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Innovative Mars entry integrated navigation using modified multiple model adaptive estimation

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ABSTRACT

A variety of anticipated missions to Mars, such as Mars base and sample return, will have to utilize precision navigation and guidance for their hypersonic entry to achieve the required landing accuracy. In order to effectively reduce the adverse impact of initial state errors and parameter uncertainties during Mars atmospheric entry and then improve entry navigation accuracy, an innovative high-precision integrated navigation algorithm for Mars entry is developed based on a modified multiple model adaptive estimation (MMAE) in this paper. First, a six degree-of-freedom (DOF) Mars entry dynamics model is derived based on the angular velocity outputs of a gyro, which can be more complete and accurate description of the state variables of an entry vehicle than the traditional three DOF dynamics models. Second, both the accelerometer outputs and radiometric measurements are adopted as the navigation observations embedded to Kalman filter bank to perform state estimation and suppress the measurement noise. Finally, a new modified multiple model adaptive estimation algorithm with exponential decay terms is proposed to overcome the inherent drawback of classical MMAE and then further improve navigation accuracy. The numerical simulation results show that the integrated navigation algorithm developed in this paper is able to accurately estimate the state variables of an entry vehicle, even in the case that the initial entry state errors and larger parameter uncertainties are taken into account.

1. Introduction

Mars landing exploration activities have been and will continue to gather scientific data and deepen the current understanding about the life origin and the solar system formation process. One of the significant engineering challenges for precisely delivering a lander from Mars atmospheric entry point to surface involves the entry, descent and landing (EDL) phase of the mission [3]. Traditional Mars entry vehicles adopt the inertial measurement unit (IMU) based dead reckoning navigation mode and the unguided ballistic trajectory entry without aerodynamic lift control, which leads to a larger landing error ellipse on the order of several hundred kilometers [2,3,21]. Future Mars missions, such as Mars sample return, manned Mars landing and Mars base, need to achieve the pin-point landing Mars within tens of meters to 100 m of a pre-selected target site. Therefore, high-precision entry navigation and active aerodynamic lift control are essential [5,15,24].

NASA has been seeking for the advanced entry, descent and landing technologies to achieve pin-point landing, which includes hypersonic guided entry, high-precision EDL navigation technology, Mars guided parachute, sky crane terminal descent and autonomous hazard detection and avoidance [3,5,30,32]. European Space Agency (ESA) fastens much attention on developing the advanced EDL navigation guidance and control technology as well. In the frame of Aurora exploration program, the high-fidelity end-to-end Entry, Descent and Landing Simulator EAGLE and the Precision Landing GNC Test Facility (PLGTF) have been set up to validate and verify the autonomous safe precision landing GNC technologies, both vision and LIDAR based, in a realistic environment [8,25]. China has already initiated the technical preparation for its own Mars landing and sample return exploration missions, and its effort is focused on the advanced navigation, guidance and control technologies for entry, descent and landing [14–17].

From the viewpoint of a navigation system, the main difficulty in achieving a high-precision Mars entry navigation comes from the following two aspects. Firstly, the dynamics models of Mars entry and related parameters usually include large uncertainties and

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errors, which greatly degrade the performance of navigation filter. The most significant sources leading to a larger Mars entry dispersion include the accumulated state estimation errors at the atmospheric entry point, the uncertainties in the atmospheric density and aerodynamic coefficients, and the random winds and gusts [7,32]. Secondly, the available navigation sensors are extremely limited in the Mars entry phase due to the existence of a heat shield against extremely adverse thermal environment. IMU is almost the only sensor that can be utilized for Mars entry navigation for a long period of time [14,31].

There have been several literatures about Mars entry navigation concepts and algorithms in the last decade. In order to overcome the adverse effects of uncertainties in the Martian atmospheric density, Heyne and Bishop adopted the adaptive sigma point Kalman filter bank to achieve precision entry navigation in the presence of a highly dynamic environment with noise and unknown forces [10]. Ely and Bishop applied the hierarchical mixture of experts' architecture to Mars entry navigation, in which the navigation filters are parameterized with various atmospheric and other spacecraft parameters [6]. Zanetti and Bishop investigated the application of multiple model adaptive estimation architecture to entry navigation during the highly dynamic hypersonic pre-parachute deploy phase, in which the high uncertainty associated with the Martian atmospheric density was addressed with multiple dynamic models comprising a filter bank [33]. The work reported in Ref. [33] was subsequently extended by including the sensor biases and scale factors into state variables to be estimated. Simulation results showed that such additions increased the robustness and fidelity of the multiple model adaptive estimation [23]. One common character of the research works mentioned above is that only IMU (accelerometer and gyro) data is considered as external measurements and then processed by a navigation filter bank. At the same time, all their works adopted the classical multiple model adaptive estimation (MMAE) algorithm. Utilizing Kalman filter processing IMU data can indeed improve the entry navigation accuracy compared to traditional dead-reckoning navigation. However, the inertial constant biases and drifts cannot be completely removed and are involved into navigation observations instead, which inevitably degrades the performance of navigation filter. Due to the presence of the phenomenon of excessive competition between the various sub-models, classical MMAE cannot precisely estimate the entry vehicle states when one of the models is closer to the real model than others. A representative simulation has been performed in Section 5 to show this inherent drawback of classical MMAE. The performance of dead-reckoning navigation alone usually degrades with time due to the inertial constant biases and drifts from IMU. One feasible solution is utilizing the external measurements to correct these inertial biases and drifts, and then improve the landing navigation accuracy [14,16,17]. However, most external measurements are unavailable due to the existence of a heat shield. Recent research shows that the ionizing plasma around the entry body has little effect on the ultra-high frequency (UHF) band (300–3000 MHz) radio communication, which can be utilized on-board in real time to significantly improve the on-board state knowledge during hypersonic flight phase [4,31]. In the past decade, an evolving network of Mars relay orbiters has provided telecommunication relay services to the Mars Exploration Rovers, Spirit and Opportunity, the Mars Phoenix Lander, and the Mars Science Laboratory (MSL), enabling high-bandwidth, energy-efficient data transfer and greatly increasing the volume of science data that can be returned from the Martian surface, compared to conventional direct-to-Earth links [31]. One task of NASA Mars technology program is developing a prototype, embedded, real-time navigation system for Mars final approach and entry, descent, and landing using the Electra and Electra-Lite transceivers [4,5] and [19]. Li and Peng have preliminarily addressed the issue of Mars entry navigation using inertial measurement unit (IMU) and orbiting or surface radiometric beacons [14]. Lévesque and De Lafontaine studied the navigation performance and observability of four measurement scenarios based on radio ranging during Mars entry [13]. Only a single Kalman filter is adopted to process the navigation measurements in both Refs. [14] and [13], which lacks of robust adaptive capability and cannot achieve a higher navigation accuracy in the presence of larger state errors and parameter uncertainties.

The aim of this paper is to develop an innovative integrated navigation algorithm for Mars atmospheric entry with higher accuracy. In order to completely and accurately describe the state variables of an entry vehicle, a 6 degree-of-freedom (DOF) Mars entry dynamics model is derived based on the angular velocity outputs of a gyro, in which the attitude dynamics is replaced by the outputs of a gyro and free of modeling errors. Both the accelerometer outputs and radiometric measurement information between the entry vehicle and the orbiting and surface beacons are utilized as the navigation observations embedded to Kalman filter bank to perform state estimation and suppress the navigation measurement noise. At the same time, a modified multiple model adaptive estimation (MMAE) methodology with exponential decay terms is proposed to overcome the inherent drawback of classical MMAE, which can effectively reduce the adverse impact of initial state errors and parameter uncertainties during Mars atmospheric entry and then improve the entry navigation and parameter identification accuracy.

The rest of this paper is structured as follows. Section 2 contrastively introduces the traditional 3-DOF Mars entry dynamics model and the new 6-DOF Mars entry dynamics model adopted in this paper. Section 3 defines the navigation measurement models utilized in the subsequent section of the integrated navigation algorithm. The modified multiple model adaptive estimation methodology with exponential decay terms and integrated navigation algorithm are developed at length in Section 4. In Section 5, simulation system compositions are described and simulation results are discussed in detail. Finally, the conclusions and suggestions regarding future research are summarized in Section 6.

2. System dynamic equations of Mars entry

As system dynamic equations are essential to predict the state variables of Mars entry vehicle, the applicability of integrated navigation filter heavily depends upon the availability of sufficiently accurate dynamic equations of Mars entry. Based on the angular velocity information sensed from a gyro, the 6-DOF Mars entry dynamic equations are derived in this section to perform the subsequent navigation filter. Traditional 3-DOF Mars entry dynamic equations are also given out to construct a complete and real dynamic simulation environment in Section 5.

2.1. Coordinate system definitions and coordinate transformation matrix

As various physical quantities are usually defined in the different coordinate systems in order to have a straightforward physical meaning, all physical quantities described in different coordinate systems must be transformed into the same coordinate to model the entry dynamic equations, construct the navigation measurements and then design the integrated navigation filter algorithm. Fig. 1 depicts the relative geometrical relationship among these coordinate systems. In order to keep the main context compact and readability, the coordinate system definitions and the coordinate transformation matrices are intentionally arranged into the Appendix A.