Deimos rendezvous mission analysis and orbital design based on the Mars survey

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Abstract—Imaging the Martian surface with a sun-synchronous orbit is a fundamental task of most current Mars exploration programs. In this paper, the Mars-Deimos multi-target orbit design is carried out for a small spacecraft that uses the spacecraft's spare spacecraft to achieve a carrier launch. Due to the 92.7° inclination of the working orbit of the main detector, Deimos detection is carried out by means of a swept intersection: The working orbit is designed for a large elliptical orbit with a critical inclination of 116.6° and a lifetime of 280 Deimos intersections. Unlike the Viking-1 orbital control, which is used to suppress arch line drift, the working track maintenance strategy designed in this paper is used only to eliminate tangential drift, and keep the consumption and frequency reducing with increasing orbital accuracy. Finally, the working orbit was analysed for its imaging, illumination and metrological/numeric transmission conditions and the spatio-temporal distribution of occult events between the small spacecraft and the main probe. Deimos imaging plan is used in the pre life descent phase, and Mars surface imaging plan is used in the post life ascent phase. The results of the analysis indicate that the full use of the carrier margin for small spacecraft launch can be carried out, for example, imaging the surface of Mars and Centaur, and covering the earth's atmosphere with the main detector. The working orbit and orbital control strategies are designed to take into account the impact of orbital determination errors and main actuators (both short-period and long-period items, etc.) on the Deimos rendezvous, and to have engineering implementation conditions.

1. INTRODUCTION

Mars, which is a Terrestrial-like planet similar in size to the Earth with a thin atmosphere, has been a hot spot in the international deep space exploration field. Mankind has launched 39 probes to Mars, most of which are planned as basic missions for imaging or surveying the Martian surface by 2007. In order to obtain good imaging results, the detector often operates in a sun-synchronous orbit with an altitude of 300-500 km and a descending intersection point between 10:30 and 11:00 AM [1]. The Earth-Mars transfer orbit needs to be designed based on the inclination of the polar orbit to allow the probe to enter the working orbit directly after being captured by Mars [2].

Mars has two C-shaped asteroid-like moons: Mars I(Phobos) and Mars II (Deimos) [3]. The two moons are irregularly shaped and orbit within the equatorial surface of Mars. The study of Phobos and Deimos soil outer layers helps to obtain information on the origin and evolution of solar system stars and planets. Viking-1 (USA) and Phobos-1/2 (Japan) were targeted by Phobos: Viking-1 successfully achieved Phobos imaging observations by means of a swept rendezvous, while Phobos-1/2 failed to
achieve Phobos detection because of probe failure. Russia planned to implement the Phobos-Grunt Sample Return Mission, which will use a sanitary approach to Phobos detection and sample return.

For Phobos and Deimos probes, both encircling and swiping can be used to achieve multiple close encounters between the detector and the fireguard. Viking-I has rendezvoused with Phobos using an elliptical orbit with a large ring-fire orbit at irregular intervals, but the rendezvous speed is large and the observable time is short; Viking-I has rendezvoused with Phobos using an elliptical orbit with a near-fire height point of 1500 km, an inclination of 39° and an eccentricity of 0.75 \[3,4\]. However, the timing of the rendezvous is very limited and the arch drift needs to be suppressed by orbital control, which does not allow for long-term observation of Phobos \[4\].

In the case of standardized launch vehicles, which often leave a certain amount of weight and space margin for each launch, consideration could be given to making full use of these margins to launch small spacecraft with the support of the Mars environment, cover atmosphere and Mars Mars exploration \[5\]. Enrichment of Mars exploration with small spacecraft inputs at low development costs and rich returns on output.

This paper addresses the orbital design for Mars and Deimos dual-target exploration of small spacecraft taking on board launch and transfer, and satisfies constraints such as vehicle orbital input and mass (orbital control capability). Since the main probe operates in an orbit with an inclination of 92.7° and an altitude of 500×500 km, the small spacecraft has to be rendezvoused in the form of a swept. To reduce the difficulty of orbital control, the working orbit is designed for a large elliptical orbit with a critical inclination of 116.6 and a lifetime of 280 Deimos intersections. Unlike the Viking-I rail control used to suppress arch line drift, the working track maintenance strategy designed in this paper is only used to eliminate tangential drift, and maintenance consumption and frequency decrease with increasing orbital accuracy. Finally, the working orbit is analysed for its imaging, illumination and metrological/numerical transmission conditions, as well as the spatio-temporal distribution of occult events between the small spacecraft and the main probe. The results of the analysis indicate that the full use of the carrier margin for a small spacecraft launch can be carried out both for Mars and Deimos surface imaging and, in conjunction with the main orbiter, for masking atmospheric surveys. The working track and control strategy design have considered track determination errors and main actuator effects on Deimos intersection, and it has the conditions for the implementation of the project.

2. MISSION ANALYSIS

The main probe performs missions such as imaging exploration of the global surface of Mars. The main detector is proposed to operate in a sun-synchronous orbit at an altitude of 500×500 km and 10:30 AM at the descending intersection, based on constraints such as imaging light requirements, imaging resolution and integration time.

The main probe performs the main mission of the Mars survey, and the Earth-Mars Transfer Orbit is designed to meet the requirement that the main probe be able to go directly into working orbit after being captured by Mars. Since the focus of this paper is on orbital design with a small detector, the design process of the ground fire transfer orbit is ignored here and the design results are given only according to the transfer window and the minimum fuel limit: The main probe reached the capture orbit with an inclination of 92.7° and an altitude of 500×76450 km on 21 September 2016. Subsequently, the main detector is captured to the working orbit by a series of in-plane orbital maneuvers (including pneumatic braking \[2\]).

The small spacecraft carries the main probe for Earth-fire transfer and Mars capture, i.e. the spacecraft needs to choose the right timing of separation and rely on its own orbital control capability to transfer to a working orbit. The carrying capacity requires the small spacecraft to have a gross weight of not more than 300 kg and to carry fuel of not more than 55 kg, taking into account platform and load mass limits. For a small spacecraft to have a working orbit with both Mars surface and Deimos imaging conditions, the working orbit needs to meet: (1) During ring fire operation, the design height of the inlet fire point is within the operating range of the load. (2) The working track has a regular or irregular intersection with Deimos. (3) Conditions for the occurrence of a cover event with the main probe. (4)
Mars surface and Deimos imaging with solar altitude angles ranging from 15° to 80° and velocity ratios not exceeding 0.01s\(^{-1}\) (Mars surface) and 0.05s\(^{-1}\) (Deimos). (5) the maximum ground shadow does not exceed 1h during the design life.

3. WORKING TRACK DESIGN AND IMPLEMENTATION

3.1. Working track design
The primary mission of the small spacecraft is to image Deimos multiple times during its lifetime, while assisting the main probe to enable Mars to perform Martian surface imaging and environmental exploration. Because of the adoption of the main rover for Mars capture and the impossibility of 90° inclination adjustment due to its own fuel constraints, the small spacecraft had to adopt a large elliptical orbit for Deimos rover detection. In order to obtain as many intersections as possible, the large elliptical orbit should freeze its near-Mars point angle as much as possible to avoid the phenomenon of arch-line motion resulting in no intersection of the two orbits. At the same time, in order to avoid a reduction in the number of intersections due to phase deviation, the regression track can be set.

Based on these ideas, the orbit can be designed as a 116.6° critical inclination orbit. And according to the regression conditions, the orbital angular rate and the rate of equatorial drift at the ascending intersection satisfy the following relationship:

\[
\begin{align*}
\omega_{\text{Deimos}} \cdot \Delta t - \Omega \cdot \Delta t &= m_1 \cdot 360^\circ \\
\omega \cdot \Delta t &= m_2 \cdot 360^\circ
\end{align*}
\]

(1)

Where \(\omega_{\text{Deimos}}\) is the orbital angular rate of Deimos around Mars, \(\Delta t\) is the rendezvous period, and \(m_1\) and \(m_2\) are intermodal integers.

According to the constraint of 500 km near the fire point height of the capture orbit, the resonance condition is:

\[
\frac{m_2}{m_1} = \frac{3}{2}
\]

(2)

A distant fire point height of 28511.2 km is obtained, namely a half-length axis of 17902.6 km (orbital period of 1212.1 min) with an eccentricity of 0.7823. In order to intersect the trajectories of the small spacecraft and Deimos, the amplitude angle of the near-fire point is taken as 25.87°, 154.13°, 205.87°, 334.13°.

According to equation (1), an average rendezvous cycle of 2.53 days would result in more than 280 rendezvous between small spacecraft and Deimos during the lifetime (two years).

3.2. Maintain control box design
Estimation and control errors in the half-length axis that would cause the small spacecraft to drift back and forth in the direction of flight could cause the spacecraft to be in danger of collision with Deimos. Whereas, since orbital estimation errors do not cause long-term accumulation in the radial direction, the
intersection of the small spacecraft with the Deimos orbital plane can be controlled to the outer radial side (as shown in Figure 1) by inclination and near-fire point amplitude capture, and the distance from this intersection to the Deimos orbit can be kept at a safe threshold, e.g. \( \Delta L = 50 \text{ km} \).

Deimos has a mass of just \( 1.8 \times 10^{15} \text{ kg} \) and runs on a half-length axis of 23460 km with an eccentricity of 0.0002 and an inclination of 1.793°. The amplitude angle of the near-Mars point drifts by approximately 26.8° over the lifetime of the spacecraft and 13.2° over the red longitude of the ascending intersection due to the influence of the non-spherical gravitational perturbation of Mars. Instantaneous change in half-length axis not exceeding 1.5 m, instantaneous change in inclination not exceeding \( 5.5 \times 10^{-5} \)° and instantaneous change in eccentricity not exceeding \( 7 \times 10^{-5} \) relative to average orbital root number. Radial distance changes due to Deimos’ own orbital changes do not exceed 4.7 km.

For a working orbit with a Mars non-spherical gravitational perturbation, the true perigee angle at the rendezvous point is 205.87°. The radial distance variation due to capture error does not exceed 4.8 km when the control accuracy of the amplitude angle of the near fire point is 0.01°.

Based on the above analysis, it is known that the rendezvous distance between the small spacecraft and Deimos will depend on the phase of the small spacecraft or the control accuracy of the half-long axis. A positioning accuracy of 10 km can be achieved based on the orbiting capability of the ground-based measurement and control system and the on-board GNC system, and the improved accuracy of the half-long axis can be achieved within 1 km. Therefore, each phase maintenance is achieved by changing the half-length axis. Based on the estimated accuracy of the half-length axis, each control amount \( \Delta a \) is taken as \( \pm 2 \) km to achieve the reciprocal motion of the small spacecraft within the control box. To avoid causing changes in eccentricity and near-Mars point amplitude, control should be selected at the same position each time; at the same time, slow changes in near-fire point amplitude will result from errors in critical inclination (end-of-life drift of 0.07°, see Section Ⅲ C), which can obviously be eliminated by selecting the control position each time it is maintained.
Taking the Deimos effective detection distance of 100 km as an example, the maintenance control box boundary should be designed to be ±86.8 km, as shown in Figure 2. The time taken for a small spacecraft to complete a motion within the control box, i.e. to maintain control, is approximately 18 orbital cycles (approximately 15 days). Under nominal conditions, the rendezvous distance between the small spacecraft and Deimos varies between 50 and 100 km.

Considering the hydrazine media thruster, a total of 50 maintenance sessions are required over the life of the thruster, each of which consumes approximately 0.03 kg of fuel (210 s specific impulse) and only 1.5 kg for maintenance control.

The working track maintenance strategy designed in this paper is mainly used to eliminate tangential drift caused by orbital errors. Viking-1's swept track maintenance is mainly used to suppress the long-term drift of the arch line caused by the J2 term perturbation, which is more consumed and not improved by the increased track accuracy.

3.3. Working orbit transfer and capture

The small spacecraft carries the main probe for Earth-Mars transfer and Mars capture, and is separated from the main probe and put into operational orbit by selecting the right time. Based on the design output of the ground fire transfer orbit: the main probe's capture orbit was chosen to be a 500×76450 km large elliptical orbit with an inclination of 92.71° and an amplitude of 334.13° at the near-fire point; after successful Mars capture, the main probe will make a series of plane manoeuvres at the near-fire point to enter a 500×500 km working orbit.

The far fire point of the small spacecraft's working orbit is between the main detector capture and the working orbit, so the main detector can separate the small detector during the working orbit capture, and the far fire point height of the intermediate orbit is 2852.3 km. After the small spacecraft is separated, the inclination adjustment $\Delta i = 23.89°$: in order to save fuel consumption, the orbital control position is arranged near the equator; in order to improve the capture accuracy, the inclination adjustment is done several times; the accuracy requirement of the inclination capture is less than 0.01°, then the angular drift of the near fire point at the end of its life does not exceed 0.07°, and the corresponding $\Delta L$ change range is 16.4 to 83.6 km (in fact, the angular drift of the near fire point can be suppressed gradually with each maintenance control). According to the calculations, the total stroke required for inclination adjustment is approximately 303.9 m/s and the fuel consumption is approximately 41.18 kg.

The inclination capture completes the rendezvous between the working orbit and the Deimos operational orbit, and a phase capture is also required to achieve the rendezvous between the small spacecraft and Deimos. Similar to maintenance control, phase capture is achieved by half-length axis control: the adjustment amount $a$ is determined by the phase adjustment amount $u$ and the adjustment period, namely:

$$\Delta u = -3\pi \frac{\Delta a \cdot m}{a}$$ (3)

where $m$ is the number of orbital laps.

Fuel consumption is inversely proportional to the adjustment period, which can be achieved by extending the adjustment time to save fuel: if the amount of phase adjustment meets $0° < \Delta u < 180^°$, it will be controlled by the "lower - higher" half-length axis; if the amount of phase adjustment meets $180° < \Delta u < 360°$, it will be controlled by the "higher - lower" half-length axis. The timing of the separation of the small spacecraft from the main probe can be selected in conjunction with phase
capture: the phase difference between the small spacecraft and Deimos can be essentially eliminated by selecting the appropriate separation timing; taking the phase difference between the two after separation as an example of 10, the fuel consumption required for phase capture is shown in Table 1.

| Adjustment cycle [days] | Number of orbital laps m | Δa [km] | Δm [kg] |
|------------------------|--------------------------|---------|---------|
| 8.4                    | 10                       | 33.2    | 0.44    |
| 16.8                   | 20                       | 16.2    | 0.22    |
| 25.2                   | 30                       | 11.1    | 0.145   |
| 33.6                   | 40                       | 8.3     | 0.11    |

Various perturbations in the ground fire transfer section will result in errors in the near-fire point amplitude; errors in inclination capture may result in end-of-life near-fire point amplitude deviations of 0.07°; therefore, near-fire point amplitude capture may be required when inclination capture is complete or mid-life. For example, if the error of the magnitude of the in-orbit near-fire point of the ground fire transfer is 1°, the adjustment manoeuvre needs to be carried out at an angle of latitude u = 154.574°, the required ΔV is 23.98 m/s and the fuel consumption Δm is about 3.2 kg.

In summary, the small spacecraft will carry out orbital manoeuvres such as inclination, near-Mars point amplitude and phase capture after the separation of the main probe mount, consuming about 44.88 kg of fuel; during its lifetime, the small spacecraft will achieve phase and near-fire point amplitude maintenance by controlling the half-length axis, consuming about 1.5 kg of fuel; taking into account the fuel required for attitude control to achieve orbital engine orientation (calculated on the basis of 10 per cent balance of orbital control consumption), the fuel required for the small spacecraft will not exceed 51.5 kg, meeting the overall mission requirement of "fuel less than 55 kg".

4. ORBITAL CHARACTERIZATION

4.1. Analysis of imaging conditions
According to the mission analysis: the small spacecraft will image Mars near the near-fire point to assist the main probe in completing global surface mapping; the small spacecraft will image during the fly-by Deimos.

According to the resolution requirements, the working altitude of the imaging payload is limited to 600 km, and the small spacecraft imaging region has a latitude range of -4° to 40° and an imaging time of 608s. Figure 4 shows the trajectory of the small spacecraft at the inferior point on the surface of Mars, with both the ascending and descending segments passing through the -4° to 40° region. The average altitude of the descending segment reaches 11036 km, which is not conducive to high-resolution image acquisition.

![Figure 4 Trajectory of small spacecraft at the sublunar point on the surface of Mars](image)
Figure 5 gives the speed-to-altitude variation in the imaging region: the speed-to-altitude variation ranges from 0.006 to 0.008 s\(^{-1}\) in the ascending orbit and reaches its maximum at the near-Mars point (i.e. \(-23.2^\circ\) latitude); the speed-to-altitude variation ranges from 1.610\(^{-5}\) to 1.510\(^{-4}\) s\(^{-1}\) in the descending orbit.

![Speed-to-height ratio curves for the ascending and descending rail sections](image)

**Figure 5** Speed-to-height ratio curves for the ascending and descending rail sections

Based on the ascending node equinox of the capture orbit after the completion of the ground fire transfer by the main detector, the variation of the solar altitude angle at \(-4^\circ\) and \(40^\circ\) latitudes is obtained as shown in Figure 6: at the beginning of the entry orbit, the altitude angle of the ascending section gradually decreases to 0\(^\circ\); then the altitude angle of the descending section increases from 0\(^\circ\) to the maximum and then begins to decrease; as the altitude angle of the descending section decreases to 0\(^\circ\), the altitude angle of the ascending section begins to increase to about 70\(^\circ\). It should be noted that both the ascending and descending sections have altitude angles greater than 0\(^\circ\) at latitude -40 during the initial entry phase.

Therefore, small spacecraft imaging of Mars should be arranged in the ascending orbit segment and the velocity-to-altitude ratio and solar altitude angle meet the imaging conditions.

![Solar altitude angle curves for the ascending and descending orbital segments](image)

**Figure 6** Solar altitude angle curves for the ascending and descending orbital segments

Since the small spacecraft is required to meet the requirement that "the small spacecraft is located between Deimos and the Sun" for optical imaging of Deimos, the small spacecraft is required to rendezvous outside Deimos, i.e. \(\Delta L > 0\). The speed of rendezvous between the two is about 2 km/s, and the speed-to-aspect ratio of imaging is 0.02 to 0.04 s\(^{-1}\). Figure 7 shows the solar altitude angle during Deimos imaging.
Figure 7 Solar altitude angle curves imaged by Deimos

The rendezvous between the small spacecraft and Deimos takes place only in the descending segment, so load imaging should be scheduled in the descending segment, and both the velocity-to-altitude ratio and solar altitude angle meet the imaging conditions. Therefore, depending on the conditions for small spacecraft imaging of Mars and Deimos, the following arrangements could be made: Deimos imaging is scheduled in the pre-life descending segment and Mars surface imaging is scheduled in the end-life ascending segment.

The luminous characteristics of the working track can be obtained according to the input conditions of the ground fire transfer track as shown in Figure 8.

The small spacecraft will remain in the sunny zone after entering orbit until December 2016; ground shadowing will occur thereafter and the longest ground shadowing time will be approximately 32 min; from March 2018 to October 2018, the small spacecraft will remain in the groundless zone. Thereafter, the detector has exceeded its design life, although it will have its longest shadow (approximately 202.7 min).

Figure 8 Curves of shading time over the lifetime

Based on the above analysis, it is known that the designed orbit meets the conditions required for imaging the Martian surface and Deimos.

4.2 Floor/apparatus visibility analysis

The visibility of the ground station and small spacecraft determines the measurement, control or digital transmission capability. Due to the remoteness of Mars from Earth, the results of the visibility analyses for the different sites are largely consistent, as shown in Figure 9. The ground station has 1 to 2 visible opportunities per day, and the minimum value of the total visible time per day is 424 min, the average value is 668 min, and the maximum value is 836.2 min. The maximum visible distance is about 40.025107 km on August 5, 2017, and the minimum on July 30, 2018, about 6.205×107 km.
In combination with the imaging conditions, the following conclusions can be drawn: during Deimos imaging, the signal attenuation at a distance of more than 100 dB is appropriate for transmission at a low code rate; during Mars surface imaging, transmission at a high code rate is possible at a slightly closer distance.

The small spacecraft and the main probe orbit at different altitudes, each visible to the other and with conditions for the occurrence of occult events. Refractive phenomena based on masked stars. It is possible to study the composition of the Martian atmosphere and its content. Figure 10 gives the distribution of the central tangent point of occult star occurrence (altitude 60 km) at latitude over its lifetime. During one orbital period, the small spacecraft and the main probe had two occurrences, one near and one away from the perigee; since the perigee of the large elliptical orbit was frozen, i.e., the perigee was at -23° latitude; therefore, occurrences above -23° latitude occurred in the segment away from the perigee and occurrences below -23° latitude occurred in the segment near the perigee.

5. CONCLUSION
Imaging the Martian surface using a sun-synchronous orbit is a fundamental mission of most current Mars exploration programs. This paper provides mission analysis and orbital design for the Mars-Deimos twin-target exploration of small spacecraft for piggyback launches using the vehicle's spare capacity. The main probe on board operates in a 500×500km sun-synchronous orbit, and the small spacecraft to achieve Deimos imaging observations requires the use of swept rendezvous, and operates in a large elliptical orbit with an inclination of 116.6°, a half-long axis of 17902.6km, and an eccentricity of 0.7823 for a critical inclination, and can achieve 280 Deimos rendezvous during its lifetime. Unlike the Viking-1 orbital control used to suppress arch drift, the working orbital
maintenance strategy designed here is designed to eliminate tangential drift only and to reduce maintenance consumption and frequency as orbital accuracy increases.

Finally, the imaging, illumination and control/data transmission conditions, as well as the spatio-temporal distribution of occult events among the "stars" were analysed for the working orbits, and the imaging conditions of Mars and Deimos were arranged according to the small spacecraft as follows: Deimos imaging was arranged in the pre-life descending segment and Mars surface imaging was arranged in the end-of-life ascending segment.

The results of the analysis showed that: the full use of the carrier margin for a small spacecraft launch, both for imaging the surface of Mars and Deimos, as well as for joint atmospheric detection with the main probe, etc.; the working orbit and control strategy was designed to take into account orbit determination errors and the impact of the main actuator on the Deimos rendezvous, and the conditions for engineering implementation.

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