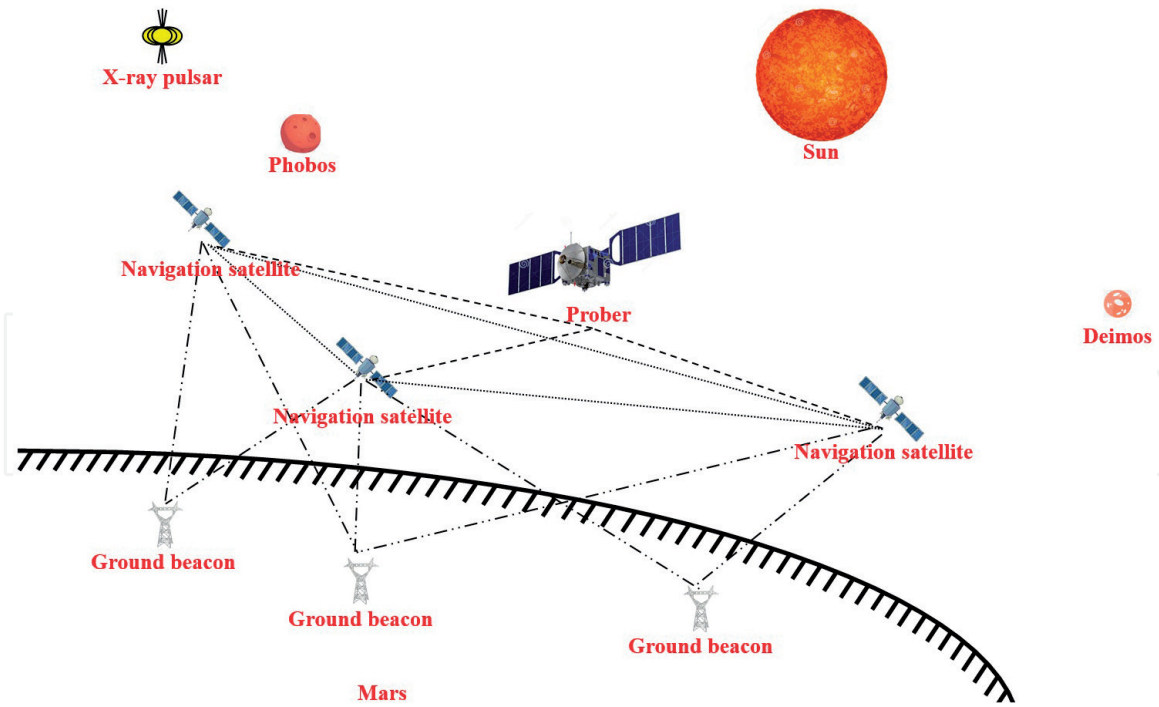
**Table 8.**  
*The drawbacks of the autonomous navigation techniques.*

and the quantum gyroscope [71] can be developed and utilized for the Mars prober. The second method is the geomagnetic matching navigation method. In past, it is thought that the geomagnetic field in Mars is weak and disorder. Recently, some scholars have disclosed that parts of the local geomagnetic fields in Mars still could be used for navigation [72]. The third method is the gravity gradient navigation [73]. It is well known the gravitational acceleration has the diversity in different locations of the Earth. This is also true in Mars. If the gravitational acceleration map of Mars can be made in future, it will be used by the autonomous navigation technique in the red planet definitely. The fourth method is the bionic navigation [74]. Like an advanced animal, this navigation method can utilize the stereo vision, the auditory, and the tactile to realize the autonomous navigation.

The miniaturization is one of most important development directions of the autonomous navigation technique; thus, the MEMS should be emphasized. The MEMS is a technology, which can construct a system in the 1-to-100  $\mu\text{m}$  degree. Sometimes its system size can have the outline in the millimeter degree. The MEMS has many merits for the aerospace application, such as the light weight, the low cost, the low power consumption, the long service life, the high reliability, the wide dynamic range, the fast response, and the easy installation. The micro-accelerometer and the silicon micromachined gyroscope are its representative products. In general, the inertial navigation system in a carrier has the application forms of the strap-down mode and the platform mode [75]. The former installs the inertial navigation sensors in the carrier directly, while the latter fixes the sensors in a platform and then puts the whole platform into the carrier. In many cases, the MEMS uses the strap-down mode to deploy its sensors. Clearly, the designing and the manufacturing of MEMS are not easy tasks. The environment test issue of MEMS is another problem. Because of its small size, the cosmic ray radiation, the low temperature, the low pressure, the zero gravity, and the impact and the vibration will also influence its service life and accuracy seriously.

Many works can be done in the navigation system and algorithm designing, and the corresponding navigation standards also need research works. **Figure 3** presents a kind of system designing for the navigation application in Mars. As we have stated, if we look both the navigation satellite and the prober as a whole, the satellite navigation can be looked as a kind of autonomous navigation method. With the assistance of the inertial and the celestial navigations, the navigation precision can be improved definitely. Some optimal algorithm can also be considered to improve the performance of the classic navigation method. For example, the genetic algorithm [76], the artificial bee colony algorithm [77], and the ant colony algorithm [78] can be used to improve the performance of the Kalman filter. Regarding





**Figure 3.**  
*The sketch map of the future development of the MGNSS.*

the standard formulation issues, at present lots of international standards have been made for the satellite navigation system. For example, the International Organization for Standardization (ISO) has made a series of standards for the GPS, including its working channel, its coding and decoding method, and its service agreement. In future, some corresponding standards should also be made for the Mars Global Navigation Satellites System (MGNSS) [79]; **Figure 3** shows its imaginary representation.

## 5. Conclusion

In this article, the autonomous navigation for the Mars exploration is reviewed and summarized. First, the popular autonomous navigation techniques are presented. The inertial navigation, the celestial navigation, the visual navigation, and the integrated navigation methods are all introduced. Their advantages and the disadvantages are presented respectively. Second, the specific autonomous navigation for the Mars exploration is addressed. The corresponding navigation techniques are illustrated for different mission phases, including the launch phase, the cruise flight phase, the EDL phase, and the roving phase. Both the autonomous navigation and the nonautonomous navigation are compared. Third, the challenges and the future development trending of Mars exploration are summarized. Some new developed techniques are illustrated. This article can help the students and the researchers to know the autonomous navigation technology in the Mars exploration mission well.

## Acknowledgements

We have used some pictures from the Internet including the photos and the cartoons. We express our thanks to the authors. This work was supported by

the National Natural Science Foundation of China under Grant No. 61975011 and the Fundamental Research Fund for the China Central Universities of USTB under Grant No. FRF-BD-19-002A.

### **Conflict of interest**

The authors declare no conflict of interest.

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