STREAK DETECTION ALGORITHM FOR SPACE DEBRIS DETECTION ON OPTICAL IMAGES

Alessandro Vananti, Klaus Schild, Thomas Schildknecht

Astronomical Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

ABSTRACT

Any image processing object detection algorithm somehow tries to integrate the object light (Recognition Step) and applies statistical criteria to distinguish objects of interest from other objects or from pure background (Decision Step). There are various possibilities how these two basic steps can be realized, as can be seen in the different proposed detection methods in the literature. An ideal detection algorithm should provide high recognition sensitivity with high decision accuracy and require a reasonable computation effort. In reality, a gain in sensitivity is usually only possible with a loss in decision accuracy and with a higher computational effort. So, automatic detection of faint streaks is still a challenge. This paper presents a detection algorithm using spatial filters simulating the geometrical form of possible streaks on a CCD image. This is realized by image convolution. The goal of this method is to generate a more or less perfect match between a streak and a filter by varying the length and orientation of the filters. The convolution answers are accepted or rejected according to an overall threshold given by the background statistics. This approach yields as a first result a huge amount of accepted answers due to filters partially covering streaks or remaining stars. To avoid this, a set of additional acceptance criteria has been included in the detection method. All criteria parameters are justified by background and streak statistics and they affect the detection sensitivity only marginally. Tests on images containing simulated streaks and on real images containing satellite streaks show a very promising sensitivity, reliability and running speed for this detection method. Since all method parameters are based on statistics, the true alarm, as well as the false alarm probability, are well controllable. Moreover, the proposed method does not pose any extraordinary demands on the computer hardware and on the image acquisition process.

1. INTRODUCTION

The problem of object detection on digital images is a problem encountered in many scientific domains and also in automated systems in our daily life. For astrometric purposes the objects to detect are in general stars or, if the object is moving, elongated spots or broad lines, we refer to usually as streaks. The detection of streaks on images, nowadays acquired with CCD or scientific CMOS devices, is an important challenge and the topic is not fully exhausted. The detection is particularly difficult when the streaks are faint w.r.t. to the background, or long within the acquired frame. Different methods can be found in the literature that try to maximize the sensitivity and at the same time to reasonably limit the computation effort to allow near real time detection and processing. Just to mention a few approaches, there is e.g. a family of stacking methods [1][2], or other methods which imply a mathematical transformation like e.g. the Radon Transform methods [3][4]. The idea of the stacking methods is to stack different images to increase the signal-to-noise ratio (SNR), while transformations in general help to extract the relevant information from the image. These and other sophisticated algorithms have usually the disadvantage that they are quite time consuming or that their sensitivity is not optimal.

In this work a detection algorithm uses image convolution with spatial filters having the geometrical form of possible streaks. The goal of this method is to generate a more or less perfect match between a streak and a filter by varying the length and orientation of the filters. The convolution answers are accepted or rejected according to an overall threshold given by the background statistics. Furthermore a set of additional acceptance criteria have been included in the detection method to reject cases where the spatial filter covers streaks only partially or where it covers in addition a star. These criteria can be derived using the statistics from background and streak signal.

2. DETECTION METHOD

The principle of the detection method is the convolution with different filters and the idea is that the filter best matching the streak should give a higher convolution answer. For this purpose filters with different length and orientation are considered. The basic shape for the filter is taken using the Gaussian cumulative distribution function, assuming for the streak a moving Gaussian point spread function. The filter is rotated using a rotation matrix on a discrete grid that reflects the pixel structure in the frame (see Figure 1). The length is gradually varied with steps of few pixels up to almost ten pixels. The steps in the orientation are around few degrees. The Gaussian distribution for the filter is considered only up to a certain cut-off. The filters with every length and orientation are convolved with the image at every pixel position. The pixel frame containing the convolution result is then filtered with an overall threshold, e.g. a 5σ threshold, where σ is the background noise.

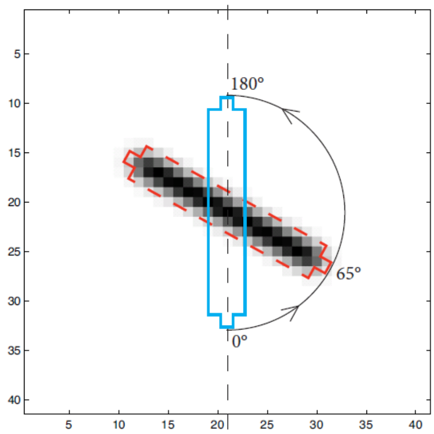

Figure 1. Rotation of filter perfectly matching an example of a streak with length 21 pixels.

After this first step several problems are still present in the processed frame. Figure 2 illustrates, from left to right, the following three main problems that may affect the correct streak detection:

1. for a bright streak the convolution result may exceed the threshold even if the filter covers only part of the streak and a large pixel region in the vicinity (Figure 2 left). As a consequence other objects in the vicinity of the streak might not be detected;
2. the result of the convolution will be above the threshold if a bright object is close to the streak and the filter is covering the streak and the bright object (Figure 2 middle). Consequently the correct orientation of the streak might not be detected;
3. if the streak is very bright the convolution result will exceed the threshold also with filters longer than the streak (Figure 2 right). Thus the length of the streak might be overestimated.

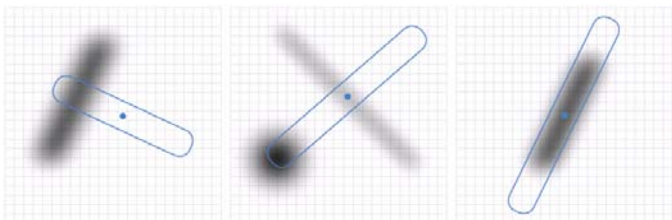

Figure 2. Problems affecting the streak detection with the convolution procedure.

To solve these problems additional steps are required:

- Angle history. The history of the best orientation for varying length is taken into account. This allows a better determination of the orientation affected in problem (2).
- Clipping. This step is a simple clipping of the overall pixel intensities. The ideal clipping value preserves the full detection probability, and its statistics can be modelled. The consequence of clipping is an enhancement of the streak features and a reduction of the problem (1).
- Length history. The change of the convolution result for a certain pixel as a function of the filter length exhibits a special pattern depending if the examined pixel is inside a streak, close to another streak or star, or in the background region. The detection/threshold conditions are a function of the template length. This step addresses the problem (1).
- Length control. When the filter is aligned with a streak, the convolution result as a function of the length gives a specific pattern. This is exploited to better estimate the length of the streak, affected by problem (3).
- Angles restriction. If the convolution answer with a given filter orientation is low, there is a certain probability that it will remain low even increasing the length of the filter. Thus it is possible to set a threshold parameter in terms of probability, below which the particular orientation is no longer considered in the incremental loop over the filter length. This reduces the overall number of orientations in which the convolution has to be calculated, improving the computation performance and the definition of the detected streak.

3. DETECTION PROBABILITY

The detection probability can be calculated from the Gaussian cumulative distribution function. Obviously, the longer the streak, the higher is the sensitivity of the detection method. The dependence of the detection probability from the streak length is shown in Figure 3 for a streak aligned with the pixel grid (90°) and the ratio between maximum pixel value and noise (MtN) of 0.6. The black plot shows the theoretical values, while in red the result obtained with the detection method over a sample of 500 streaks is shown. The probability is slightly affected by one processing step in particular, namely the “Angles restriction”. The parameter pp specified in Figure 3 is the threshold parameter described in the “Angles restriction” step. To illustrate the significance of the pp parameter the blue plot in Figure 3 shows the probability without “Angles restriction”, which is close to the ideal line also for longer streaks. The influence of the other criteria parameters can be quantified in a similar way; they can be justified by background and streak statistics and affect the detection sensitivity only marginally. Since the choice of the criteria values is based on statistics, true and false alarm probability are well controllable and can be tuned according to the requirements.

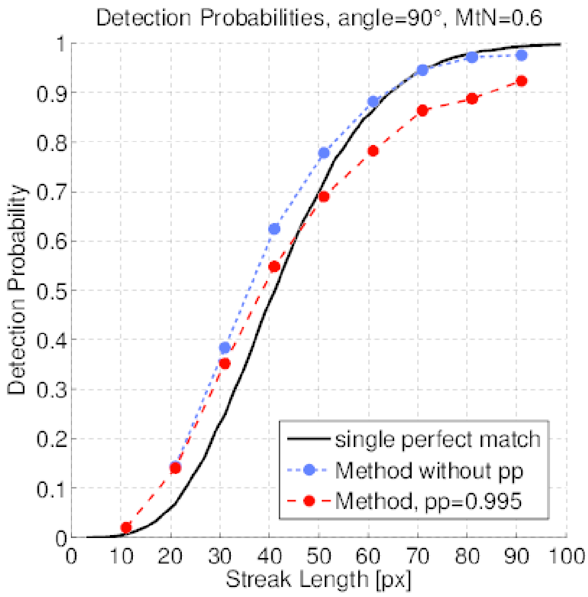

Figure 3. Detection probability as a function of length for a MtN ratio of 0.6.

4. TESTS ON SIMULATED IMAGES

To see the performance of the detection method and the improvements achieved by the different processing steps, we consider a test image (Figure 4) with simulated streaks (“L” denotes the length in pixel, “α” the orientation in degrees, and “MtN” the maximum single pixel signal-to-noise ratio). After applying the convolution step Figure 5 is obtained. Some important features are accentuated, but the single streaks are still not recognizable. An improvement is noticed in Figure 6 after the “Angle history” and “Clipping” steps. The streaks are better defined but still interconnected. After the “Length history”, “Length control”, and “Angles restriction” steps the streaks are finally well identified, also in terms of length and orientation (Figure 7).

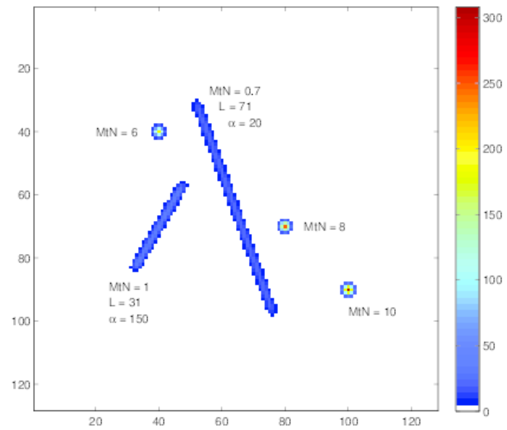

Figure 4. Test image with simulated streaks. Length, orientation, and MtN ratio are shown. The color scale indicates the pixel intensities.

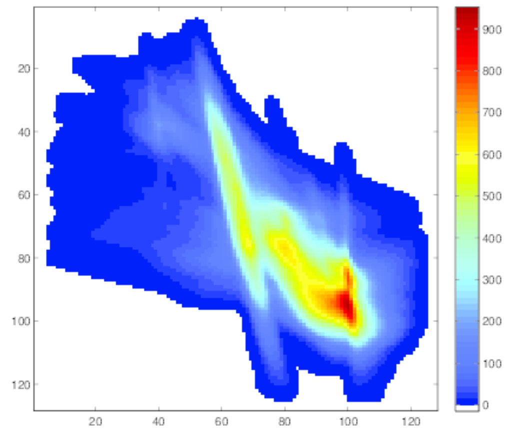
Figure 5. Pixel frame obtained after the convolution procedure.

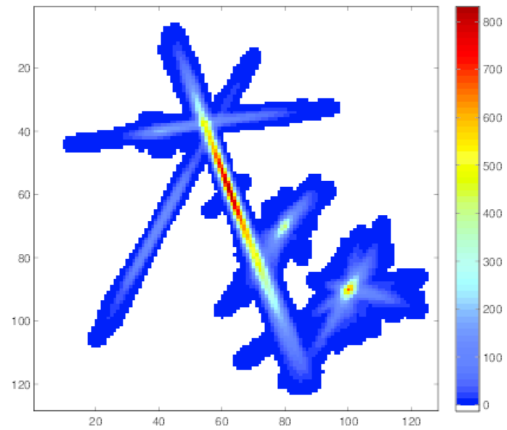
Figure 6. Pixel frame obtained after “Angle history” and “Clipping” steps.

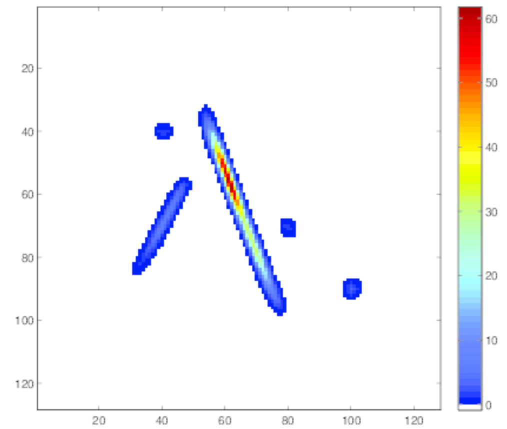
Figure 7. Pixel frame obtained after “Length history”, “Length control”, and “Angles restriction” steps.

5. TESTS ON REAL IMAGES

Tests on real images are important to assess the performance of the detection method in the presence of realistic conditions like e.g. high stellar density, non-uniform background, cosmic rays. The images were acquired in sidereal tracking mode with the ZimSMART telescope at the Swiss Optical Gound Station and Geodynamics Observatory Zimmerwald of the Astronomical Institute of the University of Bern. Before applying the detection procedure the background was subtracted based on a Gaussian fitting of the background intensity distribution. The stars were fitted to approximate circular regions with a maximum in the center and a rotational symmetric intensity distribution, and they were removed up to a certain cut-off intensity.

The detection method was tested on several real images with different streak lengths, orientations, MtN ratios, and it shows promising results. Figure 8 shows an example of acquired image with the background subtracted. In Figure 9 the same image after additional removing of the stars is displayed. Finally, Figure 10 illustrates the result of the processing with the detection method. It is interesting to note that in Figure 8 the hypothetical streaks are somehow not clear enough for the human perception to be detected. The detection procedure reveals in fact that they are quite faint with a MtN ratio around 1. The presence of the streak in the center of the frame could be confirmed thanks to the knowledge of the exact position and motion of the observed object. The second, smaller streak could not be confirmed but it is supposed to be a correct detection of a real object.

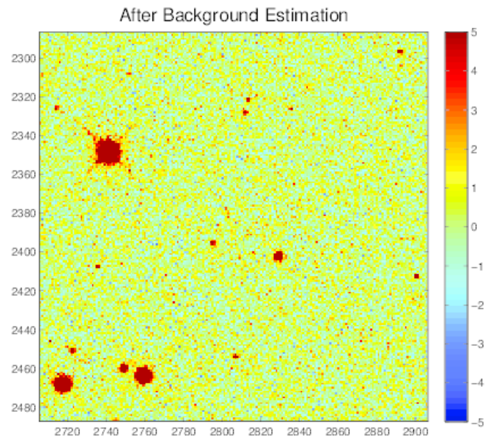

Figure 8. Real image after background subtraction. The colored scale shows the pixel intensity.

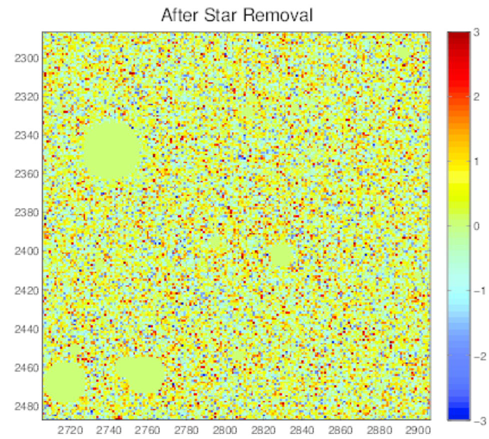

Figure 9. Real image after subtracting the background and removing the stars.

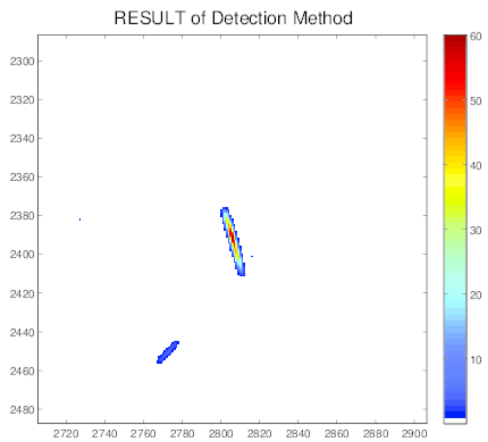

Figure 10. Real image processed with the detection method.

6. CONCLUSIONS

We have proposed a new "track before detect" method for the detection of streaks on optical images. The algorithm uses image convolution with spatial filters with varying length and orientation having the geometrical form of possible streaks. The idea is to generate a more or less perfect match between streak and filter, and to evaluate the convolution answer according to an overall threshold. A set of additional acceptance criteria is necessary in the detection method to filter partially covering streaks or remaining stars.

The detection probability, as well as the criteria parameters, can be estimated from the background and streak statistics and the true and false alarm probability can be tuned according to the requirements.

Tests on simulated and real images show promising results. The method is able to detect faint streaks of different length and orientation with a signal-to-noise ratio for the peak pixel in the streak (MtN) of below 1. Further work needs to be done to evaluate the detection and computation performance of the algorithm under different observation conditions.

7. REFERENCES

1. Yanagisawa, T., H. Kurosaki, H. Banno, Y. Kitazawa, M. Uetsuhara, T. Hanada, Comparison between four detection algorithms for GEO objects, Proceedings of AMOS Conference, Maui, Hawaii, 2012
2. Yanagisawa, T., H. Kurosaki, A. Nakajima, The stacking method: the technique to detect small size of GEO debris and asteroids, Japan Aerospace Exploration Agency, 2008
3. Ciurte, A., R. Danescu, Automatic detection of MEO satellite streaks from single long exposure astronomic images, Proceedings of International Conference on Computer Vision Theory and Applications (VISAPP), Lisbon, Portugal, 2014
4. Zimmer, P.C., M.R. Ackermann, J.T. McGraw, GPU-accelerated faint streak detection for uncued surveillance of LEO, Proceedings of AMOS Conference, Maui, Hawaii, 2013