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Autonomous navigation method based on unbiased minimum-variance estimation during Mars entry

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Abstract

Accurate navigation systems are required for future pinpoint Mars landing missions. A radio ranging augmented inertial measurement unit (IMU) navigation system concept is considered for the guided atmospheric entry phase. The systematic errors associated to the radio ranging and inertial measurements, and the atmospheric mission uncertainties are considered to be unknown. This paper presents the extension of an unbiased minimum-variance (EUMV) filter of a radio beacon/IMU navigation system. In the presence of unknown dynamics inputs, the filter joins the system state and the unknown systematic error estimation of a stochastic nonlinear time-varying discrete system. 3-DOF simulation results show that the performances of the proposed navigation filter algorithm, 100 m estimated altitude error and 8 m/s estimated velocity error, fulfills the need of future pinpoint Mars landing missions.

Keywords: Autonomous navigation; Measurement systematic errors; Unknown inputs; Extension of unbiased minimum-variance; Mars entry

1. Introduction

Mars pinpoint landing problems play an important role in future Mars missions. An increasing amount of effort has been devoted to it, and many new issues have been investigated by many researchers from different countries and international originations. The general Mars entry, descent and landing (EDL) mission is divided into four phases: the hypersonic entry phase, the subsonic parachute entry phase, the propulsive terminal descent (or powered descent) phase and the touchdown phase (Braun and Manning, 2007). To date, the Viking mission adopts the inertial measurement unit (IMU) using a dead reckoning navigation mode and an unguided ballistic trajectory, which leads to a larger landing error ellipse in the order of several hundred kilometers and thus cannot meet the requirements of future manned Mars landing and sample return missions (Jeremy et al., 2008). Other missions (e.g., Pathfinder; Mars Exploration Rover, MER) whose landing accuracies are larger than 10 km use non-lifting trajectories focused only on safe landing. Phoenix mission adopts a non-lifting trajectory and uses a gravity turn descent; nevertheless, precision landing is not required. Recently, the Mars Science Lab (MSL) adopted a guided entry using bank control to steer the vehicle through aerodynamic lifts.

Future Mars pinpoint landing missions, such as Mars sample return, manned Mars landing and Mars base, need to achieve a pinpoint Mars landing within tens of meters to 1 km of a preselected target site; therefore, high-precision autonomous navigation and active aerodynamic lift control are essential (Levesque and de Lafontaine, 2007; Kozynchenko, 2011; Li and Peng, 2011). NASA has been

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seeking EDL technologies, which include hypersonic guided entry, high-precision EDL navigation technology, Mars-guided parachute, sky crane terminal descent and autonomous hazard detection and avoidance (Braun and Manning, 2007; Brand et al., 2004; Wolf et al., 2005; Chu, 2006). China has already initiated the technical preparation for Mars pinpoint landing missions (Wei et al., 2013; Yu et al., 2014a; Wu et al., 2014).

There are three factors affecting the Mars entry navigation accuracy: the first is that the Mars entry dynamic model for the navigation filter must be accurate, the second is that the measurement data from the high-precision sensors must be correct, and the third is that the state estimation algorithms of the navigation filter must be right. In practice, however, the accuracy of the Mars entry dynamic model is degraded by many uncertain parameters for the navigation filter during the Mars entry phase (Wolf et al., 2005; Prasun et al., 2006; Prince et al., 2011). The most significant uncertainty sources, including the initial state errors at the atmospheric entry interface and the uncertainties of the atmospheric density, induce the Mars entry dynamic model errors (Prasun et al., 2006; Prince et al., 2011). Using radiometric data as a new way for Mars entry navigation is proposed by Burkhart et al. (2005). Throughout EDL, UHF transmissions from Curiosity (a MSL mission) are monitored by three Mars orbiters: the Mars Reconnaissance Orbiter, the 2001 Mars Odyssey and the European Space Agency's Mars Express (Way et al., 2013). The ranging measurement can achieve centimeter accuracy by using global positioning system (GPS) receivers modified for Mars applications. Based on the GPS technology and assuming the same parameters to be nearly constant, the navigation schemes for the state and parameter estimations are proposed (Levesque and de Lafontaine, 2007). However, unlike on the Earth, there are no orbiting satellite constellations or ground reference systems used for spacecraft global positioning on Mars, and there will not be any in the foreseeable future (Levesque, 2006). The measurement data from the sensors may be hindered by the unknown measurement systematic errors, such as radiometric beacons' error, radio signal transmission error and receiver error. In other words, the Mars entry nonlinear uncertain system has some time-varying unknown inputs in the system dynamic equations and unknown measurement systematic errors in the measurement equations. To solve these problems, the extended Kalman filter (EKF) obtained by first-order linearization of the nonlinear system may diverge. Furthermore, the unscented Kalman filter (UKF) also suffers from the problem of divergence. In other words, these methods may lead to severe degradation in data association and track quality and result in a large growth of redundant and spurious tracks.

The unbiased minimum-variance (UMV) algorithm, which has been developed for state estimation of a linear system with unknown inputs in the system dynamic model or measurement systematic errors in the measurement model, has gained the interest of many researchers during recent decades. (Renato, 2012; Crassidis and Junkins, 2012; Kitanidis, 1987; Hmida et al., 2010). When the model of the unknown inputs is available, the Augmented State Kalman Filter (ASKF), which can solve the unknown inputs filter problem by augmenting the state vector with the unknown inputs vector, is an optimal estimation (Friedland, 1969). If the model of the unknown inputs is not available, then a UMV with unknown inputs has been developed by minimizing the trace of the state error covariance matrix under an algebraic constraint (Kitanidis, 1987). The problem of state estimation for linear, time-varying, discrete-time stochastic systems with unknown inputs has been a concern of Hmida et al. (2010).

Due to the limitation of current technology, the accuracy of the IMU and radio ranging measurement is low so that the inaccurate time-varying model parameters may degrade the state estimation during the Mars entry phase. The unknown inputs and measurement systematic errors are time-varying, and models of them are not available. If they are not treated, these errors will greatly reduce the navigational performance. To solve this problem, a type of radio beacons/IMU navigation method based on the EUMV for the Mars entry phase has been researched. Because no ranging measurement caused by radio blackout is predictable in the course of the Mars entry phase, radio beacons/IMU navigation with radio blackout is also discussed. This paper is structured as follows: Section 2 briefly describes the Mars EDL sequence and navigation scheme. The traditional Mars entry dynamic equations and the new Mars entry dynamic model are introduced in Section 3. Section 4 defines the navigation measurement models. The navigation algorithm of the EUMV is designed in Section 5. In Section 6, simulation results are discussed. The conclusions are summarized in Section 7.

2. Mars EDL sequence and navigation scheme

The EDL sequence, which includes the hypersonic entry phase, the subsonic parachute entry phase, the propulsive terminal descent (or powered descent) phase, and the touchdown phase, begins at the Mars atmosphere interface (defined as an altitude of 125 km over the surface of Mars) and ends with a preselected landing site. The hypersonic entry phase starts with the vehicle entry at the Mars atmosphere interface and ends with the deployment of the supersonic parachute. When the Mars vehicle meets a design threshold (such as a final velocity less than 400 m/s and an altitude less than 10 km) after the hypersonic entry phase, the supersonic parachute is deployed. The subsonic parachute remains deployed until the velocity of the Mars vehicle reaches an additional design criteria. During the powered descent phase, the heat shield automatically separates from the lander. As a result of that, the onboard sensors and actuators in the lander are exposed. Thus, the lander has the capability of high-precision relative navigation and autonomous obstacle detection and avoidance. When the lander's