Adaptive Control Algorithm for Steady Flight of Mars UAV with Four Rotors

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Abstract: Mars exploration is a hot issue at present, and Mars aircraft will become a new tool in Mars exploring. Four-rotor aircraft will be a powerful method in Mars aircraft investigation, because of its simple structure, high reliability, besides, it can also hover in the air, take off and land repeatedly. This paper combines Mars atmospheric environment with influence of UAV flight control, and improve PID to make controller parameters adjust themselves to temperature, pressure and atmospheric density on Mars. The effectiveness of adaptive control algorithm has been checked by using MATLAB method, which make Mars UAV with four rotors fly stably.

1. Introduction
As the closest planet to earth in the solar system, Mars is the hotspot of international deep space exploration [1]. The atmospheric of Mars, which is only equivalent to the high atmospheric pressure of the earth’s 30~35km, has a density of about 0.0155kg/m³, but this still makes it possible to use an aircraft on Mars. The United States, Russia and Europe have been studying Mars probe for many years. There are main types of Mars UAV [2], such as American ARES aircraft, American MATADOR aircraft, Swiss solar Martian aircraft, GTMARS aircraft developed by Georgia Technology University and American Prandtl-m aircraft.

The fixed wing aircraft [3-5] needs very high flight speed to meet the lift requirements, and it is difficult to repeat falling off and down, and is not conducive to scientific detection task; the helicopter structure is very complex, difficult to achieve, and low reliability.

Therefore, the paper selects four-rotor UAV as the research object of Mars aircraft which has simple structure, high reliability, hovering, multiple take-off and landing characteristics. Compared to the traditional Martian vehicle, the Mars four-rotor probe extends the Mars exploration dimension from the plane to the three-dimensional space, which is a powerful complement to the Mars ground detector.

In this paper, according to the characteristics of the Mars environment[6], the improved PID control algorithm is designed for the first time so that the aircraft adapts the environment to automatically adjust the parameters of the controller, and carries out the control algorithm simulation test on the Matlab/Simulink platform, so that the aircraft can quickly respond, adjust quickly and fly stability, after the aircraft is disturbed.

2. Control structure analysis and theoretical basis
When the four-rotor aircraft is hovering or slow flying, the change rate of attitude angle is small, which makes it possible to design PID controller for the system. The line motion depends on the angular motion but the angular motion is not dependent on the line motion. The control system can
divide into the inner loop attitude controller and the outer loop position controller, according to the semi-coupling relationship. There is no coupling relationship between the height control and the yaw angle, so it can be a control channel separately. And the position controller is divided into the horizontal controller and the height controller, as shown in Figure 1.

![Figure 1. Controller.](image)

In the continuous time domain, the four-rotor aircraft controller follows the PID control theory. According to the PID control algorithm (1), the control algorithm of four-rotor aircraft can be obtained.

\[ u(t) = k_p(t)e(t) + k_i(t) \int e(\tau) d\tau + k_d(t) \frac{de(t)}{dt} \]  

(1)

\[ U_1 \] and \[ U_{2-4} \] are respectively output signal of the attitude control and position control. They are input into the motor module, then on the model of the aircraft. The position and attitude signal of the four-rotor are used as feedback, and the closed-loop control system is formed. By constantly adjusting the PID parameters, the system, which is shown in Figure 2, can reach the target position and keep stable.

![Figure 2. System structure diagram.](image)

2.1. Analysis of the influence of Mars environmental changes on Control
The research of Mars UAV is difficult. Mars’ environmental gas composition is different from that of the earth, and the density is far below the earth’s surface atmosphere. Due to the thin atmosphere of Mars, it is difficult to transfer the surface heat through the atmosphere, the surface temperature varies greatly within one day or over a long period of one year. Assuming that the surface pressure is basically unchanged, the temperature change will lead to the change of air density according to the ideal gas state equation \( pM = \rho RT \). Because the atmospheric density is directly related to the derivation of the lift and torque of the four-rotor [7], the aerodynamic performance of the propeller is changed. It caused changes in the aerodynamic and dynamic properties of the four-rotor UAV. In addition, atmospheric parameters may vary in the altitude of 0–50 meters, which will also affect flight...
stability. Therefore, it is critical to the impact of the controller that the relationship between atmospheric density, pressure, temperature and altitude of the aircraft in the Martian.

In order to analyse the influence of environmental changes on UAV flight stability, the controller is tested for environmental factors by PID simulation under varying atmospheric conditions. Fig. 3 shows attitude angle response at different temperatures. At 280k (the standard temperature based on the controller design), the controller has a better attitude stabilization effect and fast response. But at 250K, the attitude angle overshoot is serious, and the time to reach equilibrium is seriously delayed. As the 250K temperature is the daytime temperature often appearing on the surface of Mars, it can be seen that the fixed parameters of the PID controller cannot meet the control requirements of this common.

Figure 3. Attitude angle response at different temperatures.

The flight environment will change with the change of altitude. When the researchers set up a three-dimensional model about Mars atmosphere density, the height of the Mars reference radius 0~147km is evenly divided according to the interval of the Mars reference radius according to the interval of 1km, and the regularity of the density is obtained in each high layer with height variation. In this paper, the planned flight height of Mars UAV is 0~50m, which is in the surface flight range. According to the formula (2) (3), when \( h=0 \text{m}, T=241K, P=700\text{Pa}, \rho=0.0154\text{kg/m}^3 \); when \( h=50\text{m}, T=240.95K, P=696.86\text{Pa}, \rho=0.0153\text{kg/m}^3 \). According to the calculation results, it is too small to worry about temperature, pressure and atmospheric density of Mars in this space range.

3. Adaptive PID controller design

Nihon University provides a simplified model [8] of the Martian atmosphere through data fitting, using Martian atmosphere database in 2010, including atmospheric density, temperature, pressure and many other atmospheric parameters. which can reflect the atmospheric characteristics of Mars in a more comprehensive way, as shown in formula (2) (3).

\[
T = 241.0 - 0.999(h/1000) \\
P = 700 \exp[-0.09(h/1000)] \\
\rho = P/188.95110711075T
\]

At that time \( h < 7000\text{m} \), (2)

\[
T = 249.5 - 2.22(h/1000) \\
P = 700 \exp[-0.09(h/1000)] \\
\rho = P/188.95110711075T
\]

At that time \( h \geq 7000\text{m} \), (3)

Among (2) (3), \( T, P \) and \( \rho \) are respectively the air temperature, pressure and air density of the aircraft, besides \( H \) is the flying height of the aircraft.

According to the model, the atmospheric density is changing as the flight position changes, then the dynamic model makes the PID controller unable to meet stable flight of the UAV. On the basis of the designed PID controller, it is necessary to improve the controller so that it can adapt to the environmental changes and automatically adjust the controller parameters.
Reference to the landing-point temperature of the Martian vehicle "Spirit" [9], it is obtained conclusion through studying the change of short-term temperature and seasonal temperature using data from the first 240 days of Spirit.

(1) Martian surface temperature is different between the day and night, in 10 to 12 PM warming faster, 15 to 19 PM cooling faster.

(2) Measurable to the highest temperature is about 304K between 13 and 14 during the day in Mars.

(3) The lowest average temperature is 240K during the day in 190th days.

(4) Martian surface average maximum temperature is 280K appearing in the first few days.

The Mars UAV plans to use energy sources like solar cells, only perform a flight mission during the day within the temperature range of 240K-280K, to design a controller. The four-rotor body installs the temperature sensor to obtain the real-time ambient temperature. According to the relationship between temperature and atmospheric density, the temperature can be used as the input condition of the controller.

Under $P=700$ Pa, when $T=240$ K, $\rho=0.0154$ kg/m$^3$; when $T=280$ K, $\rho=0.0132$ kg/m$^3$. Therefore, the atmospheric density range of Mars UAV flight environment is 0.0129 kg/m$^3$ (earth density is about 1%) to 0.0154 kg/m$^3$.

4. Simulation results analysis

Due to the special flight environment, the core of the PID controller for Mars UAV is the determination of control parameters. Using the control strategy, it designs the attitude controller parameters first according to the semi coupling relationship of the internal and external loops, and then designs the PID parameters of the height and level controllers. At last, observe the change of the position and attitude angle by making UAV control simulation test under 7 groups of atmospheric density evenly.

The initial state of the UAV is set to: position (0,0,0) m, line speed (0,0,0) m/s, attitude angle (0.1,0.1,0.1) rad, angular rate (0,0,0) rad/s. The control target is from location point (0,0,0) to target location point (1,1,1), and hover is maintained. Through the simulation of the operation, observe the response curve of the system, constantly optimize and adjust, and finally determine the parameters of the PID controller.

| $\rho$  | roll   | pitch   | $z$ | $x,y$ |
|--------|--------|---------|-----|-------|
|        | $k_0$  | $k_1$  | $k_2$  | $k_3$ | $k_4$ | $k_5$ | $k_6$ | $k_7$ | $k_8$ | $k_9$ |
| 0.0129 | 50     | 5      | 50    | 5     | 50    | 8     | 10    | 2     | 1     | 0     | 3     |
| 0.0133 | 60     | 5      | 50    | 60    | 50    | 7.5   | 10    | 2     | 1     | 0     | 3     |
| 0.0137 | 70     | 5      | 50    | 70    | 50    | 7     | 9.8   | 2     | 1     | 0     | 3     |
| 0.0141 | 75     | 5      | 50    | 75    | 50    | 6     | 9.5   | 2     | 1     | 0     | 3     |
| 0.0145 | 78     | 5      | 50    | 8     | 50    | 5     | 9     | 2     | 1     | 0     | 3     |
| 0.0149 | 80     | 5      | 50    | 80    | 50    | 4     | 8     | 2     | 1     | 0     | 3     |
| 0.0153 | 80     | 5      | 50    | 80    | 50    | 4     | 7     | 2     | 1     | 0     | 3     |

The four-rotor yaw motion is produced by means of rotors' torque, rather than the aerodynamic force. Thus, changes in the density of Martiant atmosphere do not affect the yaw motion, and the yaw curve will not change obviously, that is, parameters of yaw controller need not be adjusted. When the air density is 0.0129 kg/m$^3$, 0.0141 kg/m$^3$ and 0.0154 kg/m$^3$, the control effect is basically unchanged when the controller parameters are fixed, as shown in Figure 4. Finally, the yaw control parameter are determined such as $k_p=3$, $k_i=1$, $k_d=4$.
According to the change trend of curve under 7 sets of atmospheric density, we can see the general trend of change. Use MATLAB/Curve Fitting toolbox for curve fitting. The equation of fitting curve is as follows:

$$k_{p\theta} = k_{p\theta} = -7.319e^6 \rho^2 + 2.19e^5 \rho - 1557$$  \hspace{1cm} (4)

$$k_{p\zeta} = -1800 \rho + 31.24$$  \hspace{1cm} (5)

$$k_{i\zeta} = -7.056e^5 \rho^2 + 1.867e^4 \rho - 113.5$$  \hspace{1cm} (6)

The correlation coefficient R-square is above 0.96, and has high correlation. Therefore, some parameters of the PID controller satisfy the above curve equation with the variation of atmospheric density, and the controller parameters can be adaptively adjusted according to the atmospheric density.

Under 0.0129 kg/m$^3$ density, simulate the control system to make UAV hover stable. For example, Figure 5 (a) (b) (c) is the control curve of roll, pitch and yaw respectively; Figure 5 (d) (e) (f) is the position control curve of x, y and z, respectively. Based on the control effect, the simulation of the four-rotor system is carried out with fixed controller parameters and various atmospheric density.
At 0.0141 kg/m³

At 0.0154 kg/m³
In two different densities, fixed parameter controller and adaptive parameter controller are used to compare the policy. As shown in Figure 6, the atmosphere density is increased, at 0.0141kg/m$^3$, the attitude and position control curve fluctuates, the aircraft system is unstable, and the control curve fluctuates more obviously when the atmosphere density value continues to increase at 0.0154kg/m$^3$. According to the PID setting method, when the curve oscillates frequently, the ratio coefficient should be increased. When the overshoot is increased, the proportional band is reduced and the differential term is reduced properly. Adjust proportional gain properly, and then adjust integral coefficient to the steady state. The controller parameters meet the setting principle in Table 1. Therefore, the improvement of the controller, the PID parameters can be adjusted according to the above fitting equation. From Figure 6, it can be seen that after the parameters are adjusted, the system response is faster and the control effect is better. The designed PID adaptive controller has good control effect.

5. Conclusion
The research of Mars four-rotor UAV has great significance for future deep space exploration. The control algorithm of UAV directly affects the flight stability of the aircraft. In order to satisfy the environment of Mars flight, a PID controller is designed, and a control algorithm is improved that adjusts the parameters of the controller adaptively to the Mars environment. The simulation results show that the adaptive PID control method has stable control effect and has application value.

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