Tianwen-1 Mars entry vehicle trajectory and atmosphere reconstruction preliminary analysis

Haogong Wei¹(✉), Wei Rao¹, Guangqiang Chen², Guidong Wang², Xin Zou¹, Qi Li¹, and Yanqi Hu¹

1. Beijing Institute of Spacecraft System Engineering, Beijing 100094, China

2. China Academy of Aerospace Aerodynamics, Beijing 100074, China

ABSTRACT

The Tianwen-1 Mars entry vehicle successfully landed on the surface of Mars in southern Utopia Planitia on May 15, 2021, at 7:18 (UTC+8). To acquire valuable Martian flight data, a scientific instrumentation package consisting of a flush air data system and a multilayer temperature-sensing system was installed aboard the entry vehicle. A combined approach was applied in the entry, descent, and landing trajectory reconstruction using all available data obtained by the inertial measurement unit and the flush air data system. An aerodynamic database covering the entire flight regime was generated using computational fluid dynamics methods to assist in the reconstruction process. A preliminary analysis of the trajectory reconstruction result, along with the atmosphere reconstruction and aerodynamic performance, was conducted. The results show that the trajectory agrees closely with the nominal trajectory and the wind-relative attitude. Suspected wind occurred at the end of the trajectory.

KEYWORDS

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1 Introduction

The Tianwen-1 Mars entry vehicle successfully landed on the surface of Mars in the southern Utopia Planitia on May 15, 2021, at 7:18 (UTC+8). The Tianwen-1 Mars exploration mission consists of three major parts: orbiting, landing, and roving. The Tianwen-1 spacecraft, launched aboard CZ-5B from Wenchang on July 23, 2020, was injected into the Mars orbit in February 2021, and it stayed in the orbit for two and a half months. Sand storm observations over the landing site and general optical surveillance tasks were conducted during this period.

The entry, descent, and landing (EDL) sequence of Tianwen-1 is shown in Fig. 1. The entry interface was 125 km with a velocity of 4.7 km/s. The entry vehicle went through “nine minutes of terror” using a trim angle of attack at approximately -10° to gain lift for banking maneuvers in most of the flight, and it reached peak heating at an altitude of approximately 60 km. A trim tab was deployed at 2.8 Mach to trim the angle of attack toward 0. The parachute deployment was triggered at

1.8 Mach, followed by parachute descent, heat shield jettison, and radar activation. The powered descent segment was initiated after backshell separation, where potential obstacle avoidance occurred. Finally, the vehicle touched down on Martian soil 510 s after entry.

A flush air data system (FADS) and an in-layer temperature-sensing system were included in the scientific instrumentation package aboard the Tianwen-1 entry vehicle to overcome the absence of *in situ* atmospheric parameter measurements and to estimate the aerothermal environment during the flight. Unlike trajectory and atmosphere reconstruction on the Earth, the reconstruction of Martian flights encounters a lack of *in situ* atmospheric parameter measurement approaches, such as sounding rockets. The application of FADS makes accurate dynamic pressure estimation possible, thereby making atmospheric reconstruction feasible. Moreover, wind-relative attitudes, such as the angle of attack and sideslip, are available because the wind component is separated from the planet-relative attitude.

✉ weihaogong@aliyun.com

Nomenclature

a_x, a_y, a_z	acceleration (m/s^2)	M_∞	free stream Mach number
ADB	aerodynamic database	p_t	total pressure (Pa)
B	angle of sideslip ($^\circ$)	p_∞	static pressure (Pa)
CFD	computational fluid dynamics	$\bar{q}_\infty$	dynamic pressure (Pa)
EDL	entry, descent, and landing	RCS	reaction control system
FADS	flush air data system	UTC	universal time coordinated
IMU	inertial measurement unit	α, AoA	angle of attack ($^\circ$)
M	mass (kg)	ρ_∞	atmospheric density (kg/m^3)

Fig. 1 Tianwen-1 entry, descent, and landing.

Research on FADS was first initiated by the US National Aeronautics and Space Administration (NASA) in the 1960s to gather air data in the hypersonic flight regime where the classical Pitot static probe failed to survive. The first application was the X-15 experimental airplane with a limited outcome. The Shuttle Entry Air Data System (SEADS) was a complete success that invented the filter algorithm [2–4]. In the development of the X-33 program, various simplifications and progress on the FADS were made to improve the overall performance [5]. This design experience on the blunt forebody was implemented thereafter on a variety of hypersonic and supersonic flight vehicles [6–8].

Trajectory reconstructions of Mars entry missions prior to the Mars Science Laboratory (MSL) relied solely on inertial measurement unit (IMU) data, which are not capable of separating wind-relative parameters, such as the true angle of attack and sideslip [9–15].

MSL was the first mission to deliver an in-depth understanding of the Martian entry environment. MSL carried an instrumentation package, known as the MSL Entry, Descent, and Landing Instrumentation (MEDLI), comprising two major subsystems: the Mars Entry Atmospheric Data System (MEADS) and the MEDLI Integrated Sensor Plugs (MISP) [16–25]. Following MEDLI, the MEDLI2 sensor suite was developed to expand the set of measurements of the MEDLI suite [26, 27].

The objectives of the Tianwen-1 in-flight scientific measurements are as follows:

- (1) Estimating the entry trajectory and aerothermal environment using flight data to support atmospheric reconstruction and design evaluation.
- (2) Reconstructing the *in situ* Martian atmosphere that the entry vehicle experienced during flight.
- (3) Evaluating the aerodynamic design, thermal

protection design, and control system performance of Tianwen-1.

This study focused on trajectory and atmosphere reconstruction using IMU and FADS data. Aerothermal environment reconstruction is beyond the scope of this study. An overview of the instrumentation, the reconstruction techniques, and a discussion of the results are presented. The lessons learned should help improve planetary EDL performance in the future.

2 Instrumentation

2.1 Inertial measurement unit

The on-board IMU stores accelerations and angular rates at 0.25–2 Hz. The sparseness of the data makes aerodynamic moment reconstruction difficult because the duration of a single control impulse of the reaction control system (RCS) is much shorter than the sampling time. It has little effect on the trajectory and aerodynamic force reconstructions, however, because RCS thrusters are activated only in pairs.

2.2 Flush Air Data System

The Tianwen-1 FADS contains seven pressure sensors connected to orifices on the heat shield. The locations of these orifices, denoted as P1, P2, $\dots$, P7 in Fig. 2, were intentionally selected for better performance while avoiding structural reinforcements. Specifically, P1 is at the center of the heatshield, P3 is the stagnation point throughout most of the flight until the trim tab deployment, and P2 and P3 are symmetrical with respect

to P1. P4, P5, P6, and P7 are arranged in a cross shape from 45° to 315° with an equal radial distance to P1.

The Martian flight data collection was initiated 15 s prior to entry and was terminated by the heat shield jettison. The pressure data were gathered at a constant sampling rate of 10 Hz. Individual calibrations were performed for all seven pressure sensors before launch. The operating temperature ranging from -40 to $+70^\circ\text{C}$ was divided into seven segments, each with specific fitting equations, to obtain high precision. Principal errors included transducer error, pipe pressure loss, and storage error, resulting in a maximum total error of no more than ± 7 Pa. As a result, only data below 80 km were available.

The corrected in-flight pressure data are shown in Fig. 3, where P1, P2, $\dots$, P7 represent the pressure data collected from the orifices corresponding to Fig. 2. No jumps or outliers were found, indicating high-quality measurements. Based on the orifice arrangement and pressure data (especially P4 through P7), an intuitive inference is that there was no significant sideslip in most of the flight.

3 Methods

3.1 Pressure model

The FADS is assisted by an aerodynamic database (ADB) covering the entire flight regime generated by computational fluid dynamics (CFD) methods. The computed points are shown in Fig. 4, where the blue crosses are the computed points of the aerodynamic database, and the red line shows the nominal trajectory. The primary objective of building such an ADB is to

Fig. 2 Pressure orifice locations.

facilitate trajectory reconstruction with a table lookup model by acquiring the pressure distribution of the entry vehicle at different wind-relative attitudes.

Fig. 3 In-flight pressure data.

Fig. 4 Aerodynamic database.

3.2 Aerodynamic state estimation

The modeling of any physical phenomenon requires a dimensional analysis by identifying the independent variables. The generic aerodynamics of the entry process suggest that the aerodynamic state vector $\mathbf{X}$ has four independent variables [2].

$$\mathbf{X} = \begin{bmatrix} \alpha \\ \beta \\ p_t \\ p_\infty \end{bmatrix} \quad (1)$$

where α is the angle of attack, β is the angle of sideslip, p_t is the total pressure, and p_∞ is the static pressure.

However, the formulation of the aerodynamic state vector $\mathbf{X}$ is not unique. A combination of the angle of attack α , the angle of sideslip β , and any two variables from the set of total pressure p_t , static pressure p_∞ , dynamic pressure $\bar{q}$, pressure ratio R , and free stream Mach number M_∞ is applicable. It is natural to select p_t and p_∞ as the other two variables in addition to the wind-relative angles because the measured data are in the form of pressure as well.

The normal shock relation is applied to calculate the pressure ratio R in the supersonic and subsonic regimes.

$$R = \frac{p_\infty}{p_t} = \begin{cases} \left[\frac{2}{(\gamma+1)M_\infty^2} \right]^{\frac{\gamma}{\gamma-1}} \left[\frac{2\gamma M_\infty^2 - (\gamma-1)}{\gamma+1} \right]^{\frac{1}{\gamma-1}}, & M_\infty > 1 \\ \left(1 + \frac{\gamma-1}{2} M_\infty^2 \right)^{\frac{\gamma}{\gamma-1}}, & M_\infty \leq 1 \end{cases} \quad (2)$$

where p_∞ is the static pressure, p_t is the total pressure, γ is the ratio of specific heats obtained from the ADB, and M_∞ is the free stream Mach number. The speed of sound is estimated using the IMU-derived velocity to compute the Mach number.

The dynamic pressure $\bar{q}$ is derived from p_∞ and M_∞ as

$$\bar{q} = \frac{\gamma}{2} p_\infty M_\infty^2 = \frac{\gamma}{2} p_t R M_\infty^2 \quad (3)$$

The relationship between the measured pressure $\mathbf{P}$ and the state vector $\mathbf{X}$ can be represented as

$$\mathbf{P} = \mathbf{f}(\mathbf{X}) + \boldsymbol{\varepsilon} \quad (4)$$

where

$$\mathbf{P} = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} f_1(\mathbf{X}) \\ f_2(\mathbf{X}) \\ \vdots \\ f_n(\mathbf{X}) \end{bmatrix}, \quad \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \quad (5)$$

Here, P_i ($i = 1, \dots, n$) is the measured pressure data corresponding to orifice i , $f_i(\mathbf{X})$ is the CFD-based pressure model, and ε_i is the error in the observed pressure p_i , assumed to have zero mean. Linearization of the pressure model results in the following approximation to Eq. (4):

$$\mathbf{P} = \mathbf{f}(\hat{\mathbf{X}}) + \mathbf{H}(\mathbf{X} - \hat{\mathbf{X}}) + \boldsymbol{\varepsilon} \quad (6)$$

where $\hat{\mathbf{X}}$ is a reference state in Fig. 4, and $\mathbf{H}$ is the Jacobian matrix:

$$\mathbf{H} = \left[\frac{\partial \mathbf{f}}{\partial \mathbf{X}} \right]_{\mathbf{X}=\hat{\mathbf{X}}} \quad (7)$$

which is also known as the sensitivity matrix. Equation (4) can be rewritten in a linear regression form:

$$\mathbf{y} = \mathbf{H}(\mathbf{X} - \hat{\mathbf{X}}) + \boldsymbol{\varepsilon} \quad (8)$$

where the residual vector:

$$\mathbf{y} = \mathbf{P} - \mathbf{f}(\hat{\mathbf{X}}) \quad (9)$$

Consequently, the best linear unbiased estimate of $\mathbf{X}$ is computed as [18]:

$$\hat{\mathbf{X}} = (\mathbf{H}^T \mathbf{S}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{S}^{-1} \mathbf{y} \quad (10)$$

where $\mathbf{S}$ is the pressure measurement error covariance matrix.

3.3 Atmosphere reconstruction

The atmospheric parameters can be estimated using both FADS and IMU data. The static pressure is one of the four elements in the best estimate of $\mathbf{X}$. The atmospheric density is derived from $\bar{q}$ and V_t as follows:

$$\rho_\infty = \frac{2\bar{q}}{V_t^2} \quad (11)$$

The axial forces can be estimated using acceleration measurements from the IMU. The axial force coefficients C_A , C_N , and C_Z are computed as follows:

$$\begin{cases} C_A = \frac{ma_x}{\bar{q}S} \\ C_N = \frac{ma_y}{\bar{q}S} \\ C_Z = \frac{ma_z}{\bar{q}S} \end{cases} \quad (12)$$

where m is the vehicle mass, a_x , a_y , and a_z are accelerations in each body axis, and S is the aerodynamic reference area.

The drag and lift coefficients C_D and C_L are defined as

$$\begin{cases} C_D = C_N \sin \alpha + C_A \cos \alpha \\ C_L = C_N \cos \alpha - C_A \sin \alpha \end{cases} \quad (13)$$

The lift/drag ratio L/D is given by

$$L/D = C_L/C_D \quad (14)$$

4 Results

4.1 Trajectory

The trajectory reconstruction of Tianwen-1 was completed mostly based on data acquired from the IMU, as shown in Fig. 5, where Fig. 5(a) shows the result of the estimated altitude versus velocity, and Figs. 5(b)–5(d)

show the Mach number, altitude, and dynamic pressure, respectively. The blue dashed line refers to the result reconstructed solely from the IMU data, and the red solid line represents the result from the combined IMU and FADS data. Atmospheric entry was initiated at 125 km, with an entry angle of -11.53° . The vehicle bears a peak pressure 134 s after entry. The differences in Mach number existing at high altitudes between the results reconstructed from the combined IMU and FADS data and that from the IMU data in Fig. 5(b) result from the low pressure of the rarefied Martian atmosphere, which cannot be distinguished by onboard pressure sensors.

4.2 Wind-relative attitude

The wind-relative attitude estimates are shown in Figs. 6(a) and 6(b). The wind-relative angles of attack and sideslip are compared with the planet-relative angles, design nominal value, and minimum and maximum design boundaries. The minimum, maximum, and nominal values were derived from the trim angles of attack. The nominal value of the angle of sideslip is basically zero. The control system constantly corrects the angle of sideslip toward zero within an acceptable range of $\pm 4^\circ$. The wind-relative and planet-relative angles match fairly well during hypersonic flight, as expected, because the magnitudes of the total velocity of the vehicle are much greater than the wind. The angles become more sensitive to wind as the vehicle decelerates, especially near the end of the trajectory.

The difference between the FADS and IMU results at low Mach numbers indicates the suspected winds, which are discussed in the following sections. The trim tab was triggered on at 2.71 Mach (in flight, 2.8 Mach nominal), approximately 250 s after entry, to level the angle of attack toward zero for succeeding parachute deployment. The corresponding jump in the angle of attack and sideslip was caused by this trim tab deployment.

4.3 Atmosphere

The combined envelope of two Martian atmosphere models was applied as the design reference [28, 29]. A comparison between the reconstructed atmospheric environment and the design envelope is shown in Fig. 7. The minimum, maximum, and nominal values are computed from the atmosphere models on the date of entry. The atmospheric density reaches the design upper bound at altitudes below 15 km. This deviation between

Fig. 5 Reconstructed trajectory.

Fig. 6 Wind-relative attitude estimates.

the flight result and the design nominal value may come from the choice of model parameters regarding entry interface, solar activity, season, optical depth, etc.

Wind components can be extracted by recomposing the wind-relative velocity into planet-relative coordinate systems. The differences between the reconstructed velocities from the IMU and the combined IMU and FADS results represent the wind components. The estimates of the local wind components in the north-east-down frame are shown in Fig. 8. The minimum and maximum values are the envelopes of the results of the two atmosphere models. The flight results fall within the design boundary. The results suggest that both a north wind component

and a west wind component exist, indicating a constant northwest wind field below 50 km. An exception is at approximately 25 km, where an east wind shear exists, as shown in Fig. 8(b). These nonzero wind components contribute to the deviation of the angle of attack and sideslip from the nominal design value.

4.4 Aerodynamics

The reconstructed aerodynamic force coefficients are shown in Fig. 9. The reconstructed coefficients are compared with the corresponding design values (the nominal dashed line) and the deviation band (the minimum and maximum dash-dot lines). Not until 130

Fig. 7 Atmosphere estimates.

Fig. 8 Wind estimates.

Fig. 9 Atmosphere estimates.

s after entry did the drag coefficient coincide with the design nominal value. The reason for this offset is that the aerodynamic force is negligible compared with the resolution of the acceleration measurements at high altitudes. The drag coefficient is only 0.02 smaller than the nominal value at most in the hypersonic and supersonic regimes, which is considered to agree fairly well. This difference was probably caused by the deviation of the atmosphere on the day of entry. A less likely but possible explanation is that the real gas effect differs from the design nominal value in features, including but not limited to the chemical reaction model and surface catalysis effect. The drag coefficient is in close agreement after the deployment of the trim tab in 2.8 Mach through 1.8. Furthermore, the lift coefficient agrees well with the design nominal value in all regimes, except for supersonic

flight. The deviation between the reconstructed results and the nominal value increases as the vehicle descends. This deviation is most likely caused by the local wind (as stated in Section 4.3), which is no longer negligible below 25 km. Consequently, the lift and drag ratio reaches the upper bound of the design value during supersonic flight. The trim angle of attack matches the design nominal value extremely well, indicating that the aerodynamic database is accurate and the control system works effectively.

5 Conclusions

A filter method for the trajectory reconstruction of the Tianwen-1 Mars entry vehicle was presented. The ADB was generated by the CFD method and covers the entire flight envelope. This is the foundation of the

trajectory and atmosphere reconstruction. A combined reconstruction approach using data from both the IMU and the FADS is proposed. The wind-relative angles, atmospheric parameters, and wind components were estimated using this approach. The *in situ* atmospheric parameters, such as density and wind, were revealed by accurate dynamic pressure estimates obtained using the FADS. The aerodynamic force coefficients were estimated and compared with the design nominal values. The experience of Tianwen-1 should benefit future planetary EDL performances.

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Conflict of interest

The authors declare that there is no conflict of interest.

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Haogong Wei is a systems engineer at Beijing Institute of Spacecraft System Engineering, working in the area of planetary entry, descent, and landing. He is the recipient of the second prize of Science and Technology Progress Award of China Aerospace Science and Technology Corporation. He received his B.S. degree in aerospace engineering from Beijing Institute of Technology, and his M.S. degree in aeronautical and astronautical engineering from Purdue University. E-mail: weihaogong@aliyun.com.

Wei Rao, researcher, was graduated from Beihang University in August 1993. He participated in the development of Chang'e-1, Chang'e-2 lunar probes and Mars probes, serving as the product assurance manager and deputy designer of Mars probes. He has won the third prize of National Defense Science and Technology Progress Award once, the special prize of National Science and Technology Progress Award twice, the National Outstanding Youth, etc.

Guangqiang Chen, senior engineer of China Academy of Aerodynamics of Aerospace (CAAA), was graduated from Beihang University in January 2008. He is academically focusing on flushing air data sensing (FADS) technologies, including algorithmic design method based on neural network technology, fault diagnosis and fault tolerance design, wind tunnel test calibration, etc. E-mail: guangqiangchen@sina.com.

Guidong Wang, researcher, Ph.D. in fluid mechanics, was graduated from Northwestern Polytechnical University in August 1998. He completed the aerodynamic identification research of dozens of flight test of Shenzhou spacecraft, lunar spacecraft, and other aircraft. He has won the first prize of Science and Technology Progress of Sichuan Province and the third prize of Science and Technology Progress of China Aerospace Science and Technology Corporation.

Xin Zou, senior engineer, was graduated from Changchun University of Science and Technology in 2009. As the chief designer of the engineer parameter measurement system, she is responsible for the measurement system design, analysis, and verification of Chang'e-5 and Mars probes. She has won the third prize of Science and Technology Progress of Beijing Municipality.

Qi Li, researcher, was graduated from Beihang University in 2008 with a degree in fluid mechanics. As the head of the Entry and Re-entry Pneumatic Department, she is responsible for the aerodynamic design, analysis, and verification of Chang'e-5 and Mars probes. She has won the first prize of Science and Technology Progress of Sichuan Province and the second prize of Science and Technology Progress Award of China Aerospace Science and Technology Corporation.

Yanqi Hu received his Ph.D. degree in space physics from National Space Science Center in 2008. Since 2008, he has been an engineer with the Beijing Institute of Spacecraft System Engineering, China Academy of Space Technology, Beijing. His current research interests include radiation effect simulation of spacecraft, space environment modeling, and Mars atmosphere.

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