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Landmark-based autonomous navigation for pinpoint planetary landing

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Abstract

A landmark-based autonomous navigation scheme is presented for pinpoint planetary landing. The dynamic model is built on the basis of measurements from Inertial Measurement Unit. Measurement models of landmarks with known coordinates and landmarks with unknown coordinates extracted from sequential descent images are developed and used to calculated the state corrections in Extend Kalman Filter, respectively. Then, the corrections are fused by a covariance intersection fusion algorithm to perform state updates. The tight coupling of the two types of landmark observations yields accurate and robust state estimates. Extensive simulations are performed, which confirm the validity of the proposed navigation scheme and analyze the effects of factors, such as the horizonal position errors and the densities of landmarks with known coordinates and the roughness of the landing surface, on the navigation accuracy.

Keywords: Autonomous navigation; Pinpoint landing; Sequential images; Landmarks; Information fusion

1. Introduction

Autonomous pinpoint landing is a critical capability for future planetary exploration missions, which requires delivering a lander to a pre-designated landing site within 100 m. As is well known, initial errors at the entry point, atmosphere uncertainties, wind drift on the parachute are the main error sources affecting landing accuracy. In order to realize pinpoint landing, these errors must be corrected during powered descent, which calls for a high-precision navigation system. This paper focuses on the navigation performance improvement of the powered descent phase.

During the powered descent phase, high-accuracy velocity, position and attitude (pose) determination, a necessity for pinpoint landing, is difficult to be fulfilled with the current technology. In current planetary landing missions, the landers have determined their poses largely depending on fusing measurements from Inertial Measurement Unit (IMU) with velocity and altitude information from doppler radar (Wang et al., 2008; Busnardo et al., 2011). However, this method does not allow for the accurate estimation of a lander's horizontal position. A possible method for enabling very precise landing is landmark-based navigation (Quadrelli et al., 2015). Numerous landmark-based autonomous navigation approaches have been proposed based on the assumption of a priori landmark information. For example, some versions of the terrain relative navigation, which are developed by NASA in the Autonomous Precision landing and Hazard Avoidance Technology (ALHAT) program, generate a pose estimate of a lander by matching descent images or topography data to a reference map (Johnson and Montgomery, 2008; McGee et al., 2015; Johnson et al., 2015). Additionally, many previous publications have developed various vision-aided inertial navigation (VAIN) methods that combine IMU measurements with image observations of landmarks with known positioning information (Li et al., 2007; Pham et al., 2012;

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Yu et al., 2014). Actually, due to the limited resolution of the reference map, it may be impossible to obtain accurate three dimensional (3D) coordinates of landmarks on the surface of planets. For example, the entire lunar imagery and digital elevation map (DEM) from Lunar Reconnaissance Orbiter data have a resolution of about 100 m/pixel and 25–30 m/pixel respectively, which is one of the main sources of lunar terrain data for ALHAT program (Shankar et al., 2008). While Mars map uncertainty of 180.8 m in planimetric distance and 30.8 m in elevation is obtained from the Mars Global Surveyor (MGS) mapping data (Shan et al., 2005). The highest resolution existing Mars maps is 1–2 m in post spacing and tens of centimeters in vertical precision, which is generated from the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) (McEwen et al., 2010). However, the high resolution map covers less than 1% of the Mars surface.Thus, position errors always exist for landmarks tracked between images. However, the previous methods do not take into account these errors. In addition, the amount of landmarks with known coordinates that can be extracted from descent images is another factor to be given consideration (Trawny et al., 2007; Mourikis et al., 2009). As the lander approaches the ground, fewer and fewer landmarks with known coordinates can be observed, which has a significant effect on the navigation accuracy. Thus, navigation based only on landmarks with known coordinates cannot fulfil the requirements of pinpoint landing.

It is worth noting that, except landmarks with known coordinates, many landmarks with unknown coordinates can be extracted from sequential descent images. Several approaches have been proposed in previous papers using unknown landmarks for navigation. For example, the Descent Image Motion Estimation System (DIMES), developed by NASA for the Mars Exploration Rovers mission, estimates the spacecrafts ground-relative horizontal velocity by tracking landmarks observed in three sequential images (Johnson et al., 2007). Another well-known method is Simultaneous Localization and Mapping (SLAM), which incorporates the 3D coordinates of landmarks into the estimator state vector and estimates these coordinates along with the vehicle's trajectory (Garcia et al., 2002; Kim and Sukkarieh, 2004). In addition, a multi-state constraint Kalman filter (MSCKF) method using unknown landmarks has been developed, which estimates the position of landmarks by employing a least-squares minimization algorithm when landmarks that have been tracked in sequential images are no longer detected in the most recently captured image (Mourikis and Roumeliotis, 2007). Another method for landing navigation without any a priori landmark information consists of building multi-view constraints as measurement equations instead of estimating the positions of landmarks (Pini and Hector, 2001; Diel et al., 2005; Zhao et al., 2012; Indelman et al., 2012; Pannhanden et al., 2011). However, when there is no external information, the system states, particularly the absolute position of the vehicle, are unobservable for these methods.

In this work, we develop a novel measurement model for landmarks with unknown coordinates and propose a navigation scheme fusing measurement models of landmarks with known coordinates and landmarks with unknown coordinates to perform state updates during powered descent. The landmark-based navigation proposed in this paper can remarkably improve navigation accuracy, which makes pinpoint landing possible.

This paper is organized as follows. In the next section, the landing vehicle dynamic model and its continuous-time linearized model are presented. Section 3 describes in detail the development of two types of measurement models corresponding to landmarks with known coordinates and landmarks with unknown coordinates, whereas Section 4 presents Covariance Intersection Update algorithm. Then, in Section 5, simulations are performed to assess the performance of the proposed navigation scheme for planetary landing and the results are discussed. Finally, Section 6 provides some conclusions.

2. Landing dynamic model

To describe the relationship between the landing vehicle and the pre-selected landing spot clearly, the following coordinate systems are introduced:

(1) L is the landing coordinate system, which is a target-fixed reference frame with its origin centered at the predetermined landing site. z_L is perpendicular to the local level plane, and the x_L and y_L axes lie in the local level plane and complete a right-handed Cartesian coordinate system. The vehicle's position and velocity are all described in the landing coordinate system.
(2) B is the body-fixed coordinate system. Its origin is located at the center of mass of the vehicle, and the three axes of symmetry of the body are defined as the three coordinate axes. The IMU measurements and biases are described in the body-fixed coordinate system.
(3) C is the camera-fixed coordinate system. Its origin is located at the center of focus of the camera. z_C points toward the center of the field of view (FOV), x_C points toward the right half of the FOV, and y_C is defined such that the system is a right-handed Cartesian coordinate system.

To address the problem that traditional dynamical modeling has difficulties in obtaining accurate torque and force models for planetary landing, the measurements from IMU are directly used for establishing dynamic model in this paper. The vehicle landing dynamic equations based on outputs of IMU are given by Mourikis et al. (2009)

$$^{L}\dot{\boldsymbol{r}} = {}^{L}\boldsymbol{v}$$