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Only feature point line-of-sight relative navigation in asteroid exploration descent stage ☆

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ABSTRACT

A new and real-time only feature point light-of-sight (LOS) relative navigation (OFPLOSRN) technology based on only onboard navigation camera (ONC) is proposed for probe approaching mission in asteroid exploration descent stage. In this new method, its real-time can be guaranteed via using only ONC sensor, and it avoids the errors of relative attitude transition matrix determination in the measurement modeling because the angles of unit feature point LOS vectors are only chosen as the measurements and these angles keep invariable in different coordinate frames. The observability of OFPLOSRN is verified by Lie-Differentiation. The numerical simulation results of simulating HAYABUSA landing mission indicate that the relative position, velocity and attitude of probe to feature region in asteroid exploration descent stage can be estimated by the new OFPLOSRN method with sufficient accuracies.

1. Introduction

Asteroid exploration is greatly helpful for discovering the primitive nature of universe formation and the potential collision hazard to Earth [18]. In February 2001, the near-Earth asteroid rendezvous probe NEAR firstly made a mission of landing on an asteroid surface [7,8]. Also, in November 2005, the Japanese HAYABUSA probe successfully performed asteroid touchdown and sampling mission, and returned back to Earth in June 2010 [9,16]. Although these probes accomplish their asteroid exploration missions, they more or less have a man-in-the-loop, cost a lot of time or some unpredictable faults happen due to the remote communication delay with Earth and complex space environment, such as the antenna pointing bias of NEAR leading to the interruption of communication with Earth, and the attitude control devices (Reaction Wheels (RWs)) fault and the relative position determination bias of HAYABUSA leading to the sampling failure of its released MINERVA explorer [15,24]. To avoid these and similar problems, an autonomous, firm and reliable guidance, navigation and control (GNC) system of probe will play an important role of guarantee in future asteroid exploration missions. Especially to stably land on an asteroid surface and avoid close collision, the relative navigation system of probe must be absolutely autonomous and intelligent with high accuracy and cannot be like the GNC systems of traditional asteroid exploration missions, such as those in the NEAR and HAYABUSA, only with a simple range detection and control via the laser imaging detection and ranging (LIDAR) sensor [7–9,16].

Differently from the soft landing of big body, such as the Moon and the Mars, the landing environment of an asteroid is special and these special factors include small magnitude of asteroid gravity, unknown asteroid gravity model, the small size of asteroid, low landing height and short landing time of probe, and so on. Also, not like the relative navigation via measuring the light-of-sight of asteroid centroid in the stage of probe flying around asteroid [14], the measurement targets in asteroid exploration descent stage involve only the feature points on the surface of asteroid. For these conditions in asteroid exploration descent stage, to obtain an absolutely autonomous and intelligent relative navigation method, some research works are developed. An autonomous navigation and joint attitude determination method has been presented via measuring the normal vector perpendicular to landing plane with three LIDAR sensors [5]. However, this relative navigation algorithm is inclined to be unreliable because of the measurement information merely involving the direction of probe relative to the landing plane of asteroid. Also, the relative navigation algorithm using LIDAR sensors to track feature points [10,13] can be regarded as an ideal method, but the time of LIDAR scanning every feature point cannot be guaranteed congruously, the relative navigation is considered unreal-time, and the state estimation accuracy of the relative navigation will be insufficient. Therefore, with the development of 3D technology (including real-time image

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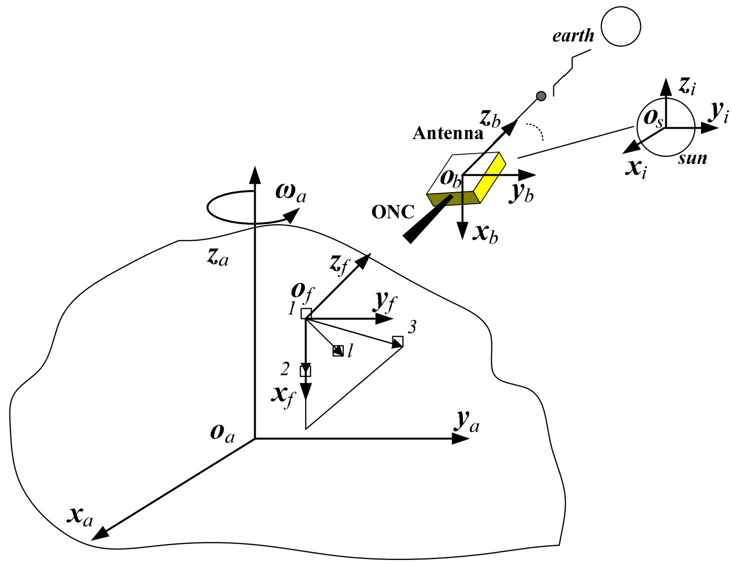

Fig. 1. Coordinate system sketch of asteroid exploration.

processing, feature point tracking and matching) [20], the purpose of this paper is to present a new and real-time only feature point light-of-sight (LOS) relative navigation (OFPLOSRN) technology based on only onboard navigation camera (ONC) for probe approaching mission asteroid exploration descent stage.

In this new method, the real-time of OFPLOSRN can be guaranteed via using only ONC sensor, and it avoids the errors of relative attitude transition matrix in the measurement modeling because the angles of unit feature point LOS vectors are only chosen as the measurements and these angles are invariable in different coordinate frames. The 3D model of asteroid provides the length information between two feature points for measurement modeling. Using the basic theorem of triangle geometry and the filter method, the relative position and velocity of probe to asteroid feature region can be estimated from only angles of unit feature point LOS vectors measured via only ONC sensor, and the relative attitude of probe to asteroid feature region can be solved by vector attitude determination methods, such as moving least squares (MLS) and q-method [17,23]. Also, in order to evaluate the presented relative navigation algorithm, the observability of OFPLOSRN is analyzed by Lie-Differentiation [12].

The organization of this paper is as follows. First, the mathematic model of OFPLOSRN is established. Next, based on three feature points, the observability of OFPLOSRN is demonstrated by Lie-Differentiation and its error analysis is given. Finally, numerical simulations are implemented to verify the presented OFPLOSRN via simulating the HAYABUSA approaching mission.

2. Mathematic modeling for Only Feature Point LOS Relative Navigation (OFPLOSRN)

In this section, to obtain the mathematic model of OFPLOSRN, the process noise model and the measurement model of OFPLOSRN are, respectively, established by the motion equations of probe relative to asteroid and only feature point LOS angles measured by ONC sensor.

2.1. Coordinate systems

To depict the process of probe approaching to asteroid, four coordinate frames as seen in Fig. 1, including the inertial frame of asteroid centroid $\boldsymbol{S}_i$, the fixed coordinate frame of asteroid centroid $\boldsymbol{S}_a$, the fixed coordinate frame of feature points $\boldsymbol{S}_f$ and the probe body frame $\boldsymbol{S}_b$, are established for OFPLOSRN.

The origin of the inertial frame $\boldsymbol{S}_i$ locates at the center of sun, and its three axes $\boldsymbol{x}_i$, $\boldsymbol{y}_i$ and $\boldsymbol{z}_i$ point to the inertial space. This frame is a reference frame to be used to determine the inertial attitude of probe and depict the absolute orbit dynamic model of asteroid and probe. **NOTE**: the inertial attitude determination via sun sensor, star sensor and gyros, and the absolute orbit dynamic propagations of asteroid and probe in the inertial frame $\boldsymbol{S}_i$ are not main content for the OFPLOSRN algorithm and will not be given in this paper, but they can be acquired in Ref. [6] and will be used in the simulation directly.

The fixed coordinate frame of asteroid centroid $\boldsymbol{S}_a$ has the origin at the centroid of asteroid, the $\boldsymbol{z}_a$ axis points to maximum inertia axis of asteroid, the $\boldsymbol{x}_a$ axis points to the minimum inertia axis of asteroid, and the $\boldsymbol{y}_a$ axis perpendicularly forms a right-handed set with the $\boldsymbol{x}_a$ and $\boldsymbol{z}_a$ axes. Also, the fixed coordinate frame of asteroid centroid $\boldsymbol{S}_a$ rotates around the maximum inertia axis $+\boldsymbol{z}_a$ with an approximately constant spin angular velocity $\boldsymbol{\omega}_a$.

The fixed coordinate frame of feature points $\boldsymbol{S}_f$ as a landing reference frame of probe approaching to asteroid, has the origin on the feature point 1 ($F1$), the $\boldsymbol{x}_f$ axis points to the feature point 2 ($F2$), the $\boldsymbol{y}_f$ axis lies in the plane formed by the $F1$, $F2$ and the feature point 3 ($F3$) and perpendicular to the $\boldsymbol{x}_f$ axis, and the $\boldsymbol{z}_f$ axis perpendicularly forms a right-handed set with the $\boldsymbol{x}_f$ and $\boldsymbol{z}_f$ axes. **NOTE**: three feature points are not on the same line and not less than three feature points are necessary to establish this frame.

The body frame $\boldsymbol{S}_b$ has the origin at the center of mass of probe, and its three axes $\boldsymbol{x}_b$, $\boldsymbol{y}_b$ and $\boldsymbol{z}_b$ respectively point to three principle axes of probe body. Also, a high frequency gain antenna is installed in the $+\boldsymbol{z}_b$ axis communicating with the Earth, and the ONC is installed in $-\boldsymbol{z}_b$ axis to measure the directions of feature points and the angles between feature points.

If the 3D model and true size of asteroid have been obtained via probe flying around asteroid for more than half a year, the range vector $\vec{\boldsymbol{F}}_{12f}$ from the $F1$ to the $F2$ and the range vector $\vec{\boldsymbol{F}}_{13f}$ from the $F1$ to the $F3$, in the fixed coordinate frame of feature points $\boldsymbol{S}_f$, can be also expressed as the range vectors $\vec{\boldsymbol{F}}_{12a}$ and $\vec{\boldsymbol{F}}_{13a}$ in the fixed coordinate frame of asteroid centroid $\boldsymbol{S}_a$. Therefore, the