Detecting GEO Debris via Cascading Numerical Evaluation for Lines in Image Sequence

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ABSTRACT

This paper presents a novel method to detect trajectories for Geosynchronous Earth Orbit (GEO) debris in image sequences. As far as a ground-based observation is concerned, detecting GEO debris is not so easy because debris often appear very faintly in image frames. A simple but effective way to detect such faint debris is decreasing a threshold value of binarization applied to an image sequence as preprocessing. However, a low threshold value of binarization leads to extracting a large number of image objects other than debris, which become obstacles to detect debris trajectories and cause high computational load. In order to detect debris from binarized image frames with a mass of obstacles, this work proposes a method that numerically evaluates the characteristics of a line segment connecting two image objects on different image frames, which is a candidate of debris trajectory. The proposed method adopts a cascading numerical evaluation based on the physical properties of GEO debris image. During a series of the processes for the proposed method, displacement between two image frames for each line segment, direction of the line segments, and continuity of image objects on each line segment are evaluated in a stepwise manner. Subsequently, the total process is iterated in order to make the performance of the debris detection robust by changing combinations of the two image frames to compute the line segments. The effectiveness of the proposed method is demonstrated by experiments using real observation image sequences obtained from the telescopes at Lulin Observatory in Taiwan.

1. INTRODUCTION

Approach to evaluate space debris environment is twofold. One is ground-based approach and another is space-based approach. Whereas relatively large numbers of data have been obtained from the both approaches for the Low Earth Orbit (LEO), data from ground-based observation have not been sufficiently obtained for the Geosynchronous Earth Orbit (GEO) mainly due to a long distance between the objects and the Earth [1].

Detecting debris in GEO from observation image sequences is not so easy because they often appear much more faintly than surrounding stars in image frames. A simple but effective way to detect such faint objects is decreasing a threshold value of binarization applied to an image sequence as preprocessing. However, a low threshold value of binarization leads to extracting a large number of image objects other than debris, which become obstacles to detect debris trajectories and cause high computational load. In order to detect debris from binarized image frames with a mass of obstacles, this work proposes a method with a cascade architecture, which numerically evaluates a number of line segments connecting two image objects on different image frames based on their characteristics.

In the previous study [2], a stepwise method to detect debris trajectories from a binarized image sequence was derived. Whereas the method in the study also numerically evaluates features of image motion in the image sequence, extremely-faint debris are not necessarily detected because a threshold value of the binarization retains a value so that it does not cause abrupt increase in fault detections as well as in computational load.

On the other hand, the method proposed in this work adopts a cascading numerical evaluation based on the physical properties of GEO debris in an image sequence. Even if very low threshold value is applied for the image binarization, a cascade architecture in the proposed method sufficiently reduces the number of the candidates of debris trajectory and finally detects several debris from hundred billions of the candidates.

The other similar methods aiming at detecting faint debris in an observation image sequence have been proposed by the other groups [3][4]. However, they need to eliminate star images and the other artifacts based mainly on background subtraction techniques for a certain size of block images before or while applying the algorithms. On the other hand, our method does not require specific parameter adjustments to obtain preprocessed images, and is suitable to automated processing for a number of observation image sequences.

This paper consists of four sections. Starting with an introduction in Section 1, assumptions of observation image sequences are briefly explained in Section 2. Section 3 describes a method to detect GEO debris via cascading numerical evaluation on characteristics of the line segments obtained from preprocessing of an image sequence. In Section 4, results from an experimental test are shown to demonstrate the effectiveness of the proposed method, and a conclusion is made in Section 5.

2. OBSERVATION IMAGE SEQUENCES

In this work, observation image sequences aiming at target debris are assumed that they are obtained from a search observation approach. A series of the observation images are taken for the same area with a telescope fixed in the topocentric, Earth-fixed coordinate system or in the topocentric equatorial coordinate system [5]. Images of the debris in GEO taken from the above coordinate system appear to be point-like for small exposure time and move in their own directions across an image frame, whereas stars seem to be brighter points or streaks moving in the same direction.

3. DEBRIS DETECTION VIA CASCADING NUMERICAL EVALUATION FOR LINES IN IMAGE SEQUENCES

3.1 Preprocessing

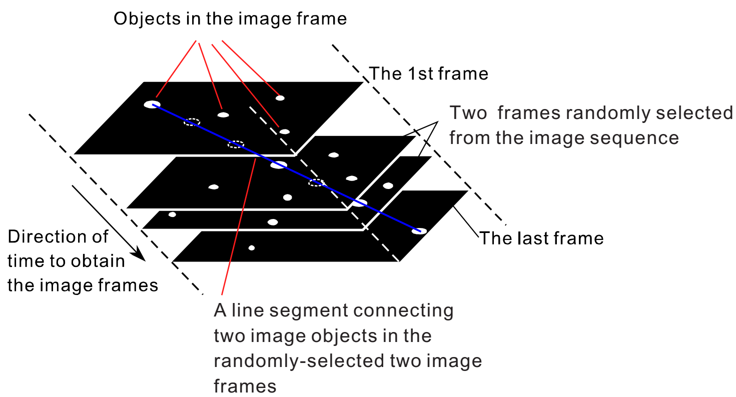

Fig. 1. Line segments obtained from a binarized image sequence.

Prior to conducting the cascading numerical evaluations on candidates of debris trajectories, original image sequence is preprocessed in a relatively simple manner. A binarization is firstly conducted based on a threshold value of image brightness, and then all the line segments connecting two image objects on different image frames, which are randomly selected in the image sequence, are computed as schematically shown in Fig. 1. During this process, a threshold value for the binarization is set small enough not to remove debris in image frames. The two different image frames are randomly selected for the first and last several frames in an image sequence so that position error of the image object in each frame may not increase an error of debris motion direction. Meanwhile, a displacement between two image frames for each line segment is estimated in advance from the locations of the two image objects in the selected image frames.

3.2 Stage 1: Numerical evaluation on displacement of image object between two image frames

In the first stage of the cascading numerical evaluation, candidates of debris trajectories are selected using displacement between two image frames for each line segment. Image motion of orbital debris can be predicted by a Monte-Carlo simulation, which is based on probability densities with sizes and masses of the fragments generated from a spacecraft's breakup event. In the case of this study, target debris are assumed to be fragments from a rocket

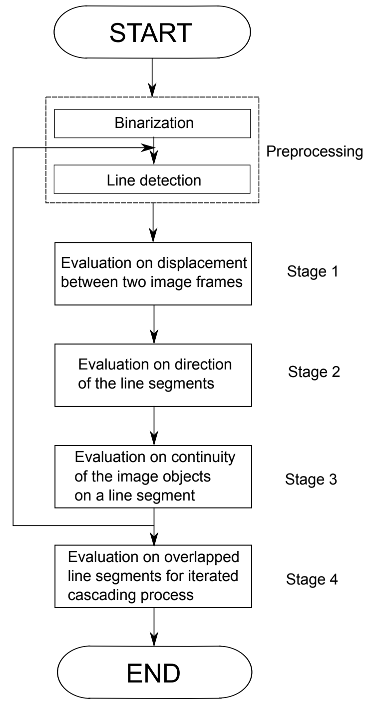

Fig. 2 Flowchart of the proposed method.

body US Titan 3C Transtage called "1968-081E", and the proposed method is applied to image sequences obtained at Taiwan Lulin Observatory from Oct. 20 to 22 in 2011. Reference [2] estimated that the maximum velocity of the target fragments is 3.5 arcsec/sec in the image frame by one hundred Monte-Carlo runs, and it corresponds to 9.9 pixels/frame for the above observation condition. Therefore, this study sets the threshold value for the displacement between two image frames to 10 pixels/frame.

3.3 Stage 2: Numerical evaluation on direction of the line segment

After evaluating the frame-by-frame displacement of debris candidate for each line segment, motion directions of the debris candidates are evaluated. Since line segments corresponding to specific motion directions are almost impossible to be detected as exact debris trajectories, they are rejected based on their slope angles in the image plane. For example, sidereal rotation appears to be a linear motion in a certain direction in the image plane, line segments that share the direction can be rejected as the trajectories of stars. In the case of this study, all the star images move horizontally in the image frames. Also, stiff lines running in a certain direction that do not move in the image sequence are sometimes seen because of local difference of mean brightness in an image frame, which is caused from charge transfer process of a charge-coupled device (CCD). In the case of this study, short vertical lines in the center of the image frames are seen as the above effect of CCD, and they are rejected from the debris candidates.

3.4 Stage 3: Numerical evaluation on continuity of the image objects on a line segment

In the third stage, a numerical evaluation is conducted for continuity of the image objects on each line segments. Since noise images mainly caused from background of the image frame can be wrongly detected on the line segments and survive through the previous processes, they are filtered out based on the number of the image objects on the line segment. In this study, all the line segments which contain less than cN_{seq} ($0<c<1$, N_{seq} : the total number of frames in an image sequence) frames are rejected, supposing that they have a low possibility of becoming an exact debris trajectory.

3.5 Stage 4: Evaluation on overlapped trajectories for iterated cascading processes

Although the above cascade process is effective to decrease number of the line segments in the binarized image sequence, false detections can occur because the above processes crucially depend on a combination of the two

Table 1. Observation condition on the test image sequences.

Observation site (WGS 84)	**National Central University (NCU)** **Lulin Observatory in TAIWAN** **Longitude: 120°52'25" E** **Latitude: 23°28'07" N** **Altitude: 2862 m**
Specification of CCD camera	**CCD format: 2048×2051 pixels** **Pixel scale: 3.03 arcsec/pixel** **Field Of View: 1.74 deg×1.78 deg**
Observation period	**October 20 to 22, 2011**
Target	**1968-081E fragments**
Observation zone (the equatorial Coordinates for the image center)	**RA: 43.5°, Dec: 8.5°**
Frame-to-frame time	**Approx. 8.56 sec/frame** **(Exposure: 5.9 sec, Read-out time: 2.66 sec)**
The number of the data set	**48 (Oct. 20), 66 (Oct. 21), 75 (Oct. 22)**
The number of the frames for each data set	**32 (Oct. 20), 29 (Oct. 21), 29 (Oct. 22)**

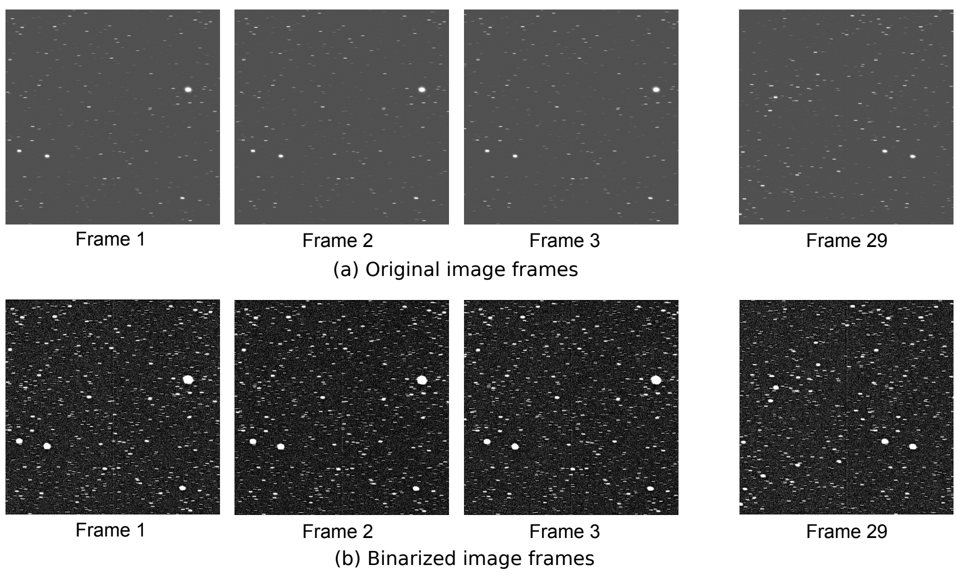

Fig. 3 An image sequence for the experimental test.
(Data set name: 111022_deb054, (a) Original, (b) Binarized)

image frames selected in the preprocessing. In order to make the proposed method more robust, the cascading process is iterated several times changing combinations of the image frames to compute the initial line segments.

Then, in the final stage, only the line segments that appear in the same location in the spatial-temporal domain more than once are detected as exact debris trajectories. The flowchart of the proposed method is shown in Fig. 2.

4. EXPERIMENTAL TEST USING ACTUAL OBSERVATION IMAGE

In order to show the effectiveness of the proposed method, an experimental test was conducted. Table 1 shows an observation condition on the image sequences applied for the test. Fig. 3 shows an example of the observation image sequence (original and binarized ones). As shown in the Fig. 3(b), binarized image frames contain an enormous number of image objects due to a low threshold value of the binarization, which generate hundreds of billions of line segments from randomly-selected two image frames in an image sequence. In this work, ten image sequences that were obtained on the same day (Oct. 22, 2011) are applied to the proposed method. As stated in Section 3.1, the two image frames were randomly selected for the first and last five frames in the preprocessing.

Table 2. Results of the experimental test.

Data set	Detected debris (Proposed)	Detected debris (Previous)	Detected debris (Stacking method)	The number of the line segments (Initial) $[\times 10^{11}]$	The number of the line segments (Stage 1) $[\times 10^{9}]$	The number of the line segments (Stage2) $[\times 10^{9}]$	The number of the line segments (Stage3)	The number of the line segments (Stage4)
111022_deb020	1	0	1	1.125	4.426	4.281	25	14
111022_deb023	1	1	2	0.416	1.695	1.640	10	10
111022_deb026	3	2	3	0.801	2.997	2.899	28	28
111022_deb034	1	0	1	0.899	3.683	3.562	2	2
111022_deb040	1	0	1	1.750	6.819	6.594	9	6
111022_deb052	1	0	2	1.452	5.256	5.084	5	4
111022_deb054	4	1	3	2.011	7.608	7.356	89	27
111022_deb058	1	0	1	4.481	1.614	1.559	138	4
111022_deb061	2	0	1	1.988	7.654	7.401	21	12
111022_deb073	1	0	2	1.834	7.116	6.882	12	8

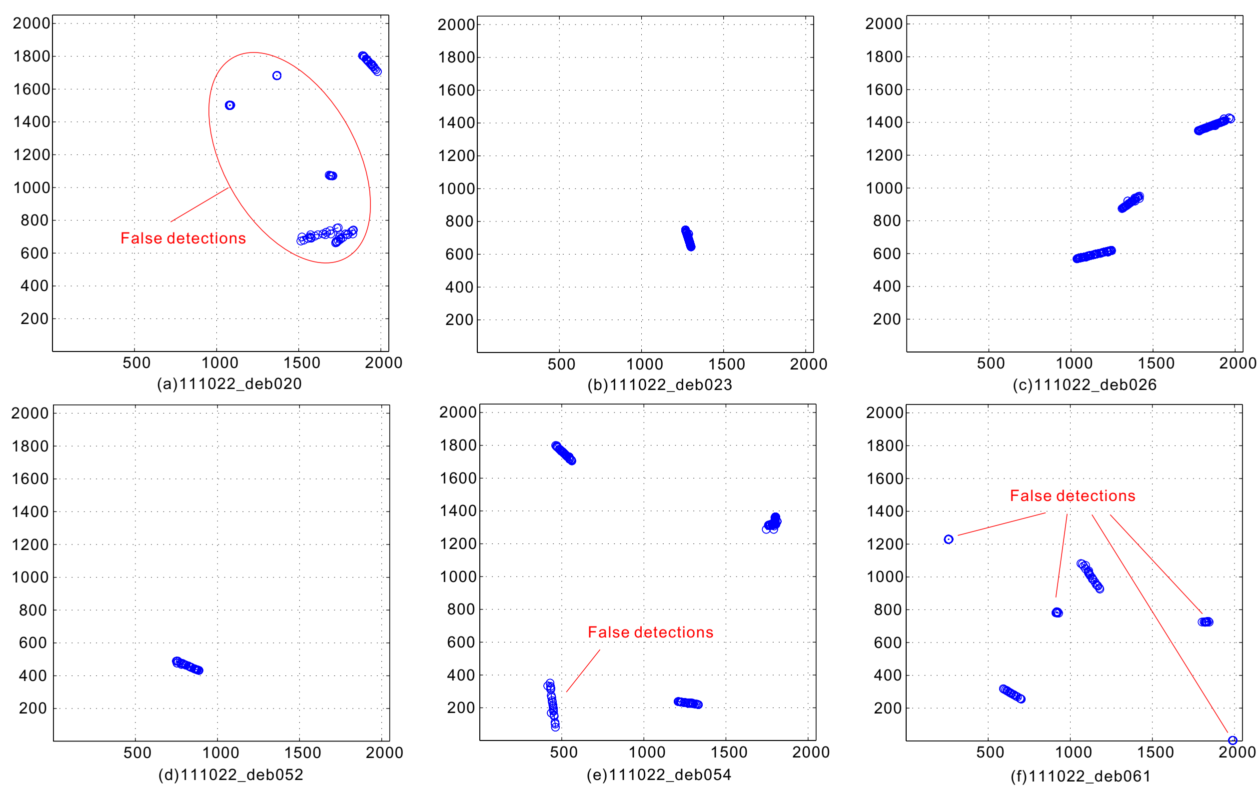

Fig. 4 Debris trajectories in the image frame detected by the proposed method.

For each stage of the cascading evaluations, the value of the coefficient *c* in Stage 3 was set such that c = 0.7, and the number of the iterations in Stage 4 was set to 5. Note that the ten image sequences contain more than one debris that were not detected by our previous method, whereas they were detected by the other method proposed in [3].

Table 2 shows numbers of the debris trajectories detected by the proposed method, our previous method, and the other method called a "stacking method" combined with a field programmable gate array (FPGA), respectively. The table also shows the number of the candidate trajectories, which were left in each stage of the proposed algorithm.

As shown in the table, the proposed method clearly improves detection performance of our previous method, whereas that does not necessarily for the stacking method. For the cases that fail to detect debris trajectories (e.g. "**111022_deb023**", **"111022_deb052"**, and **"111022_deb073"**), one of the main reasons of the failure is the fact that the proposed method is more sensitive to the threshold value of the image binarization than the stacking method is. As for the observation image sequence treated in this work, a threshold value of the binarization during the preprocessing cannot be uniquely given. Night sky included in the background of the observation image is extracted as large objects in the binarized image frame obtained from extremely low threshold value, and it often covers fainter objects such as space debris in the image frame. Furthermore, the numbers of noise images easily increase by a minute change of the threshold value, which causes to overlap the regions of the faint debris and noises in the image frame.

On the other hand, in some image sequences such as seen in "**111022_deb054"** and "**111022_deb061"**, more debris than by the stacking method were detected by the proposed method. One possible reason is given as follows. As for the stacking method, a median image is created for faint debris by stacking local block images consisting of target debris, and the next block image to stack for each frame is appropriately (or thoroughly) selected considering unknown direction and displacement of the debris motion. Even though all the possible debris motions are considered, some debris can be missed because of discretization error for the motion direction, which can be more serious depending on the size of the block images. Meanwhile, the proposed method processes the line segments obtained from all the combinations of the objects in randomly-selected two image frames, where debris for various motion directions are hardly missed.

As shown in Table 2, the number of candidates of the debris trajectories actually decreases with respect to the stage of the cascading processes. The numerical evaluation for continuity of the image objects in Stage 3 is the most effective, and decreases the number of the line segments by 7 to 9 orders of magnitude. The order of the numerical evaluation can adjust the performance to remove obstacles, and the one stated above is suitable to maximize detection performance. Note here that final number of the debris candidates does not necessarily equals the one of the exact debris in the image sequence, because not only some of them include false detections but also they can be caused from a few shorter but the same line segments and can overlap with respect to the number of the iterations in Stage 4.

Fig. 4 shows that the proposed method accurately detects debris trajectories whereas in some cases false detections are seen as in Figs. 4(a) and 4(b). False detection can occur from noise images fixed at certain points and the other artifacts or celestial bodies, which survive the evaluations in the processing stages.

The other defect of the proposed method is also seen in its computational load. The average total processing time for each result in Table 2 was about 53 hours (2.2 days) using a personal computer with 2.93GHz CPU and 12GB RAM, and it is not desirable for such a long computational time to determine debris orbits based on a follow-up observation right after detecting debris images by the proposed method. In order to tackle with the problem, some high-speed processing techniques such as a General-purpose computing on Graphics Processing Units (GPGPU) are necessary.

5. CONCLUSION

In this work, a novel method to detect trajectories for Geosynchronous Earth Orbit (GEO) debris in image sequences was proposed, and its effectiveness was demonstrated through the experimental test using real observation image sequences. Whereas some pros and cons of the proposed method are made clear, a couple of issues still remain. One is how to set appropriate threshold value for the image binarization so that it should be sufficiently low without spoiling images of faint debris. Another is the computational time to obtain final result from the series of the processes. They should be discussed in detail in future work.

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