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Observability analysis of Mars entry integrated navigation

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Abstract

This paper studies three schemes of Mars entry navigation: inertial measurement unit (IMU) based dead reckoning (DR), IMU/orbiter based integrated navigation, and IMU/orbiter/Mars surface beacon (MSB) based integrated navigation. We demonstrate through simulations that first scheme, IMU based DR, produces substantially large state estimation errors. Although these errors are reduced by adding two Mars orbiters, the system is only barely observable. However, by adding two MSBs in above configuration, the position and velocity estimation errors are reduced to the scope of 10 m and 0.5 m/s respectively and the navigation system becomes completely observable. Finally, the estimability of states is investigated; it is observed that velocity variables or velocity variables linear combinations can be estimated better than position variables.

Keywords: Mars entry integrated navigation schemes; Observability; Condition number; Fisher information matrix; Estimability

1. Introduction

To date, NASA has successfully landed seven landers on the surface of Mars, including Viking 1 and 2, Mars Pathfinder (MPF), Mars Exploration Rovers (MER-A, MER-B), the 2007 Phoenix and the Curiosity landed on 5th August, 2012. The landing accuracy has been achieved, from 150 km of the target for MPF to 35 km for MER, to within 5–10 km of the target for Phoenix (Wolf et al., 2004), and to 2.2 km for the Curiosity (Mendeck and McGrew, 2011). The improved landing accuracy is achieved through advanced navigation and guidance techniques. Before the Curiosity, all the landers adopted DR navigation approach. The MPF, MER-A and MER-B all flew unguided ballistic trajectories during Entry, Descent, and Landing (EDL) (Li and Xiu, 2014). For the Curiosity, many new technologies were used to ensure high precision landing. For example, in final approach, Mars network based navigation was used to navigate the spacecraft to the desired entry point in the atmosphere (Lightsey et al., 2008). The Mars network, including two orbiters-Mars Resonance Orbiter (MRO) and Mars Express (MEX), were employed during Mars entry phase to provide outside navigation measurement (Morabito et al., 2014). And lift based guidance was used by modulating the bank angle during a hypersonic entry phase (Mendeck and McGrew, 2011). An innovative Sky Crane maneuver was used at the descent stage (Kornfeld et al., 2014). Although the improved landing precision has been achieved by Curiosity, it still cannot meet the needs of "pinpoint landing", that is within 100m of the target (Wolf et al., 2004). For future Mars exploration tasks, the Mars airplane can be used at the altitude of about 3 km when the pullout maneuver starts. With this technique, the Mars airplane can be maneuvered to any location of interest (Liu et al., 2013).

One of the factors that contribute to the landing dispersion lies in our ability to navigate the vehicle. Mars entry phase is the most challenging part among Mars EDL (Braun and Manning, 2007). Due to the remote distance

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from earth, traditional methods used for the deep space exploration such as ground based stations for tracking, observation and communication seem to be unreliable. It is due to the fact that communication between ground and deep space lasts for several minutes and the whole EDL lasts only for seven minutes. So the Mars vehicles have to navigate autonomously. Recent years, X-ray pulsar based deep space autonomous navigation has aroused great interests among researchers (Sheikh et al., 2006; Cui et al., 2013; Wei et al., 2013; Graven et al., 2008; Ray et al., 2008). Yu has used X-ray pulsar and Mars network based real-time navigation for Mars final approach (Cui et al., 2013). Wei has presented the modeling and results of autonomous navigation of Mars probe using X-ray pulsars (Wei et al., 2013). However, this method may not be appropriate for Mars entry navigation due to time limits and signal attenuation caused by Mars atmosphere. Another limitation of Mars entry navigation is the lack of measurement devices. Since the vehicle is protected through a heat shield against the aerodynamic heating environment, conventional navigation devices like radar altimetry, LIDAR, and optical sensors cannot be used during Mars entry phase (Li and Peng, 2011). Besides Mars orbiter based navigation, an innovative navigation scheme is proposed by Lévesque and Lafontaine (2007), in which the MSBs are used for state and parameter estimations. On the basis of MSBs based navigation, Yu and Cui optimised the configuration of the MSBs by using genetic algorithm (Abraham et al., 2013) and taking the observability as a performance index (Yu et al., 2015). After that they made a thorough observability analysis of Mars entry navigation by using radiometric measurements from MSB (Yu et al., 2014). However, in these researches, observations are added one by one by trials to make the navigation system observable, which may spend a lot of efforts when the dimension of the system is high. In our paper, the relationship between FIM and observability is used to determine the number of the observations directly. On the other hand, in these researches, the role of Mars orbiters in navigation is neglected. The conclusions made by these researches are partial, because the obtained results are only from the observations of MSBs. In practical cases, the MSBs should be used as a backup of Mars orbiters. The investigations of integrated navigation have been done by Li et al. (2014a,b) and Wu et al. (2014). However, a common problem is that the rotation of Mars is neglected in both state equations and measurement equations, which will have a significant effect on the landing precision (Lévesque, 2006). For example, at the equator level, the ground velocity of Mars is $v_M = \omega_M R_M = 7.0882e{-}5\,[\mathrm{rad/s}]^{*}\,3397.2\,[\mathrm{km}] = 0.2408\,[\mathrm{km/s}]$, where ω_M is Mars rotating angular velocity, R_M is Mars radius, "$*$" means the product of two scalars. In general, Mars entry lasts several minutes, in this paper 250s, which means that the target landing site at the equator moves about $d = v_M t = 0.2408\,[\mathrm{km/s}]^{*}\,250\,[\mathrm{s}] = 60.2\,[\mathrm{km}]$. Although the movement distance reduces with the latitude getting closer to the poles, Mars rotation has to be taken into account for the landing accuracy to be within 100 m of the target.

In this context, our contributions include that: (1) Three Mars entry navigation schemes: IMU based DR, IMU/orbiter based integrated navigation, and IMU/orbiter/MSBs based navigation are comprehensively analyzed and discussed under Mars rotation which is neglected by most of previous articles. (2) The condition number of the observability matrix is used to evaluate the performance of the navigation environment. And to determine the number of outer observations used for filtering, the relationship between FIM and observability is used instead of by trials one by one, which will save efforts when the dimension of a system is high. (3) When the navigation system is totally observable, the estimability of the states is further investigated which proves that the velocity variable is more observable by adding the rate measurements. The rest of this paper is organised as follows: Section 2 builds Mars entry dynamic model under Mars rotation. Section 3 presents the technical tools: observability of the system, the relationship between observability and FIM, and the estimability of the states. Section 4 presents the simulation results of three navigation schemes. Section 5 is the conclusion.

2. Mars entry dynamic models

In this section, the mathematical model describing Mars entry dynamics is presented, which is based on assumption that the vehicle is only affected by gravity, atmosphere lift and drag during Mars entry (Fowler and Ghosh, 2003). In order to build the entry dynamic model and measurement model, the coordinate frames have to be defined first.

2.1. Definitions of coordinate frames

(1) *Mars centered inertial coordinate frame (MCICF)*: denoted by $\mathbf{X}^i, \mathbf{Y}^i, \mathbf{Z}^i$. This frame is depicted in Fig. 1, where its origin is centered on Mars, the $\mathbf{X}^i$ axis points toward the Martian vernal equinox direction, the $\mathbf{Z}^i$ axis points in the direction of the Martian North pole and the $\mathbf{Y}^i$ axis completes the right-handed system. The $\mathbf{X}^i$ axis and $\mathbf{Y}^i$ axis are on the equatorial plane. The MCICF is non-rotating with respect to the stars.

(2) *Mars centered fixed coordinate frame (MCFCF)*: denoted by $\mathbf{X}^m, \mathbf{Y}^m, \mathbf{Z}^m$. This frame is similar to the MCICF coordinate frame. The difference is that its $\mathbf{X}^m$ axis points in the direction of the Martian prime meridian, and the $\mathbf{Y}^m$ axis completes the right-handed system. The MCFCF rotates around Mars along the $\mathbf{Z}^m$ ($\mathbf{Z}^i$) axis. The rotation angle is Θ which can be calculated by $\Theta = \Theta_0 + \omega_M t$. The coordinate transformation from MCICF to MCFCF is