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On the observability of Mars entry navigation using radiometric measurements

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Abstract

A thorough observability analysis of the Mars entry navigation using radiometric measurements from ground based beacons is performed. This analysis involves the evaluation of the Fisher information matrix which is derived from the maximum likelihood estimation. A series of navigation cases with multiple beacons are investigated, and both range and range-rate measurements are considered. The determinant of Fisher information matrix is used to quantify the observability of navigation system, while the trace of Fisher information matrix is used to determine the lower-bound of estimation errors. For one and two beacon cases, the navigation system is unobservable. However, the eigenvectors of Fisher information matrix give the observable and unobservable component. When three or more beacon measurements are employed, the states of entry vehicle become observable. Some valuable analytic conclusions on the relationship between the geometric configuration of beacons and observability are obtained consequently. Finally, simulation results from two navigation examples indicate that our effort is useful for understanding and assessing the observability of the Mars entry navigation using radiometric measurements.

Keywords: Observability; Mars entry navigation; Fisher information matrix; Radiometric measurements; Geometric configuration

1. Introduction

The Mars landing vehicles in the future need to land precisely at certain locations in order to gather samples with high scientific quality, so even more stringent landing precision requirements may be necessitated (Braun and Manning, 2007). The Mars entry phase is the most unpredictable and dangerous period among the Mars entry, descent, and landing phases. There is much uncertainty in the entry point, atmospheric density, and aerodynamic characteristics of the entry vehicle in this period (Steinfeldt et al., 2010). Meanwhile, the advanced atmosphere guidance may need the full state feedback requiring the accurate knowledge of all states (Lévesque, 2006, 2007). Therefore, an accurate autonomous navigation in the Mars entry phase plays an important role in fulfilling the pinpoint landing.

In order to improve the navigation capability in the Mars entry phase, the navigation scheme based on Mars networks consisting of orbiters and ground beacons was developed. Lightsey proposed different navigation schemes using radiometric measurements for the Mars approach and entry phases, and indicated that a more accurate navigation could be obtained (Burkhart et al., 2005; Lightsey et al., 2008). Furthermore, Pastor demonstrated that the position of radio beacons might be a great contributor to the navigation capability (Pastor et al., 2000). However, in these researches, very little attention has been paid to the relationship between the beacon configuration and the navigation capability

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(in other words how to locate beacons to achieve an adequate navigation capability).

The observability of a navigation system, which is one of the key indexes associated with navigation capability, may bridge this gap. Therefore, the observability analysis is indispensable for the design of a navigation scheme. Although for linear dynamical systems, the observability Gramian and observability matrix arise naturally in many problems pertaining to observability analysis, the observability for nonlinear systems has still not been completely understood. Significant attention on the observability analysis has been received (Hermann and Krener, 1977; Singh and Hahn, 2005; Woffinden and Geller, 2009; Huxel and Bishop, 2009; Maessen and Gill, 2012). However, for these attempts, the analytic conclusions about the contributor to the observability can hardly be drawn. Particularly, Yu innovatively proposed a nonlinear observability analysis method based on the quadratic approximation (Yu et al., in press). Although he tried to optimize the beacon configuration based on observability analysis, the contribution of beacon configuration to the observability of entry vehicle's states is still ambiguous.

Alternatively, from an estimation theory point of view, the lower-bound of the estimation error covariance matrix can be estimated by the inverse of Fisher information matrix (FIM) according to the Cramér–Rao inequality (Crassidis and Junkins, 2011). Therefore, the observability of a navigation system can be analyzed by examining the FIM. In this circumstance, some useful analytic conclusions can be obtained. Jauffret discovered the link between the invertibility of Fisher information matrix and the observability of a parameter estimated in a nonlinear problem (Jauffret, 2007), which builds the foundation of our research. Meanwhile, the implementation of observability analysis based on FIM has been dramatically extended. Dogancay generated the trajectory of uninhabited aerial vehicle which minimized the localization uncertainty by solving a nonlinear programming problem using the approximation of FIM (Dogancay, 2012). Cui chose the optimal navigation pulsars for Mars final approach navigation using X-ray pulsars by evaluating the FIM of spacecraft's position (Cui et al., 2013). More systematically, Crassidis performed the analysis to study the observability of the attitude and position determination problem for cases involving different number of vector observations (Crassidis et al., 2000; Sun and Crassidis, 2002). The radiometric measurement for Mars entry navigation has its own special characteristics and difficulties, so further investigations are required for the observability analysis. Besides, related researches on the range-only measurements (Song, 1999; Bishop et al., 2010; Song et al., 2012) also inspire us to move forward. However, in these studies more attentions had been paid to the 2-dimensional cases, and the analyses gave no consideration to the range-rate measurements which are also vital information sources for the Mars entry navigation.

This paper extends previous researches to the 3-dimensional Mars entry navigation using both range and range-rate measurements from ground based beacons. An analytic relationship between the beacon configuration and observability is investigated. First of all, a review of the measurement equations of Mars entry navigation is presented. Then a generalized loss function derived from the maximum likelihood estimation for the position and velocity is given. Next, the Fisher information matrices of the entry vehicle's position and velocity are derived. The observability and the lower-bound of estimation errors are then determined by evaluating the determinant and trace of the Fisher information matrices. Additionally, the observability analyses of the Mars entry navigation with multiple ground based radio beacons are performed using the eigenvalues and eigenvectors of the information matrix. Based on these analyses, some innovative analytic conclusions are obtained consequently, which is valuable for further investigations. Finally, two navigation scenarios with three radio beacons are considered, which demonstrate that the analysis is useful for understanding and assessing the observability of the Mars entry navigation using beacon data. Furthermore, the sensitivity of the observability with respect to different uncertainty sources is preliminarily discussed.

2. Observation model and the Fisher information matrix

In this section, the observation models of Mars entry navigation using radiometric measurements from ground based beacons are reviewed. Then, the Fisher information matrix is derived. Next, the observability and lower-bound of estimation errors are investigated by analyzing the determinant and trace of the Fisher information matrix.

2.1. Observation model

Recent investigations indicate that high frequency radio signals could penetrate the plasma sheath around the entry vehicle during the Mars entry phase (Morabito, 2002). On the basis of this research, the autonomous navigation based on Mars networks is proposed to improve the navigation capability for the future Mars landing missions. With high frequency transceivers mounted on the entry vehicle and ground based beacons, the spacecraft-to-beacon relative range and range-rate can be measured to compute the state estimation for the entry vehicle throughout the entry phase. The schematic of the quantities involved in the Mars entry navigation using radiometric measurements from ground based networks is shown in Fig. 1.

The states of an entry vehicle are defined as its position $r = [x, y, z]^T$ and velocity $v = [v_x, v_y, v_z]^T$ in the Mars J2000 inertial frame (X, Y, Z) (See Fig. 1). The high frequency transceiver such as the "Electra" (Lightsey et al., 2008) can provide radiometric measurements between the Mars entry vehicle and network beacon by measuring the range