Landing Control Scheme of Mars Probe

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Abstract: The successful launch, continuous flight, subsequent circling, landing and patrol of Tianwen-1 Mars probe show that deep space exploration is one of the most challenging fields of high technology in the world today. Problem one:Because the landing process of the detector is constantly changing, the landing process is firstly simplified into three stages for research. Secondly, the stress analysis of the three stages is carried out and the corresponding dynamic equations are established, and the nonlinear programming model is established. At last, the shortest landing time of the detector is 41.7426s through Matlab solution. Problem two:It is determined that the power deceleration stage is the main stage of fuel consumption, and the force analysis of this stage is carried out. The corresponding dynamic equations are established and the equations based on the law of conservation of energy are written. Taking energy as the objective function, energy conservation and kinematics equation as constraints, the nonlinear programming model is adopted, and finally, the minimum fuel consumed by the detector in the EDL process is m0=0.0272kg through Matlab solution. Problem three:Considering the coincidence between the landing process of the detector and the actual situation, the relevant data of the landing process of Tianwen-1 is collected at first. Secondly, the relevant data are fitted by interpolation method, and finally, the movement trend of each stage is solved by Matlab, and then the optimal control scheme is obtained.

1. Introduction

1.1 Related Background

1.1.1 Mars Probe-Tianwen-1

Mars probe, that is, an artificial spacecraft used to survey Mars. It consists of three parts: the surround, the lander and the patrol.

In the history of world space flight, Tianwen-1 not only left the imprint of Chinese people on Mars for the first time, but also successfully achieved the three goals of circling, landing and patrolling Mars in one mission for the first time, which fully demonstrated the wisdom of Chinese astronauts and marked China's entry into the world's advanced ranks in the field of planetary exploration [1].

1.1.2 Edl Process

The entry, descent and landing of Mars probe Tianwen-1 are the most critical links in the whole landing process of Mars. EDL process, that is, four stages in the deceleration landing process.

The first stage: the atmospheric deceleration stage. When the Mars probe enters the Martian atmosphere, the relative speed of the probe is between 4 and 7 km/s, and it reduces the speed to about 2Ma by using the aerodynamic resistance generated by the atmosphere in Mars.

The second stage: parachute deceleration stage. Parachute is a common deceleration device in the deceleration system of space landing. When the landing patrol decreases to a certain speed, that is, about 2Ma, open the damping umbrella to further consume the kinetic energy of the detector, so as to achieve the purpose of deceleration [2].

The third stage: the dynamic deceleration stage. Because the atmosphere of Mars is thin, after the deceleration in the first two stages, it still has a speed of about 95m/s. The engine carried by the lander will find a suitable time to start in the opposite direction of its own movement, which will generate a reverse thrust on itself, so as to achieve the effect of using the power of the engine to slow down.

The fourth stage: the landing buffer stage, in order to ensure a safe landing on the surface of Mars, it is necessary to reduce the speed of the probe to a relatively static state with Mars.

1.2 Problems to Be Solved

1)Determine the control scheme with the shortest time required by the detector during landing.

2)For a given landing time, in order to achieve the minimum energy consumption, the control scheme of the detector.

3)Determine the control scheme that can keep the landing process of the detector consistent with the public images and data.

2. Problem Analysis

2.1 Overall Analysis

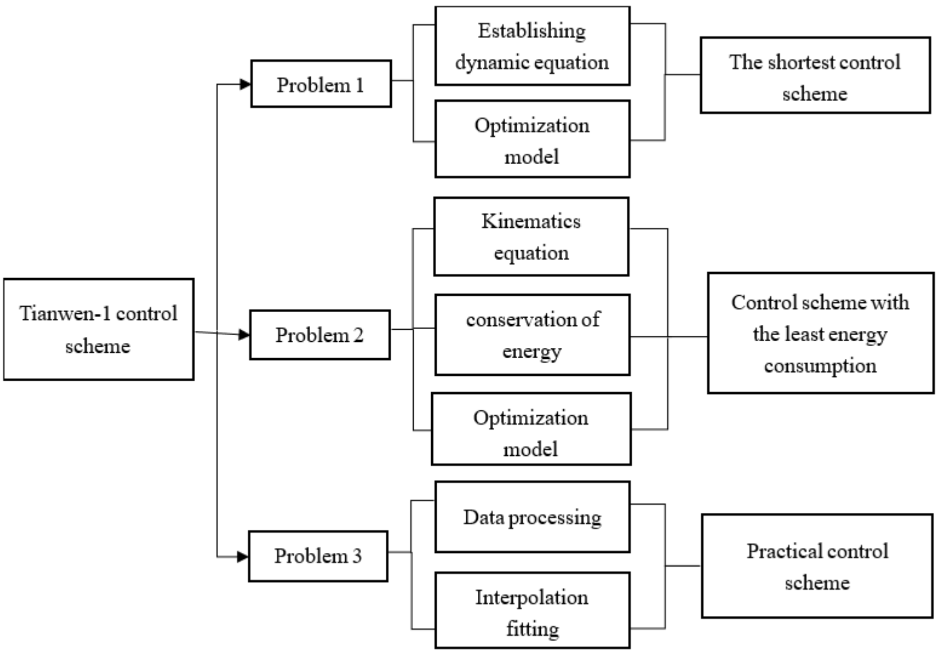

Fig.1 The General Idea of the Problem

2.2 Analysis of Specific Problems

For problem 1:

In order to determine the control scheme that makes the detector spend the shortest time in the landing process. Firstly, the four stages of landing process (pneumatic deceleration stage, parachute deceleration stage, dynamic deceleration stage and landing buffer stage) are analyzed, and it is concluded that only the first three stages need to be considered, so the goal can be achieved by minimizing the sum of the three stages. Secondly, the stress analysis of each stage is carried out, and the corresponding dynamic model is established. Finally, by describing the dynamic models of each stage, the control scheme with the shortest time consumption in the landing process is obtained by using Matlab.

For problem 2:

For a given landing time, in order to determine the control scheme that the detector consumes the least energy in the landing process. First of all, after consulting the data, we know that the stage of energy consumption is mainly in the third stage, that is, the power deceleration stage; Secondly, the force analysis of the detector in the third stage is carried out, and the kinematics equation and momentum conservation equation in this stage are obtained. Combined with the kinematics equations of each stage in the first problem, the relevant models are established. Finally, the minimum mass m_0 of energy used in the third stage is obtained by solving the above model.

For problem 3:

In order to make the landing process as consistent as possible with the public audio-visual and written materials. First, find the relevant information and data about Tianwen-1's landing; Secondly, combining the models of Problem 1 and Problem 2, we screen the obtained information data and get effective data from it. Finally, the model is introduced, the data is fitted by interpolation, and the effective data is substituted into the model to obtain the control scheme.

3. Model Assumptions

3.1 Only Consider the Gravitational Influence of Mars on Tianwen-1

Because the landing stage of Tianwen-1 is near Mars, far away from the earth, the sun and other planets, we can ignore the influence of the forces of other planets except Mars, and only consider the forces of Tianwen-1 and Mars, that is, the probe landing problem is simplified as a two-body problem.

Actually, the mass of the earth is $M_E = 5.965 \times 10^{24}$ kg ,the mass of the Mars is $M_M = 6.417 \times 10^{23}$ kg , the mass of the sun is $M_s = 1.989 \times 10^{30}$ kg ,The distance from Tianwen-1 to the earth is $r_E = 1.67 \times 10^{10}$ m,The distance from Tianwen-1 to the earth is $r_S = 1.66 \times 10^{11}$ m,The distance between Tianwen-1 and Mars is $r_M = 1.25 \times 10^5$ m,So the gravitational acceleration of the earth to Tianwen-1 is

$$g_E = \frac{GM_E}{r_E^2} \approx 1.4272 \times 10^{-6}\ (\mathrm{kg/s^2}) \quad (1)$$

The gravitational acceleration of Mars Tianwen-1 is

$$g_M = \frac{GM_M}{r_M^2} \approx 2.7404 \times 10^{3}\ (\mathrm{kg/s^2}) \quad (2)$$

The gravitational acceleration of the sun's Tianwen-1 is

$$g_s = \frac{GM_s}{r_S^2} \approx 4.8 \times 10^{-3}\ (\mathrm{kg/s^2}) \quad (3)$$

It can be seen that Tianwen-1 is mainly affected by the gravity of Mars.

3.2 The Non-Inertial Coordinate System of Fire Center is Approximate Inertial Coordinate System

The rotation speed of Mars is $\omega = 7.0882 \times 10^{-5}$ rad/s,The maximum centrifugal acceleration of Tianwen-1 is

$$\alpha = \omega^2 r \approx 0.1026\ \mathrm{kg/s^2} \quad (4)$$

The non-inertial coordinate system is approximated to the inertial coordinate system, and the maximum possible acceleration error is far less than the acceleration caused by the gravitational force of Mars. Therefore, the influence of the non-inertial coordinate system is not considered in the soft landing process.

3.3 The Landing Track and the Falling Track Are on the Same Plane

From 3.1 and 3.2, without considering the rotation and revolution of Mars and the gravitational force of other celestial bodies, if the landing preparation orbit and the falling orbit are not on the same plane, the main deceleration engine needs to provide more lateral thrust, thus increasing the fuel consumption. Therefore, it is reasonable to design the landing preparation track and the falling fire track on the same plane in practice.

3.4 Only the First Three Stages Are Considered in the Landing Process

The EDL (landing) stage can be divided into four stages, including pneumatic deceleration stage, parachute deceleration stage, power deceleration stage and landing buffer stage in turn. Starting from the separation of Tianwen-1's orbiter from the lander, that is, entering the atmosphere, according to the relevant data, it can be found that Tianwen-1 is 125km away from the surface of Mars, while in the landing buffer section, Tianwen-1 is only 100m away from Mars when hovering over Mars. Since 100m is far less than 125km, only the remaining three stages need to be considered.

3.5 Tianwen-1 is Only Affected by the Gravity of Mars in the Aerodynamic Deceleration Stage

First of all, when entering the stage of aerodynamic deceleration, Tianwen-1 needs to trim the angle of attack with the help of the engine. At this time, Tianwen-1 will receive a thrust from the engine in the horizontal direction. However, the force in the horizontal direction only acts as a balance for the detector and has no influence on the vertical direction. Therefore, it is unnecessary to consider this thrust when the detector is landing. At present, some data show that the atmospheric density in Mars is only 1% of the earth's atmospheric density, and there is great uncertainty. Therefore, the air resistance of Mars atmosphere to the probe is not considered in the aerodynamic deceleration stage.

4. Symbol Description

Symbol descriptions are shown in Table 1

Table 1 Symbol Description

Symbol	Description	Unit
s_i(i=1,2,3)	Distance of stage i	m
t_j(j=1,2,3)	At the end of stage j	s
v_k(k=1,2,3)	instantaneous velocity of stage z	m/s
g_M	Gravity acceleration of Mars	N/kg
C	Resistance coefficient of damping umbrella	cd
ρ	The atmospheric density of Mars	kg/m^3
S	Windward area of damping umbrella	m^3
a_m(m=1,2)	acceleration	m/s^2
F_{re}	Air resistance caused by damping umbrella	N
F_{engine}	Thrust generated by the engine	N

5. Establishment and Solution of the Model

5.1 The Analysis and Solution of Problem 1

5.1.1 Analysis

Firstly, through the force analysis of the three stages of the landing process, the dynamic equation is established, and the relationship between speed and time in each stage is obtained. Then, the shortest control scheme is obtained by Matlab solution and the v-t images of each stage are drawn.

5.1.2 Solution

1)Preparation of model

There are three main stages in the landing process of Tianwen-1, namely, pneumatic deceleration stage, parachute deceleration stage and dynamic deceleration stage. Carry out force analysis of each stage, As show in fig.2. draw the corresponding force analysis diagram and establish the dynamic equation of each stage.

Pneumatic deceleration section:

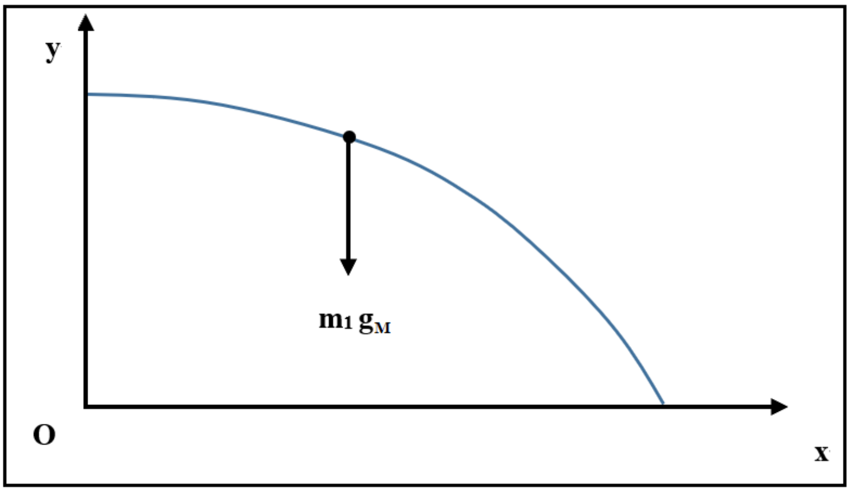

Fig.2 Force Analysis of Pneumatic Deceleration Section

After analyzing the hypothesis, it is concluded that in the first stage, that is, the power deceleration stage, after the orbiter is separated from the lander, the probe is only affected by the gravity of one Mars. At this stage, the detector moves uniformly at the initial velocity v_0=4800m/s and the acceleration is the gravitational acceleration g_M of Mars. The kinetic equation is as follows:

$$\begin{cases} v_1 = v_0 + g_M t \\ S_1 = v_0 + \frac{1}{2} g_M t^2 \end{cases} \quad (5)$$

The Parachute deceleration section is shown in fig 3:

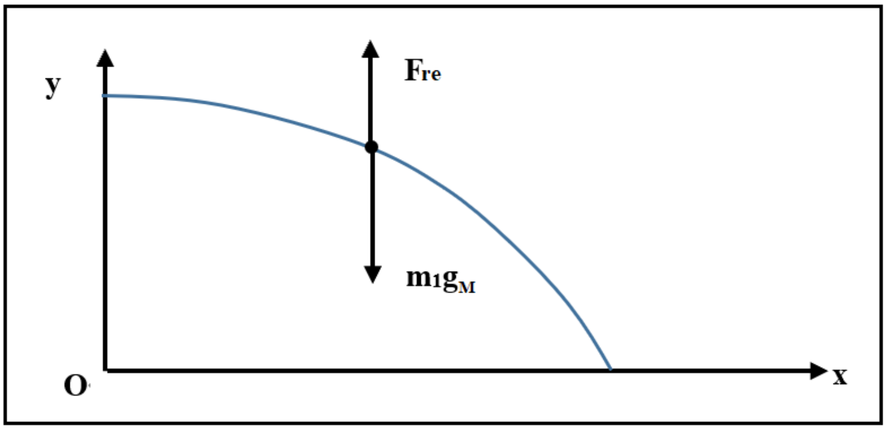

Fig.3 Force Analysis of Parachute Deceleration Section

When the damping umbrella is opened, the detector will not only be affected by the gravitational force of Mars, but also by the air resistance F_{re} of the damping umbrella, which is related to the air resistance coefficient C, the atmospheric density ρ of Mars, the windward area S and the velocity V of the damping umbrella. Using the linear least square method, the air resistance coefficient is 2.95753. After the size of the damping parachute is determined, the windward area can be determined. The area of the Tianwen-1 parachute is 200 m^2, and the air resistance is directly proportional to the square of the speed [3]. Therefore, the scaling coefficient can be set to k,

$$k = \frac{1}{2} C \rho S \quad (6)$$

The magnitude of air resistance can be written as:

$$F_{re} = kv^2 \quad (7)$$

After considering the air resistance caused by the damping umbrella, the speed will not decrease indefinitely, and it will eventually tend to a stable value, and then the motion will be uniform linear motion. This stable value v_2 can be obtained by the equation:

$$F_{re} = m_1 g_M \quad (8)$$

v_2=35.9m/s

The dynamic equations in the second stage are:

$$\begin{cases} v_2 = v_1 + a_1 t \\ F_{re} - m_1 g_M = m_1 a_1 \\ S_2 = \int_{t_1}^{T} v_2 \, dt + v_2(t_2 - T) \end{cases} \quad (9)$$

Power deceleration section: As shown in Figure 4:

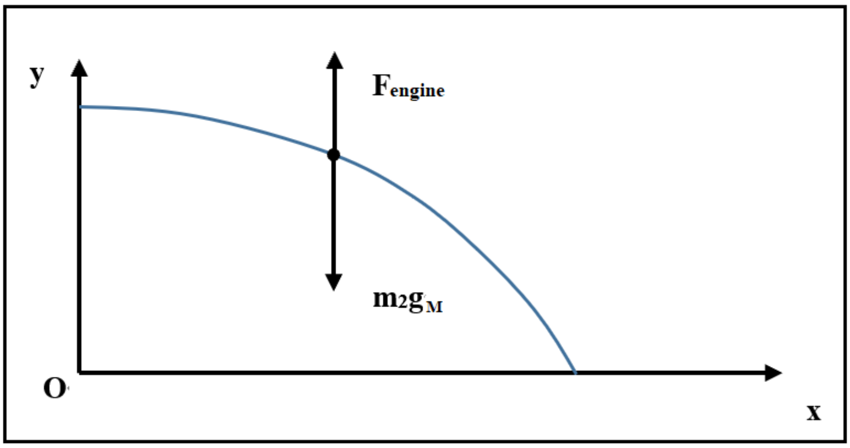

Fig.4 Force Analysis of Deceleration Section

At this stage, the detector is affected by the constant thrust F_{engine} of the engine and the gravity of Mars. At this stage, the detector makes uniform deceleration motion with initial velocity v_2 and acceleration a_2.

The kinematic equations in this section are as follows:

$$\begin{cases} mg_M - F_{engine} = ma_2 \\ v_3 = v_2 + a_2 t \\ S_3 = \frac{1}{2} v_2 (t_3 - t_2) \end{cases} \quad (10)$$

2)Establishment of model

Decision variable: the landing time of Tianwen-1 t_3

Objective function: A control scheme whose objective is to minimize the time of the detector during landing:

$$\min \ z = t_3 \quad (11)$$

Constraint condition:

$$\begin{cases} v_1 = v_0 + g_M t \\ S_1 = v_0 t + \frac{1}{2} g_M t^2 \\ v_2 = v_1 + \int_{t_1}^{T} a_1 dt \\ m_1 g_M - F_{re} = m_1 a_1 \\ S_2 = \int_{t_1}^{T} (v_1 + \int_{t_1}^{T} a_1 dt) dt + v_2 (t_2 - T) \\ v_3 = v_2 + a_2 t \\ S_3 = \frac{1}{2} v_2 (t_3 - t_2) \\ m g_M - F_{engine} = m a_2 \end{cases} \quad (12)$$

3)Solution of the model

The v-t image of pneumatic deceleration section is shown in the figure 5:

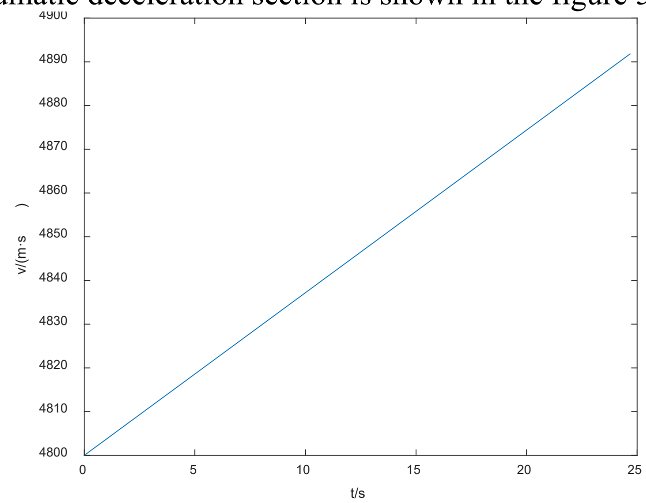

Fig.5 V-t Image of Pneumatic Deceleration Section

Through the analysis of the first stage, the v-t image of the pneumatic deceleration stage is drawn by Matlab, and it can be seen that in this stage, the detector moves in a straight line with uniform acceleration at an initial speed of 4,800 m/s and an acceleration of 3.72m/s^2, and the time t_1 consumed by the detector in the first stage is 24.6947s.

The v-t image of the parachute deceleration section is shown in the figure 6:

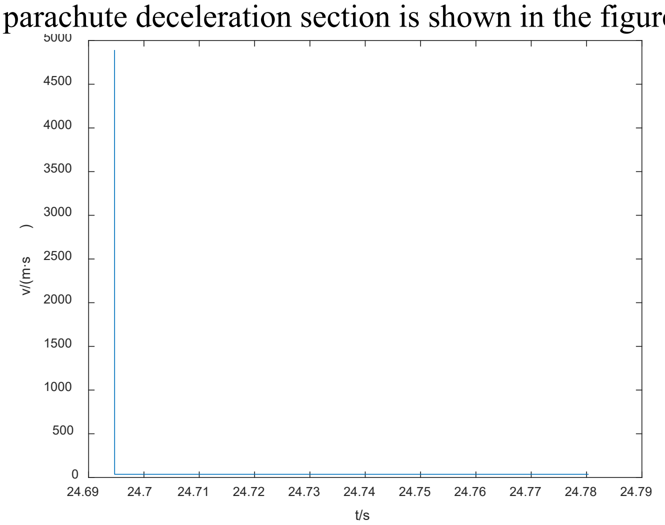

Fig.6 V-t Diagram of Parachute Deceleration Stage

According to the v-t image of the parachute system in the deceleration stage, there are two movements of Tianwen-1 in this stage. First, the detector is acted by the air resistance F_{re} at the moment when the parachute is just opened. At this moment, the resistance and the gravitational force of Mars exist at the same time, and the detector moves slowly. The time t_2 from the first stage to the deceleration is 24.7378s Secondly, the Tianwen-1 won't always slow down. When the air resistance is equal to the gravity of Mars, the resultant force will be zero. The detector will move at a constant speed of 35.9m/s, and the time t_3 from the first stage to the constant speed will be 24.7804s. Finally, the total consumption time in the deceleration stage of the parachute system is 0.0857s..

The v-t image of the deceleration section is shown in the figure 7.

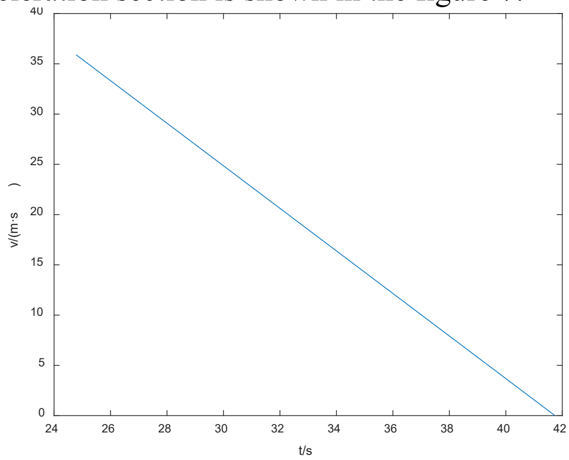

Fig.7 V-t Image of Power Deceleration Section

Through the analysis of dynamic deceleration, the v-t image of this section is obtained by Matlab solution, and the detector is affected by the thrust of the engine and the gravity of Mars at the same time. At this point, the detector moves at a uniform deceleration, and the time consumed by the detector at this stage is 16.9622s.

The three stages of the EDL process are analyzed respectively, and the shortest time consumed by each stage is obtained by Matlab solution. Based on the above, the shortest time t_4 consumed by Tianwen-1 in the landing process is 41.7426s s.

5.2 Analysis and Solution of the Problem 2

5.2.1 Analysis

Firstly, through analysis and hypothesis, it is determined that the power deceleration stage is the main energy consumption stage, and according to the energy quality consumption, the operation scheme with the least energy consumption is determined. Secondly, the kinematics equations of each stage are combined with the conservation of energy, the relevant models are established, and the control scheme with the least energy consumption is solved by Matlab.

5.2.2 Solution

1)Preparation of model

During the landing process of the probe, this paper only considers the energy consumption in the third stage in the research of the probe landing process. Assuming that the energy in other stages has no influence on this study, it can be neglected.

In the process of landing in Tianwen-1, the given time is set as T, and it is assumed that T is large enough and conforms to the actual situation, so as to avoid the influence of time on energy consumption. In order to minimize the energy consumption, firstly, the mass m_0 of fuel is determined as the decision variable, and secondly, the objective function of minimizing the energy consumption is determined, that is, the mass m_0 of fuel is minimized.

The unit of specific impulse (specific impulse) is m/s, and the following relation is satisfied:

$$F = v\frac{dm}{dt} \quad (13)$$

Where f is the thrust of the engine, and the unit is n; v is specific impulse, in m/s; dm/dt is the kilogram of energy consumption per unit time[4]. According to the relevant data, the specific impulse of liquid engines related to aerospace is 4600 m/s. Tianwen-1 consumes 0.625kg of fuel per second..

By formula:

$$n = \frac{dm}{dt} \quad (14)$$

availableness:

$$F = vn \quad (15)$$

The n is the kilogram of energy consumption per unit time..

When solving problem 2, we mainly consider the energy consumption of the power deceleration section and combine it with the dynamic equations of other stages in problem 1 to solve the objective function.

The force analysis of the deceleration section is shown in Figure 8:

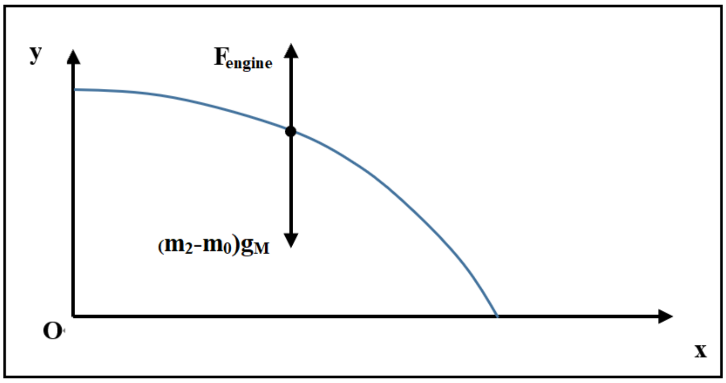

Fig.8 Force Analysis of Deceleration Section

The dynamic equation can be obtained from the stress analysis in the third stage:

$$F_{engine} - (m_2 - m_0)g_M = (m_2 - m_0)a_3 \quad (16)$$

2)Establishment of model

Decision variable: mass of fuel, m_0

Objective function: A control scheme aiming at minimizing fuel consumption:

$$min\ z = m_0 \quad (17)$$

Constraint condition:(power deceleration section)

$$\begin{cases} n = \frac{dm}{dt} \\ F_{engine} = vn \\ F_{engine} - (m_2 - m_0)g_M = (m_2 - m_0)a_3 \\ m_0 = \int_{t_2}^{t_3} n\, dt \\ v_3 = v_2 + \int_{t_1}^{T} a_3 dt \\ S_2 = \int_{t_2}^{t_3} (v_1 + \int_{t_2}^{t_3} a_3 dt) dt + v_3(t_3 - t_2) \end{cases} \quad (18)$$

3)Solving the model

According to the optimization model established above, the minimum mass of fuel consumption is obtained through Matlab solution, and the v-t image in the landing process is drawn, as shown in the following figure 9:

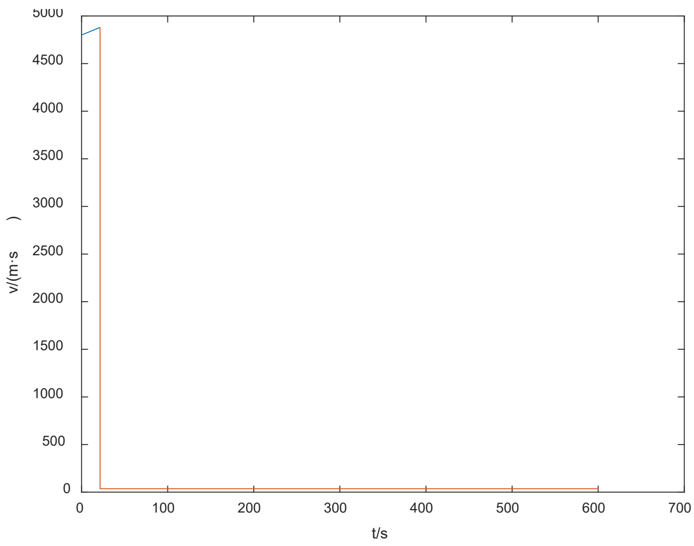

Fig.9 V-t Image of Edl Process

According to the image, the time in the pneumatic deceleration section is 21.4769s, the time in the parachute deceleration section is 578.4795s, and the time in the power deceleration section is 0.0436s Finally, the minimum fuel consumed by the probe during landing is 0.0272kg.

At the same time, according to the above conclusion, the s-t image in the landing process is drawn by Matlab as follows figure 10:

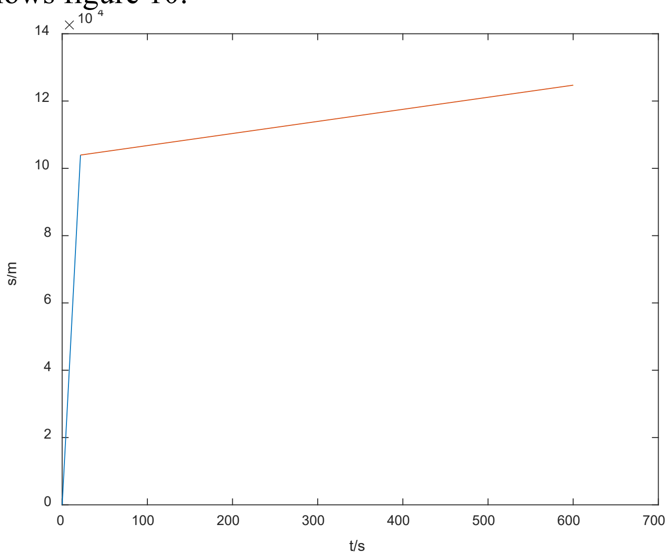

Fig.10 s-t Image of Edl Process

From the s-t image drawn by Matlab, it can be seen that the distance traveled by the detector is the largest in the first stage. Because the Tianwen-1 is only affected by the gravitational force of Mars in the first stage, the descending speed is faster and faster, and the traveling distance is also increased. The distance traveled in the third stage is the shortest. In order to achieve the goal of minimizing fuel consumption, the distance of power deceleration section should be shortened as much as possible.

5.3 Analysis and Solution of Problem 3

5.3.1 Analysis

After collecting the relevant information, the obtained information and data are screened combined with the models of question 1 and Question 2 to obtain the speed and time information and data of tianwen-1 detector in each stage. According to the above data, the model is introduced and the data is fitted by the interpolation method, and the effective data is replaced into the model to get the control scheme.

5.3.2 Solution

1)Preparation of model

The landing process of the probe is divided into four stages. In the pneumatic deceleration stage, the probe decelerates by the resistance of the Martian atmosphere. In the deceleration section of the parachute system, when the speed of the Mars probe reaches 2Ma, the probe opens the damping parachute and decelerates it through the resistance of the damping parachute; At the power deceleration stage, the Tianwen-1 still has a speed of 95m/s, and at this time, the engine mainly provides 7500N for its deceleration; In the landing buffer phase, the probe finally landed according to the distance of about 100m from the surface of Mars.

Sort out the speed and time data of Tianwen-1 in each stage of landing process. See the following table 2 for specific data:

Table 2 Speed and Time Data of Each Moment

Number	velocity(m/s)	time(s)
1	v_0=4800	t_0=0
2	v_1=460	t_1=300
3	v_2=250	t_2=340
4	v_3=95	t_3=390
5	v_4=3.6	t_4=480

2)Establishment of model

In order to make the control scheme closer to the real situation, the air resistance of the detector in the pneumatic deceleration section is taken into account and set as F_{re}.

The models of each stage are as follows:

$$\begin{cases} \textit{First stage} \quad v = v_0 + a_0 t \quad 0 < t < t_1 \\ \textit{Second stage} \begin{cases} v_1 = v_0 + a_0 t_1 \\ v = v_1 + \int_{t_1}^{t_2} a_1\, dt \quad t_1 < t < t_2 \end{cases} \\ \textit{Third stage} \begin{cases} F_{engine} - (m_2 - m_0) g_M = (m_2 - m_0) a_3 \\ v_3 = v_2 + \int_{t_1}^{T} a_3 dt \\ v_2 = v_1 + \int_{t_1}^{T} a_1 dt \end{cases} \end{cases} \tag{19}$$

After the model is established, the data from the landing process of the probe is brought into the model and fitted.

3)Solution of the model

Through the velocity and time data in Table 2, the v-t image fitted by Matlab is shown in the following figure 11:

Pneumatic deceleration section:

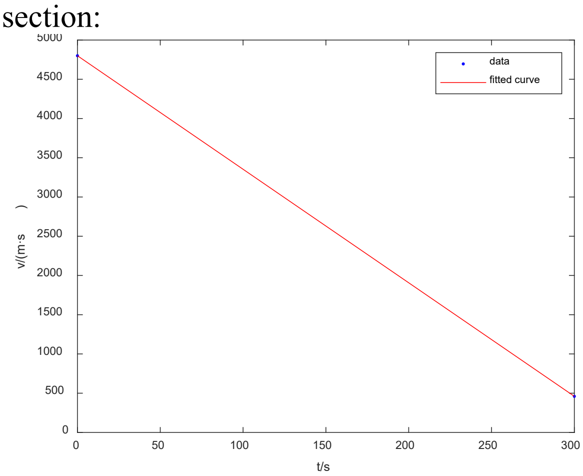

Fig.11 V-t Image of Pneumatic Deceleration Section

In the first stage, that is, the pneumatic deceleration section, the detector makes a uniform deceleration motion with an initial speed of 4,800 m/s and an acceleration of 14.47m/s^2.

At this point, the relationship between speed and time is:

$$v = -14.47t + 4800 \qquad 0 < t < 300 \qquad (20)$$

Parachute deceleration section as shown in Figure 12:

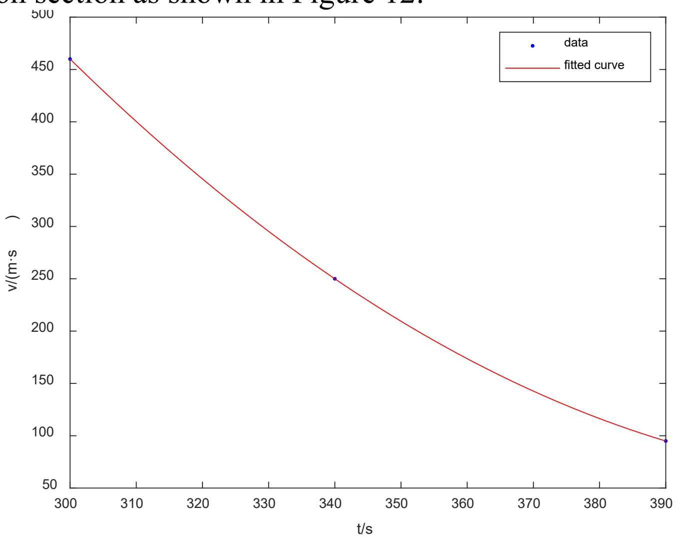

Fig.12 V-t Image of Parachute Deceleration Section

In the second stage of the landing process, that is, the parachute deceleration section, the probe decelerated at an initial speed of 460m/s. At this point, the relationship between speed and time is:

$$v = 0.02389x^2 - 20.54x + 4472 \qquad 300 < t < 390 \qquad (21)$$

The Power deceleration section is shown in Figure 13:

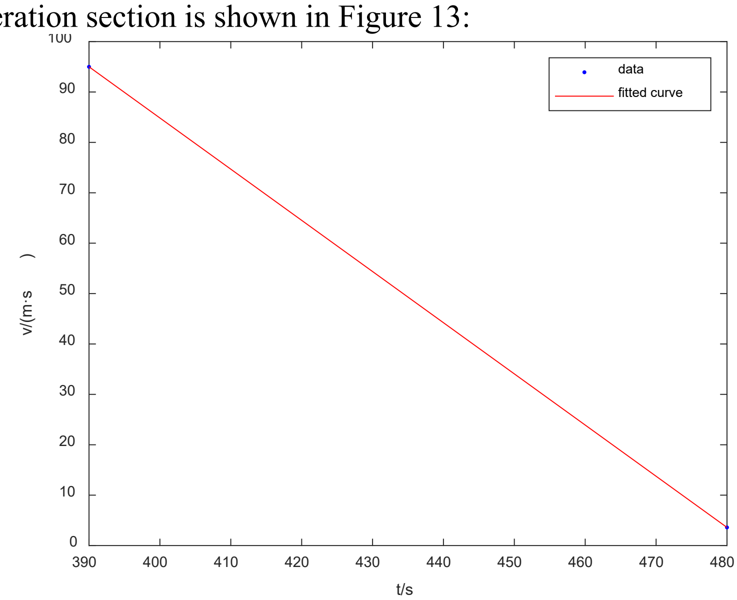

Fig.13 V-t Image of Power Deceleration Section

In the dynamic deceleration section, the detector makes a uniform deceleration motion with an initial speed of 95m/s and an acceleration of 1.016m/s^2.

At this point, the relationship between speed and time is:

$$v = -1.016t + 491.1 \qquad 390 < t < 480 \quad (22)$$

6. Error Analysis

(1) When solving the problem, the height of the probe relative to the center of the Mars sphere changes, which will make the acceleration of gravity constant, so there will be some errors.
(2) In the stress analysis of question 1 and question 2, because the air resistance is related to the air resistance coefficient, and the resistance coefficient is affected by the air density of different heights, setting the air density to a fixed value will cause some errors to the resistance, but will not affect the solution of the final model.
(3) Question 3: When fitting, there are few published materials, and due to the limitation of data, it is impossible to fit a more accurate v-t function image.

7. Model Evaluation and Promotion

7.1 Advantages of Model

(1) In this paper, many factors affecting the landing of the probe to Mars are fully considered. For example: air resistance coefficient, parachute area, etc.
(2) Solve practical problems according to relevant kinetic equations and the law of conservation of energy. At present, the law of conservation of energy is quite mature and has high reliability.
(3) The model established in this paper is closely related to the reality, and at the same time, considering the actual situation, it makes the model more practical.

7.2 Disadvantages of Model

The model involves a wide range of data, and it is not easy to obtain it. If the problem is properly assumed without affecting the solution results, it may lead to errors in the results to some extent.

7.3 Model Generalization

The model building process is shown in Figure 14:

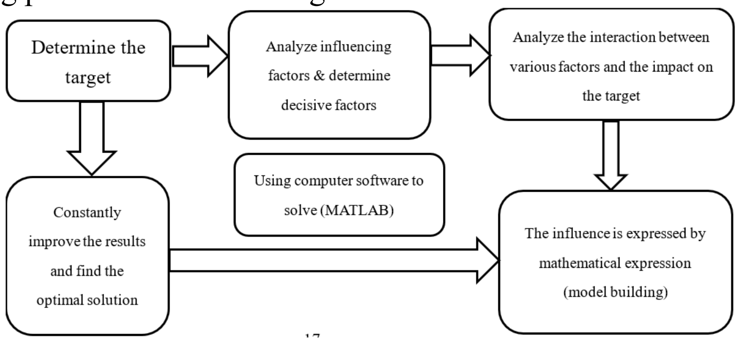

Fig.14 the Process Diagram of Establishing the Model

First question:
Considering many factors, this model can be applied to minimize the cost and maximize the profit in real life.
Second question:
The nonlinear programming model is established, and the control scheme with the least energy consumption is solved by Matlab. The law of conservation of energy can be applied to some practical problems in life.
Third question:
Among them, the resistance of the detector in the pneumatic deceleration section is considered, assuming that the resistance in this section is a constant value. If you want to further popularize it, you can consider the influencing factors of the resistance in this section, such as the resistance coefficient and the atmospheric density of Mars.

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