Mars Atmospheric Entry Guidance Design by Sliding Mode Disturbance Observer-Based Control

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Abstract

One of the demands for future Mars exploration is pin-point landing, in which the landing precision should be less than one hundred meters and is two orders of magnitude higher than the current level. In the process of the high-speed vehicle entering a rarefied atmosphere with highly uncertainties as the Mars atmosphere, the trajectory deviation caused by entry guidance can be the major part of the total landing errors. Due to modeling errors such as the atmospheric modeling error and the vehicle’s aerodynamic model inaccuracy, the more the guidance law depends on the models, the larger the trajectory dispersion can be. To reduce the impact of model errors on guidance performance, a guidance law based on the second-order sliding mode variable structure control is developed for reference trajectory tracking. The guidance law which is tested in a real entry scenario is proved to be evident in reducing the control gain and the requirement for control ability. The proposed guidance law also shows accurate tracking for the reference trajectory and high precision of the landing sites, and thus has the potential to be applied to online guidance.

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Keywords: Sliding mode; Disturbance observer; Mars; Entry guidance; Monte Carlo simulation

1. Introduction

When the Mars science laboratory successfully landed on the surface of Mars, the active guidance showed its unprecedented high landing precision in all Mars landing missions so far. However, the Mars exploration program to
land a mass of about 0.8 tons on a site as high as +2 km Mars orbiter laser altimeter (MOLA) elevation with 10 km of accuracy has reached the limits of the Viking-era technology qualification [1]. Moreover, future Mars missions will likely need to land more close to the scientifically interesting locations such as the ancient southern high lands. Therefore the more precise EDL (Entry, Descent and Landing) technology is required. In the entry phase, the vehicle experiences hypersonic deceleration from the entry interface to the parachute deployment site. The error in the entry phase can be the main part of the total errors due to the limited landing-site modifiability in decent and landing phases. Therefore, a closed-loop entry guidance, which can achieve better landing precision and accommodate for the errors in the atmosphere model, the uncertainties in vehicle aerodynamic characteristics, and the dispersions in vehicle entry states, is required.

Entry guidance algorithms can be divided into two categories: predictor-corrector guidance and reference trajectory tracking guidance. The predictor-corrector guidance [2, 3], which can predict the future states during the vehicle entry flight and adjust the control accordingly, requires fast on-board computation and relies on system model. The reference trajectory tracking guidance [4, 5] tracks the reference trajectory designed prior to the entry. Therefore the reference trajectory tracking guidance algorithm has some degree of model-independence.

The sliding mode control theory has been applied to attitude control and guidance for some vehicles. Hall and Shtessel [6] presented the application of a sliding mode disturbance observer driven by sliding mode control to improve reusable launch vehicles flight control performance in terminal area energy management and approach/land regions. Lin and Hsu [7] developed an adaptive fuzzy sliding-mode control method which was applied to the command to line-of-sight guidance law design. Harl and Balakrishnan [8] developed a sliding mode terminal guidance for generating the approaching and landing trajectories online just depending on the initial and final conditions of the approaching and landing phase. Furfaro, Cersosimo and Wibben [9] developed a multiple sliding surface guidance for asteroid descent and landing in which two sliding surfaces were employed to generate online targeting trajectories.

In this paper, a novel reference trajectory tracking guidance based on sliding mode control with a sliding mode observer is developed. The non-linear guidance called as sliding mode guidance (SMG) has its foundation on the second-order sliding mode control theory. To achieve tracking the reference trajectory, a sliding mode surface which is a function of the errors between the desired states and the current states is introduced. The sliding surface and its derivative are driven to zero under the bank angle command generated by the guidance law. In addition, to enhance the robustness of the guidance law, a sliding mode observer is designed by means of introducing an auxiliary sliding mode control variable to estimate the external disturbances and model uncertainties. Because the auxiliary sliding mode control variable includes adaptive robust compensation based on a Lyapunov function, the stability of the auxiliary sliding surface can be guaranteed.

2. Equations of motion

Considering the entry flight in the Martian atmosphere, the vehicle can be simplified as a mass point while neglecting its attitude motion. Then the current state of the entry vehicle can be represented by six state variables, such as the radial distance from the center of Mars $r$, the geocentric longitude $\theta$, the geocentric latitude $\phi$, the magnitude of velocity relative to the Martian atmosphere $V'$, the flight path angle between the relative velocity vector and the local horizontal plane $\gamma$, and the heading angle between the projection of the relative velocity vector on the horizontal plane and the north direction $\psi$. The heading angle is positive in a clockwise direction from the north. Neglecting the wind as well as the Coriolis and centrifugal terms due to Mars rotation, the equations of entry motion for a vehicle over the spherical Mars can be formulated as follows [10]:
\[
\begin{align*}
\frac{dr}{dt} &= V \sin \gamma \\
\frac{d\theta}{dt} &= \frac{V \cos \gamma \sin \psi}{r \cos \phi} \\
\frac{d\phi}{dt} &= \frac{V \cos \gamma \cos \psi}{r} \\
\frac{dV}{dt} &= -\frac{D}{m} - g(r) \sin \gamma \\
\frac{d\gamma}{dt} &= \frac{1}{V} \left[ \frac{L \cos \sigma}{m} + \left( \frac{V^2}{r} - g(r) \right) \cos \gamma \right] \\
\frac{d\psi}{dt} &= \frac{1}{V} \left[ \frac{L \sin \sigma}{m \cos \gamma} + \frac{V^2}{r} \cos \gamma \sin \psi \tan \phi \right] \\
D &= \frac{\rho S C_n V^2}{2} \\
L &= \frac{\rho S C_l V^2}{2} \\
g(r) &= \frac{\mu M}{r^2}
\end{align*}
\]

where \(D\) is the drag acceleration, \(L\) is the lift acceleration, \(g(r)\) is the gravitational acceleration, \(\sigma\) is the bank angle which is positive in a clockwise direction from the view toward the vehicle’s head, \(m\) is the vehicle’s mass, \(S\) is the vehicle’s reference surface area, \(C_l\) and \(C_d\) are the lift and drag coefficient respectively, and \(\mu\) is the Mars gravitational parameter.

The downrange \(R\) that vehicle has passed over the Mars surface satisfies

\[
\frac{dR}{dt} = V \cos \gamma 
\]

Because the downrange always decreases when a vehicle enters into the Martian atmosphere, the radial distance \(r\) can also be expressed as the differential with respect to the downrange \(R\) as follows:

\[
\frac{dr}{dR} = \tan \gamma 
\]

\[
\frac{d^2r}{dR^2} = \frac{1}{V^2 \cos^2 \gamma} \left[ L \cos \sigma - g(r) \cos \gamma + \frac{V^2}{r} \cos \gamma \right]
\]

An extra benefit of taking the derivative of \(r\) with respect to \(R\) is that it can make sure the vehicle reaching the landing point at the fixed downrange no matter how the total time varies.

3. Sliding mode control with a sliding mode disturbance observer

This section presents the continuous sliding mode control that is applied to tracking the output of a multi-input multi-output (MIMO) system with nonlinear feedback. To ease the burden of the reaction control system (RCS), a
sliding mode disturbance observer (SMDO) is introduced, which can reduce the switch gain of the control and eliminate the chattering effect.

3.1. Continuous sliding mode control for MIMO system

A nonlinear MIMO system can be described as [11]

\[
\begin{align*}
\dot{x} &= f(x) + g(x)u \\
y &= h(x)
\end{align*}
\]

where

\[
f(x) \in \mathcal{R}^n
\]

\[
h(x) = [h_1, h_2, \ldots, h_m]^T \in \mathcal{R}^m
\]

\[
g(x) = [g_1, g_2, \ldots, g_m] \in \mathcal{R}^{m \times m}
\]

\[x \in \mathcal{R}^n, \ y \in \mathcal{R}^m, \ u \in \mathcal{R}^n\]

\[g_i \in \mathcal{R}^n, \ (i = 1, 2, 3, \ldots, m)\]

Through feedback linearization, system (5) can be transformed into the following form:

\[
\begin{bmatrix}
y_1^{(r_1)} \\
y_2^{(r_2)} \\
\vdots \\
y_m^{(r_m)}
\end{bmatrix} =
\begin{bmatrix}
L_{f_1}^{r_1}h_1(x) \\
L_{f_2}^{r_2}h_2(x) \\
\vdots \\
L_{f_m}^{r_m}h_m(x)
\end{bmatrix} +
\begin{bmatrix}
L_{g_1}^{r_1}L_{f_1}^{r_1-1}h_1(x) & L_{g_2}^{r_2}L_{f_2}^{r_2-1}h_2(x) & \cdots & L_{g_m}^{r_m}L_{f_m}^{r_m-1}h_m(x) \\
L_{g_2}^{r_2}L_{f_1}^{r_2-1}h_1(x) & L_{g_2}^{r_2}L_{f_2}^{r_2-1}h_2(x) & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
L_{g_m}^{r_m}L_{f_1}^{r_m-1}h_1(x) & \vdots & \vdots & L_{g_m}^{r_m}L_{f_m}^{r_m-1}h_m(x)
\end{bmatrix}u
\]

(6)

where \(L_{f_i}^{r_i}h_i(x)\) and \(L_{g_i}^{r_i}L_{f_i}^{r_i-1}h_i(x)\) \((i = 1, 2, \ldots, m)\) are Lie derivatives, and \(r_i\) \((i = 1, 2, \ldots, m)\) is relative degree.

To describe the deviation between the output in the system and the desired command, a tracking error is introduced:

\[
s_i = c_{i, r_i-1} e_i^{(r_i-1)} + c_{i, r_i-2} e_i^{(r_i-2)} + \cdots + c_{i, 1} e_i^{(1)} + c_{i, 0} e_i + \int e_i \, dt
\]

(7)

where \(c_{i, j} \ (j = 0, 1, \ldots, r_i - 1)\) is the coefficients, \(e_i^{(j)} = \frac{d^j}{dt^j} \ (j = 0, 1, \ldots, r_i - 1)\), \(e_i = y_{i, \text{des}} - y_i \ (i = 1, 2, \ldots, m)\), \(y_{i, \text{des}}\) is the desired output and \(y_i\) is current output in the system. It is assumed that \(c_{i,j}\) is chosen to satisfy the Hurwitz requirement, thus a sliding mode variable vector consisted of \(s_i \ (i = 1, 2, \ldots, m)\) can be as follows:

\[
s = [s_1, s_2, s_3, \cdots, s_m]^T \in \mathcal{R}^m
\]

and a sliding surface is introduced:
From the Eq. (6), the sliding variable dynamics are derived as

\[
\dot{s} = K \begin{bmatrix}
L_{b_1} L_{f}^{-1} h_1(x) & L_{b_2} L_{f}^{-1} h_1(x) & \cdots & L_{b_n} L_{f}^{-1} h_1(x) \\
L_{b_1} L_{f}^{-1} h_2(x) & L_{b_2} L_{f}^{-1} h_2(x) & \cdots & L_{b_n} L_{f}^{-1} h_2(x) \\
\cdots & \cdots & \cdots & \cdots \\
L_{b_1} L_{f}^{-1} h_m(x) & L_{b_2} L_{f}^{-1} h_m(x) & \cdots & L_{b_n} L_{f}^{-1} h_m(x)
\end{bmatrix} u
\]

where

\[
K = [\kappa_1, \kappa_2, \kappa_3, \cdots, \kappa_m]
\]

\[
\kappa_i = j_{i,z}^{(r)} + c_{i,\eta} e_i^{(r-1)} + c_{i,\zeta} e_i^{(r-2)} + \cdots + c_{i,0} e_i^{(0)} + e_i - L_f^j h_i(x), \quad (i = 1, 2, \cdots, m)
\]

Defining a new control variable:

\[
\dot{\tilde{u}} = K \begin{bmatrix}
L_{b_1} L_{f}^{-1} h_1(x) & L_{b_2} L_{f}^{-1} h_1(x) & \cdots & L_{b_n} L_{f}^{-1} h_1(x) \\
L_{b_1} L_{f}^{-1} h_2(x) & L_{b_2} L_{f}^{-1} h_2(x) & \cdots & L_{b_n} L_{f}^{-1} h_2(x) \\
\cdots & \cdots & \cdots & \cdots \\
L_{b_1} L_{f}^{-1} h_m(x) & L_{b_2} L_{f}^{-1} h_m(x) & \cdots & L_{b_n} L_{f}^{-1} h_m(x)
\end{bmatrix} u
\]

\[
\tilde{u} = [\tilde{u}_1, \tilde{u}_2, \cdots, \tilde{u}_m]^T
\]

Then, Eq. (9) can be rewritten as

\[
\dot{s} = K^0 + \Delta K - \tilde{u}
\]

where \(K^0 = [\kappa_1^0, \kappa_2^0, \cdots, \kappa_m^0]\) is the known vector, and \(\Delta K = [\Delta \kappa_1, \Delta \kappa_2, \cdots, \Delta \kappa_m]\) is the unknown vector with bound due to external disturbances and model uncertainties.

Finally, the output in a MIMO system can be asymptotically tracked and the sliding variable dynamics can be guaranteed stable under the control of \(\tilde{u}\) or \(u\).

### 3.2. Sliding mode observer based on sliding mode control

The unknown vector \(\Delta K\) is bounded as

\[
\|\Delta \kappa_i\| \leq a_i, \quad (i = 1, 2, \cdots, m)
\]

To estimate the bounded disturbance \(\Delta \kappa_i\), two auxiliary sliding mode variables are introduced:

\[
\eta_i = s_i + z_i
\]
\[ \dot{\eta}_i = \dot{s}_i + \dot{\eta}_i \]  
(14)

\[ \dot{\eta}_i = -\kappa^0_i + \ddot{u}_i - v_i \]  
(15)

Considering the Eq. (11), and using Eqs. (13), (14) and (15), the \( \eta_i \) dynamics is given by

\[ \dot{\eta}_i = \Delta \kappa_i - v_i \]  
(16)

From the Eq. (16), the problem is transformed to design an observer \( v_i \). Using the Lyapunov stability theory, a Lyapunov function can be formulated as [12]

\[ V_i = \frac{1}{2} \eta_i^2 \]  
(17)

Taking into account Eq. (16), the derivative of the Lyapunov function is

\[ \dot{V}_i = \eta_i \dot{\eta}_i = \eta_i (\Delta \kappa_i - v_i) \]  
(18)

To guarantee the sliding surface \( \eta_i \) approaches zero in finite time, \( v_i \) must be chosen to keep \( \dot{V}_i \) negative. This can be done by choosing \( v_i \) as follows.

\[ v_i = \begin{cases} (a_i + \varepsilon_i) \text{sign}(\eta_i), & \text{if } |\eta_i| > \mu_i \\ (|\dot{\eta}_i| + \varepsilon_i) \text{sign}(\eta_i), & \text{if } |\eta_i| \leq \mu_i \end{cases} \]  
(19)

where \( \varepsilon_i \) is tiny positive increment, \( \mu_i \) is positive amount relative to the RCS accuracy, and \( \dot{\eta}_i \) is given by

\[ \dot{\eta}_i = G(s) v_i(s) \]  
(20)

where \( s \) is a Laplace variable and \( G(s) \) is a transfer function of a low-pass filter.

The sliding mode control \( \ddot{u}_i \) in Eqs. (10), (11) and (15) can be designed as

\[ \ddot{u}_i = \kappa_i^0 + k_i s_i + \dot{\eta}_i \]  
(21)

where \( k_i \) is the gain.

To guarantee the stability of the original sliding variable \( s_i \), another Lyapunov function is introduced:

\[ V_i = \frac{1}{2} s_i^2 \]  
and its derivative is

\[ \dot{V}_i = s_i \dot{s}_i \]  
(22)

While \( |\eta_i| \leq \mu_i \), using Eqs. (11), (12), (19) and (21), the Eq. (22) can be transformed into
\[ \dot{V}_i = s_i (-k_i s_i + \Delta k_i - \dot{\nu}_w) \]

It is assumed that \(|s_i| < \zeta_i\), and then the gain \(k_i\), with which \(s_i\) can be stable and approaches zero as time increases, should satisfy the following inequality:

\[ k_i > \frac{|\Delta k_i - \dot{\nu}_w|}{\zeta_i} \]  

(23)

Considering the sliding mode control \(\tilde{u}_i\) without the sliding mode observer, the original high gain control can be

\[ \tilde{u}_i = k_i^0 + k_i s_i \]  

(24)

Through similar conditions and similar Lyapunov-based analysis, the gain satisfies

\[ k_i > \frac{a_i}{\zeta_i} \]  

(25)

Comparing inequality (23) and inequality (25), because \(\Delta k_i - \dot{\nu}_w\) \(\leq a_i\) as time increases, the stability of the sliding dynamics can be achieved via much lower control gains due to the use of sliding mode observer.

4. Entry SMG design for low L/D vehicles

This section presents a novel non-linear guidance for the low L/D vehicles’ pin-point landing on Mars. The SMG is based on the second-order sliding mode control with a sliding mode observer, and it employs tracking a reference trajectory with the range as the independent variable. Owing to tracking a reference trajectory, the dependence on models which are uncertain during the entry flight is avoided as much as possible. In addition, sliding mode control (SMC) is robust against the disturbance of external environment, thus the SMG based on the SMC well inherits the robustness. Further more, because the uncertainty and disturbance can be estimated by the sliding mode observer, the control gain is great reduced and the chattering phenomenon is eliminated.

4.1. Longitudinal guidance based on sliding mode control with observer

The bank angle denotes the orientation of the vehicle with respect to the airflow. The longitudinal guidance changes the bank angle, which results in the change of the vehicle’s lift direction, and then the range and the landing point can be modified. The objective of the longitudinal guidance is to generate an appropriate bank angle command, which can be achieved by the SMG algorithm given below.

Considering Eqs. (1), (3), (4) and (7), the sliding variable dynamics is introduced:

\[ s_i = e + ce' \]  

(26)

and its derivative is

\[ s'_i = e' + ce'' \]  

(27)

where
\[ e = r_{\text{ref}} - r \]
\[ e' = \tan \gamma_{\text{ref}} - \tan \gamma \]
\[ e'' = (\tan \gamma_{\text{ref}})' - \frac{1}{V^2 \cos^3 \gamma} \left( L \cos \sigma - g \cos \gamma + \frac{V^2}{r} \cos \gamma \right) \]

The differential here is with respect to the downrange, and the subscript “ref” indicates the state along the reference trajectory.

From Eqs. (13), (14), (15), (16), (19), (20) and (21), another sliding dynamics is introduced:

\[ s_v = s_i + z \quad \text{(28)} \]

and its derivative is

\[ s'_v = s'_i + z' \quad \text{(29)} \]

where

\[ z' = -k^0 + \dot{u} - v_{\text{ob}} = - \left[ -\frac{cL \cos \sigma}{V^2 \cos^3 \gamma} - \frac{c}{V^2 \cos^3 \gamma} \left( -g \cos \gamma + \frac{V^2}{r} \cos \gamma \right) + c\left( \tan \gamma_{\text{ref}} \right)' + \left( \tan \gamma_{\text{ref}} - \tan \gamma \right) \right] - v_{\text{ob}} \]

\[ v_{\text{ob}} = \begin{cases} (a + \varepsilon) \text{sign}(s_v), & |s_v| > \mu \\ |\dot{v}_{\text{ob}}| + \varepsilon \text{sign}(s_v), & |s_v| \leq \mu \end{cases} \]

\[ \hat{v}_{\text{ob}}(s) = G(s)v_{\text{ob}}(s) \]

\[ \ddot{u} = k^0 + k_s s_i + \hat{v}_{\text{ob}} = \frac{cL \cos \sigma}{V^2 \cos^3 \gamma} \]

and Eq. (29) can be rewritten as

\[ s'_v = \Delta \kappa - v_{\text{ob}} \quad \text{(30)} \]

Through the similar analysis in the previous section, the stability of the sliding mode dynamics is guaranteed by using

\[ k_s > \frac{\Delta \kappa - \hat{v}_{\text{ob}}}{\zeta} \]

where \( \zeta \) is the domain of the sliding mode variable \( s_i \).

Through above analysis and deduction, to assure that the sliding variable \( s_i \) and its derivative \( s'_i \) reach the sliding surfaces respectively:

\[ s_i = 0 \quad \text{(31)} \]
the bank angle command is

\[ \sigma = \cos^{-1}\left( \frac{V^2 \dot{\gamma} \cos \gamma}{cL} \right) \]  

(33)

4.2. Lateral guidance strategy

From Eq. (1), it can be obtained that if the sign of the bank angle is changed, the lift vector will point to the side out of the longitudinal plane and the vehicle will steer out of plane. Thus, the cross range can be determined by controlling the sign of the bank angle. The lateral guidance algorithm is to design a dead band boundary relative to the cross range and change the sign of the bank angle while the cross range exceeds the boundary [13].

The cross range variable \( \chi \) is defined by

\[ \chi = \sin^{-1}\left[ \sin \frac{ \text{range to go} \sin(\psi - \Psi) } \right] \]  

(34)

where \( \text{range to go} \) is the range to go, \( \psi \) is the current heading angle, and \( \Psi \) is the line-of-sight azimuth angle along the great circle to the landing site.

The boundary relative to the cross range is defined as

\[ \chi_c = c_iV + c_u \]  

(35)

When the cross range exceeds the boundary defined by Eq. (35), the sign of the bank angle is reversed.

5. Simulation results and analysis

In this section, to evaluate the robustness and the performance of the SMG, a Monte Carlo simulation with 500 runs has been performed. The standard conditions and parameters are similar to those used by Benito [14], and are shown in Table 1, including the initial altitude \( h_0 \), initial longitude \( \theta_0 \), initial latitude \( \phi_0 \), initial velocity \( V_0 \), initial flight path angle \( \gamma_0 \), initial heading angle \( \psi_0 \), the vehicle’s mass \( m \) and reference surface area \( S \). The vehicle used in the simulation is a MSL-like capsule as described in reference [14], and the aerodynamic coefficients \( C_L \) and \( C_D \) and the Martian atmospheric model are also similar to the models in that reference. The ending condition of the simulation is that the altitude decreases to the deployment altitude \( h_f \). The condition for the deployment and the desired longitude \( \theta_d \) and latitude \( \phi_d \) are shown in Table 2.

In these simulations, dispersions are considered for the initial altitude, longitude, latitude, velocity, flight path angle, heading angle, vehicle’s lift coefficient and drag coefficient and the atmospheric density \( \rho \). These dispersions are shown in Table 3 and are modeled by Gaussian distribution to simulate the perturbations of states and the off-nominal conditions.
Table 1. Standard simulation conditions and parameters

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<th>Units</th>
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<td>( \theta_s )</td>
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<td>( \phi_0 )</td>
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<td>deg</td>
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<tr>
<td>( V_0 )</td>
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</tr>
<tr>
<td>( \gamma )</td>
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<td>deg</td>
</tr>
<tr>
<td>( \psi )</td>
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<td>deg</td>
</tr>
<tr>
<td>( m )</td>
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<td>kg</td>
</tr>
<tr>
<td>( S )</td>
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<td>m²</td>
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Table 2. Deployment conditions

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<td>( \phi_f )</td>
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Table 3. Dispersions in Monte Carlo Simulations

<table>
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<tr>
<td>( \phi )</td>
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</tr>
<tr>
<td>( V )</td>
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</tr>
<tr>
<td>( \gamma )</td>
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<td>deg</td>
</tr>
<tr>
<td>( \psi )</td>
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<td>deg</td>
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<td>( C_s )</td>
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<td>-</td>
</tr>
<tr>
<td>( C_o )</td>
<td>15%</td>
<td>-</td>
</tr>
<tr>
<td>( \rho )</td>
<td>15%</td>
<td>-</td>
</tr>
</tbody>
</table>

Figures 1-3 shows the single simulation in the nominal condition. To see the tracking performance of SMG, Fig. 1 shows the actual radial distance from the center of Mars and the flight path angle, in comparison with the reference ones. In Fig. 1, the referenced radial distance and flight path angle that varied with range are plotted in solid red line, while the actual ones are plotted in dotted blue line. From Fig. 1, it can be seen that the reference trajectory is asymptotically tracked and the final error of the radial distance and flight path angle is reduced to less than 1km and less than 0.5 deg respectively.
Fig. 1. Referenced and actual radial distance and flight path angle

Fig. 2 shows the command of the bank angle that the SMG algorithm generates during the vehicle’s entry flight. At about the 100 s and the 160 s, the sign of the bank angle is reversed. It is the result of the function of the lateral guidance strategy. In the whole entry process, the saturation of the control capability is well avoided own to the SMG.

Fig. 2. Bank angle command vs. time

To see the effect of the sliding mode observer, two simulations are implemented under the same condition. First a baseline simulation is run, in which the sliding mode observer is removed from the SMG and the low gain control given by Eq. (21) is replaced by a continuous high gain control given by Eq. (24). In addition, under the same initial condition, another simulation in which the proposed SMG is implemented is run.

Considering that the sliding mode variable will converge to the sliding mode surface near the end of the entry flight in above two simulations, the motion that how the derivative of the sliding variable given by Eq. (27) varies with time in the two simulations after the sliding variable reached the sliding surface is presented in Fig. 3. From Fig. 3, it can be seen that with the sliding mode observer, the chattering phenomenon is effectively eliminated. Through the comparison between the two simulations, it can be obtained that the control gain using sliding mode observer is just as about half as that in the baseline simulation. Due to the reduced control gain, the burden of RCS is eased.
Figure 4 presents the representative of the trajectories for 500 Monte Carlo simulations, and displays how the altitude varies with the range. It can be seen that although there are initial deviation at start of the vehicle’s entry, 500 trajectories gradually converge to the reference trajectory as the vehicle approaches the deployment site at the altitude of 8 km.

Figure 5 shows the deployment sites for 500 Monte Carlo simulations. The inner and outer circles respectively represent the sites which are 2 km and 5 km away from the desired deployment site. In the 500 runs, 454 (or 90.8%) locate in the 2 km circle of the target, and 100% locate in the 5 km circle of the target. The largest deviation from the desired deployment site is 2.85 km. The mean miss distance of 99.7% Circular Error Probability (CEP) is 1.29 km. The miss distance of 500 deployment sites shows the SMG performs well in tracking reference trajectory under multiple error sources given in Table 3. Thus it is proved that the SMG is robust against external disturbances and model uncertainties.
6. Conclusions

A novel nonlinear guidance has been developed for a low lift-to-drag ratio vehicle which enables precision landing on Mars. This guidance method is called Sliding Mode Guidance, and is based on the sliding mode control with a sliding observer. The SMG generates the bank angle command to track the predesigned trajectory and guides the vehicle to the desired deployment site. Because the SMG is based on tracking reference trajectory, the dependence on models is reduced. Thus, the SMG shows some robustness with respect to external disturbances and model uncertainties such as the variations in atmospheric density and vehicle aerodynamic characteristics.

The SMG algorithm is tested in off-nominal conditions in which initial perturbations, external disturbances and model uncertainties are considered. In these tests, the SMG performs well in tracking reference trajectory and precision guidance. Furthermore, due to the reduction in control gain with the role of sliding observer, the requirement on the control ability is relatively low.

It should be pointed out that this guidance method has lower demand for computation relative to the predictor-corrector approach, and can be used in online studies.

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