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Simultaneous detection of multiple debris via a cascade of numerical evaluations and a voting scheme for lines in an image sequence

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A B S T R A C T

This paper presents a novel method to simultaneously detect multiple trajectories of space debris in an observation image sequence to establish a reliable model for space debris environment in Geosynchronous Earth Orbit (GEO). The debris in GEO often appear faintly in image sequences due to the high altitude. A simple but steady way to detect such faint debris is to decrease a threshold value of binarization applied to an image sequence during preprocessing. However, a low threshold value of binarization leads to extracting a large number of objects other than debris that become obstacles to detect debris trajectories. In order to detect debris from binarized image frames with massive obstacles, this work proposes a method that utilizes a cascade of numerical evaluations and a voting scheme to evaluate characteristics of the line segments obtained by connecting two image objects in different image frames, which are the candidates of debris trajectories. In the proposed method, the line segments corresponding to objects other than debris are filtered out using three types of characteristics, namely displacement, direction, and continuity. First, the displacement and direction of debris motion are evaluated to remove irrelevant trajectories. Then, the continuity of the remaining line segments is checked to find debris by counting the number of image objects appearing on or close to the line segments. Since checking the continuity can be regarded as a voting scheme, the proposed cascade algorithm can take advantage of the properties of voting method such as the Hough transform, i.e., the robustness against heavy noises and clutters, and ability of detecting multiple trajectories simultaneously. The experimental tests using real image sequences obtained in a past observation campaign demonstrate the effectiveness of the proposed method.

1. Introduction

Establishing a reliable model for space debris environment is important to safely manage space objects in Geosynchronous Earth Orbit (GEO). Whereas a reliable model in Low Earth Orbit (LEO) has been established through ground-based and space-based approaches [1,2], the one in GEO has not yet because of the high altitude. Space-based approach has been relying on retrieval missions for spacecraft exposed in space for long time such as NASA's Long Duration Exposure Facility (LDEF) [3] and ESA's European Retrievable Carrier (EURECA) [4]. The other state-of-the-art space-based methods such as [5] have also emerged. However, all those space-based methods are targeting objects in LEO, and are currently challenging for GEO. Thus this paper considers ground-based approach and proposes a novel method to detect debris trajectories in GEO using image sequences obtained by ground-based optical observation.

Several investigators have proposed methods to detect debris for GEO in image sequences obtained by optical observation [6–13]. A conventional method called a stacking method [6–8] detects faint debris by stacking the blocks in image frames (image patches) consisting of debris candidates, in which searching all possible directions of debris motion in the other frames is required. Since the method causes heavy computational load in searching debris motion, a method using a Field Programmable Gate Array (FPGA) board was also proposed. Although the stacking method is useful to highlight faint debris, it was not clarified how to select the blocks with debris candidates in the first frame. On the other hand, the same authors proposed a debris detection method focusing on their linear trajectories in image sequences [7]. However, the study assumed that original image sequences are well preprocessed so that only debris candidates are left in the observation image frames. For the both studies, it was neither clarified how to select debris candidates in the first frame, that are followed by tracking their locations in the other image frames, nor sufficiently discussed how to detect a reliable debris

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candidates all through the processes.

The other work [9] proposed a clustering algorithm based on luminance distribution and shape parameter of image objects in order to distinguish target objects from background noises. The method using luminance and shape information may be hardly used for detecting debris in GEO, because the luminance and sizes of image objects are too faint to obtain distinctive patterns of luminance distribution and shape parameter of debris.

The other researchers derived methods to track faint debris based on a particle filter algorithm [12,13]. Whereas those methods can track a debris motion more effectively than the stacking method by prediction, the initial distribution of debris position has to be determined. However, it was not clearly indicated how to select debris candidates in the first frame.

A study [10] proposed algorithms utilizing RANdom SAmple Consensus (RANSAC) [14] which is a method of robust model fitting. The algorithm detects debris using a Bayesian model based on probability distributions on observation data and a priori information of debris such as linear track, speed, and hot pixels. However, well-prepared image preprocessing and registration are required in order to extract debris candidates as well as to suppress background noises. Furthermore, since the RANSAC can basically be applied to a single model fitting, the algorithm requires sequential procedure to detect multiple debris. Because the number of debris is unknown, it might be intractable especially in setting a stopping criterion.

This paper proposes a method to simultaneously detect trajectories of multiple debris including faint ones. Our method does not need to appropriately select debris candidates to be tracked such as seen in [6–8,12,13]. Moreover, since the proposed method is based on a cascade of numerical evaluations and a voting scheme to narrow down multiple debris candidates, it does not rely on a randomized scheme such as the RANSAC, which may require a lot of iterations to find debris in a large number of noises and clutters, i.e., under the very low inlier ratio situation, and to detect multiple debris sequentially.

In the proposed method, the candidates of debris in each image frame are extracted by an image binarization technique during preprocessing. A study [15] proposed an approach using a relatively high threshold value of binarization, which often divides an image of faint object such as a star or a space debris into some parts. Thus a method to synthesize the parts of the same object is required afterward.

On the other hand, the proposed method decreases a threshold value of binarization, which is a simple but steady way to detect faint debris. However, a low threshold value of binarization leads to extracting a large number of image objects other than debris, which becomes obstacles to detect debris trajectories. In order to detect debris from binarized image frames with massive obstacles, this work uses a voting scheme combined with numerical evaluations for the characteristics of the line segments connecting two image objects on different image frames, which are candidates of debris trajectories. The numerical evaluations are used to select appropriate line segments based on their characteristics, which are related to debris physical properties such as displacement and direction. Then, the voting scheme checking the continuity of the remaining line segments is applied to find debris. The cascade of the numerical evaluations and voting scheme are effective to detect faint debris in a night sky background, while filtering out other objects. The effectiveness of the proposed method is demonstrated by experimental tests using real image sequences obtained in a past observation campaign held at Lulin Observatory in Taiwan, that were aiming at searching for fragments generated from a rocket body in GEO called “1968-081E”.

This paper consists of six sections. Section 1 briefly describes the background and objective of this study. Section 2 defines a coordinate system to characterize debris and surrounding stars motions in image sequences. The algorithm with the cascade of the numerical evaluations and voting scheme is proposed in Section 3. Section 4 demonstrates the effectiveness of the proposed method by applying to the real image sequences. Various features of the proposed method are discussed in Section 5 by comparing the results of the experiments with the other methods in the past studies. Section 6 concludes the paper with a comment on future work.

2. Image sequences obtained from a search observation

This work assumes an observation technique called a search observation to obtain optical images for space debris in GEO. A topocentric, Earth-fixed coordinate system [16] is defined as in Fig. 1. Search observation is conducted using a telescope fixed on the origin of the coordinate system $(I_t J_t K_t)$. The telescope points in a target direction, in which many fragments from a specific object can be seen with high probability. The target direction is expressed by the topocentric declination δ_t and the topocentric right ascension α_t, which is derived from the topocentric local hour angle $(LHA)_t$ and the local sidereal time $\theta_{LST}(t)$ such that $\alpha_t = \theta_{LST}(t) - (LHA)_t$ [16]. Note here that the target direction is settled without any directional control during one slot of observation time. In the image sequence, stars seem to be relatively bright objects moving in the same direction because of their sidereal rotation whereas debris in GEO seem to be faint and small ones moving in various directions. Fig. 2 shows the first three frames and the last frame of an image sequence, which were obtained from an observation campaign at Lulin Observatory in 2011. Fig. 2(a) depicts the original image sequence after applying a series of preprocessing of dark, bias, and flat-field frame calibrations. Fig. 2(b) represents binarized image frames for Fig. 2(a). The dotted squares in Fig. 2(b) show an area containing a debris in GEO. The close-up images of the debris are shown in Fig. 2(c), in which the dotted circles depict the movement of the debris.

3. Simultaneous detection of multiple debris trajectories via a cascading algorithm

As shown in Fig. 2, the observation image sequence contains a large number of star images and may include fainter debris images. Each object in an image frame is extracted through an image binarization. Luminance values of pixels in a digital image have a distribution between 0 and the maximum value, which depends on the maximum number of bits. Given a threshold value for the distribution, we can obtain a binarized image by allocating 0 (black) or 1 (white) for all the pixels based on whether the pixel values exceed the threshold value or not. If relatively high threshold value is given for an observation image frame, brighter stars are left as shown in Fig. 3(b). On the other hand,

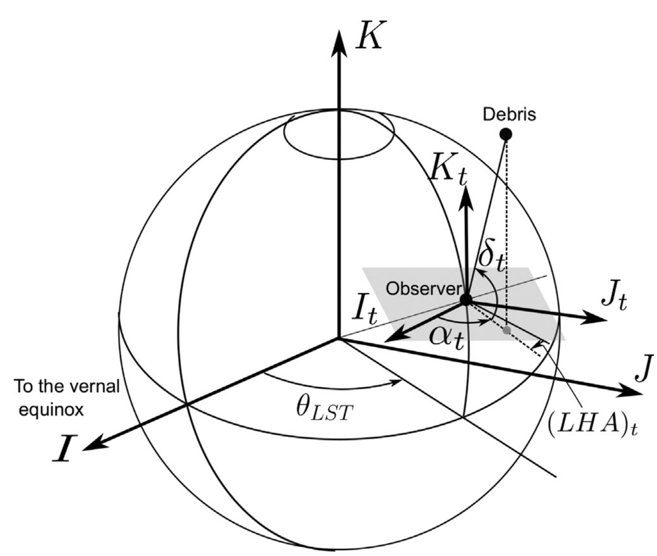

Fig. 1. A topocentric coordinate system $(I_t J_t K_t)$ to conduct a search observation.