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Autonomous orbit and attitude determination for Earth satellites using images of regular-shaped ground objects

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ABSTRACT

Orbit and attitude determination (OAD) is a crucial problem in spacecraft missions. For Earth satellites, especially Earth-observing satellites, images of ground landmarks are feasible to be used for autonomous OAD. Previous studies have demonstrated the possibility of image-based OAD using the light-of-sight (LOS) vector to ground point feature as measurement. However, valid ground point features might not always be available, for example, when the ground landmarks have smooth edges. Besides, when ground landmarks are regular-shaped, this method would discard useful shape information of the objects and affect OAD precision. Aimed at the problem, we present a new OAD scheme using onboard images of regular-shaped ground objects. In the scheme, the LOS vector to the center of the ground objects is used as measurement and is obtained based on the widely-used 3D reconstruction algorithms in machine vision. With the help of an extended Kalman filter (EKF), orbit and attitude parameters can be estimated. The OAD performance of the scheme is assessed using Monte-Carlo simulations. Results demonstrate the feasibility of the scheme and the substantial influence from both lighting constraints and image sampling frequency on the OAD performance. The scheme is also compared with a deterministic scheme, which directly derives position and attitude parameters purely based on the 3D reconstruction algorithm. For the current sensor precision, the proposed scheme is found to have a better performance.

1. Introduction

Knowledge of orbit and attitude is necessary in spacecraft missions. Current orbit and attitude determination (OAD) still relies heavily on the participation of ground stations and GNSS constellations (for example GPS), which results in large operation costs and bears the risk of signal disturbance and blockage in situations of emergency. One crucial aspect of present and future space projects is to develop spacecraft autonomy. This means spacecraft operation depends entirely on payload instruments, which could help to reduce ground operation costs and also increase satellite survivability in a complex environment.

In the deep space filed, autonomous optical navigation has played an important role in many space missions [1] since it appeared in Deep Space 1 mission [2]. For earth satellites, although the autonomous OAD technic has not been applied in actual missions yet, related theoretical studies have been conducted [3–8]. In these studies, different autonomous measurement models were established using observations obtained from a series of payloads such as cameras, star sensors, X-ray detectors as well as magnetometers and the corresponding performances are evaluated based on simulations. Among the autonomous OAD methods, the method based on images of ground objects draws a lot of attention and has a good application prospect. This is especially the case for Earth-observing satellites, which have cameras onboard and requires no additional OAD payload. The method involves obtaining a light-of-sight (LOS) vector as measurement for OAD, which describes the direction from the camera onboard to the known object. Markley [9,10] presented one such method based on LOS vector to ground landmarks and demonstrated the possibility of autonomous OAD of a spacecraft. Using coastlines as the observation landmarks, Straub and Christian [11] verified the feasibility of autonomous orbit determination and assess the performance with varying orbit inclinations and altitudes. Li, Xu and Zhang [12] analyzed the influence of image resolution, pointing accuracy and lighting constraints on the performance of image-based orbit determination.

However, these studies are all based on onboard images of ground point features and use the LOS vector to the point feature as measurement. This could lead to some drawbacks. First of all, valid ground point features might not be available under some cir-

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cumstances, for example, when ground landmarks have a smooth shape with no sharp edges. Besides, this method might discard useful shape information of the ground objects. For regular-shaped large ground landmarks that cover several pixels in the observed image, discarding useful shape information would make it difficult to select a proper point to represent them, which would affect precision of the LOS vector and further affect the performance on OAD.

Aimed at the problem above, it could be helpful to make use of other information rather than point features, for example, shapes. With the prescribed shapes as constraints, the direction to the center of the object shape can be obtained with precision and used as LOS vector measurement. Besides, in some cases, position and attitude could be directly derived using shape information. Another advantage of using regular-shaped object is the high availability of these objects. Since a large majority of artificial constructions are designed in regular shapes, they can be easily recognized and extracted from images. This makes it a good choice to use them as ground objects in autonomous operations of satellites.

The derivation of LOS vectors to regular-shaped ground objects can be considered as a sub-problem of the reconstruction of a 3D object from its 2D projection (also referred to as pose estimation of 3D objects). As a fundamental problem in machine vision and computer vision, a large amount of studies on this topic have been conducted with consideration of different shapes. The Perspective-n-Point (PNP) problem was first presented in 1981 [13], which then led to a wide discussion about the properties of solutions considering different numbers of point features and line features [14–16]. For more complicated shapes, different estimation algorithms are proposed based on the characteristics of the shapes. Van Den Heuvel [17] and Sun and Wang [18] constructed closed form solutions to the pose estimation problem of parallelogram feature from the view of algebra and projection geometry respectively. Shi, Zhang and Liu [19] developed a pose estimation algorithm for an orthogonal corner in a single view and extended the algorithm to general corner situations.

Apart from shapes composed by straight lines, there are also studies on the pose estimation based on features characteristic of conic curves. Haralick and Chu [20] proposed a general method to iteratively estimate the pose of quadratic-curved features. Using two particular projected chords of a circle image, Chen and Huang [21] established a circle pose estimation algorithm in all viewing conditions from the perspective of geometry. Shiu and Ahmad [22] provided the mathematics for circle pose estimation in different ways and expanded the method to sphere situations. Christian [23] demonstrated the possibility of location estimation method using the image of a tri-axial ellipsoid with a known attitude. However, for the ellipse, there hasn't been a detailed description of a closed-form solution of pose estimation.

In this work, we presented an autonomous orbit and attitude determination scheme using onboard images of regular-shaped ground objects. Four commonly seen shapes are chosen including parallelogram, corners, ellipse and ellipsoid. Compared to the scheme in the navigation of planets and asteroids which also uses shapes of surface objects, the proposed scheme differs in the way shape is used. The former scheme simply uses shapes of surface features to identify the center of the corresponding image and uses the vector from the projection center to the identified center as a proxy of the LOS vector. On the contrary, the proposed scheme directly obtained the LOS vector based on the shape properties (e.g. eccentricity of ground and image ellipse) and the geometry relation between the regular-shaped objects and their images. The performance of the scheme was then investigated from two ways with simulations. Firstly, we focused on the influence of lighting constraints and image sampling frequency on the determination performance. In addition, when parallelogram and corners are used as object features (see Section 2), satellite position and attitude can also be determined by a deterministic scheme, which is purely based on geometrical derivation. We therefore further assessed the performance of the proposed scheme against the deterministic scheme.

To this end, the remainder of this paper is organized as follows. Section 2 provides an introduction of the pose estimation algorithms for objects with different shapes. The LOS vector, which can be generated in all the algorithms is used as measurements in the next section. A detailed description of the proposed scheme is given in section 3, including the dynamic model, the measurement model, and the filter model. Section 4 presents an assessment of the scheme using simulations. Finally, some brief conclusions are drawn.

2. Pose estimation for regular-shaped objects

On Earth's surface, many man-made objects have regular shapes. Some commonly seen shapes include 3D ellipsoid, cuboid, corner and 2D parallelogram, conic curves. When imaging these objects, the projected images can be obtained. By combining information of the projected images and partially known properties of these object shape, their pose can be reconstructed. Given the symmetry of the regular shapes, closed-form solutions of pose determination can be obtained in most cases.

In this part, pose estimation algorithms for different shapes including parallelogram, orthogonal corner, ellipse and ellipsoid are presented. Many existing studies have investigated the estimation process for object parallelogram and corner, but none has addressed ellipse in detail. Thus, in the following paragraphs, we only present a brief description for the first two shapes based on previous studies [17–19,24–26], but provide a detailed derivation process for ellipse.

2.1. Parallelogram and orthogonal corner

In the algorithms for both object shapes, the input is image coordinates of the projected lines and sizes of the object shapes. The goal is to estimate the pose of the object in the image coordinate system.

When estimating the pose of an object parallelogram, the first step is to determine the direction vector of the object plane. As illustrated in Fig. 1, the projection center and the object parallelogram forms a pyramid. Using coordinates of the projection center and image lines, four triangular lateral faces of the pyramid can first be defined in the image system. The direction vector of the object plane can then be determined with the help of the perpendicular relation between the normals to the four lateral faces and a set of parallel sides of the base of the pyramid.

The next step is to obtain the position of the object center by using image coordinates of the four corners of the parallelogram. Given that each corner is the intersection point of two lateral faces and the base of the pyramid, this forms a set of equations that define the four corners. Image coordinates of these corners can then be expressed with only one unknown parameter related to the distance between the projection center and the object plane (pyramid height). In order to calculate this distance, a volumetric approach is used. The main idea is to calculate the volume of the pyramid in two ways, either by using the four corner points or by multiplying the area of the base by the pyramid height, thus forming an equation to solve the unknown parameter. In this way, the coordinates of the four corners are obtained. So are the position of the object center and the direction vector (LOS vector) to the object center. It is worth noting that if only the unit LOS vector is required, the unknown parameter in the coordinates of the four