Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author

Quantitative evaluation of source detection strategies in astronomical images

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Abstract. In astronomical imaging great efforts have been done aiming to perform automatic detections of stellar bodies in wide field images or in large surveys. These images contain large volumes of data at different intensity scales and often have a high component of noise. For these reasons, even the source detection done by visual inspection is a challenging task. With the idea to improve this source detection process, different automatic tools have been proposed. We present in this paper a review of the main approaches for the automatic detection of sources in astronomical images. Several approaches that use images at different frequency bands are analysed in order to find out their advantages and drawbacks, and to specify the key points that make them remarkable for the astronomical community. We classify the most important techniques into different strategies according to the type of pre-processing applied and the strategy used to deal with the detection problem. A qualitative and quantitative evaluation of the results of the most outstanding approaches is also presented. Finally, we discuss on the open research fields of the astronomical object detection.

1. Introduction

The detection of astronomical sources seems an easy task in comparison with other computer vision problems: the typical scenario is to deal with bright sources on dark backgrounds. Nevertheless, there are some difficulties associated with astronomical image processing that make this task not so simple. Astronomical objects do not have clear boundaries, and their sizes and intensities can vary considerably in the same image. Moreover, astronomical images often have a high component of noise. Therefore, the main challenge in astronomical object detection is to separate those pixels that belong to astronomical bodies, from those others that belong to background or noise.

In this paper we review the most widely used strategies in astronomical source detection. We propose a new classification based on two main steps: the pre-processing and the detection criterion. Moreover, we also provide a quantitative and qualitative comparison of the detection strategies accordingly to their reported results.

2. Pre-processing

Pre-processing steps transform raw images in some way, and new images with the same information content that the original ones, but with better conditions, are created. Thus, the images are adapted to facilitate the posterior analysis. In astronomical imaging, the objectives of pre-processing are, for instance, to reduce the noise, to estimate the background, or to emphasise the objects.We present a classification by dividing the pre-processing step in basic pre-processing, Bayesian approaches, matched filtering and multi-scale strategies.

- **Basic pre-processing.** There are a range of techniques that, although being simple, offer a good performance. They are basically used to reduce noise and to enhance sources. Among this basic pre-processing we find for instance simple filtering techniques (as median, average, or Gaussian), background estimation, background subtraction, or morphological operations.

- **Bayesian approaches.** Their objective is to provide a probability map with higher values in the zones where an astronomical object is more likely to be placed, and lower values in the zones that are more likely to be sky. They are based on Bayesian inference, where a set of evidences is used to update the probability that a hypothesis can be true. It is a maximisation over a set of parameters that involves a likelihood (an expression for the probability to obtain the data given a particular set of values) and a prior (some knowledge about the data).

- **Matched filtering.** Is the most commonly used filtering strategy. This filter convolves the image with the profile of the objects that are expected to be found (e.g. PSF for detection of point sources or other patterns to extended sources). In addition, the MF may also be used to subtract the background locally, and it is also a filter to consider when the images present quite amount of noise.

- **Multi-scale approaches.** Astronomical data generally has a complex hierarchical structure, and for this reason a more suitable way to represent it is in the multi-scale space. Thus, images are decomposed into components at different scales (different spatial frequencies), and objects become emphasised in some scales. Depending on the nature of the objects, they may appear in more or less scales, and closer to low or high frequency scales. The wavelet transform (WT) is by far the most used multi-scale decomposition.

3. Detection criteria

The goal of detection is to locate the astronomical objects and separate them from the background (the sky). Regarding to the detection step, two strategies stand out among the rest: thresholding and local peak search.

- **Thresholding.** It is a simple method to perform image segmentation. A greyscale image is converted to a binary one where the pixels have only two possible values: 0 or 1. These two values are assigned to pixels which intensities are below (0) or above (1) an specified threshold. In astronomical images (and in many other fields), thresholding is used to decide which regions (connected pixels) are considered as objects and which ones are considered as background.

- **Local peak search.** It consists in searching those pixels that are considered peaks, or, in other words, those pixels that are a local maximum in a neighbourhood. A local peak search is often accompanied by a posterior step, that establishes or corrects the pixels around the peak that belong to the object. Many times, this last step is a fitting process, which is possible because the nature of the objects is well known. So the local peak search as such, provides a list of candidates that can be the central points of an object.

- **Other methods.** Even though most of the classical approaches are based on thresholding and local peak search, there are other strategies to detect astronomical objects. In many cases these approaches have been developed during the last few years, and they are more focused on the techniques from the computer vision and machine learning fields. They are based for instance on classification, segmentation, or more complex morphological operations.

4. Reported results

We provide a comparison of the results obtained from the outstanding approaches in astronomical source detection. Table 1 summarises the techniques that they used and the performance that they obtained.

Table 1. Summary of the results presented in the literature. We show the pre-processing and detection criterion used, the type of the used images (real or simulated), the number of detected objects, the evaluation measures, and the performance. Slashes ("/") separate different experiments, while values in parentheses refer to the number of detections of the ground truth. "n/a" means "not available".

Article	Pre-processing	Detection	Image type	Detections	Measures	Performance
Slezak et al. (1988)	Basic	Thresholding	Optical (real)	363	TP FP	353 10
Damiani et al. (1997)	Basic Multi-scale	Local peak search	X-ray (real)	453	Missed	10 (75,47)
Starck et al. (1999)	Multi-scale	Thresholding	Mid-infrared (sim)	46	TP FP	45 1
Andreon et al. (2000)	n/a	Other	Multi-band (real)	2742/3776	TP FP	2059/2310 (2388) 683/1466 (1866)
Freeman et al. (2002)	Basic Multi-scale	n/a	X-ray (real)	148	Coincidences	81 (12,27)
Perret et al. (2008)	Basic	n/a	Multi-band (real)	17	Recall (%)	82%/87%
Peracaula et al. (2009a)	n/a	Other	Radio (real)	83	TP FP	70 (68) 13 (33)
Peracaula et al. (2009b)	Basic Multi-scale	Thresholding	Radio (real)	86	TP FP	71 (68) 15 (33)
Guglielmetti et al. (2009)	Bayesian	n/a	X-ray (sim)	100	TP FP	64/41/25 (56/37/23) 8/9/0 (4/1/1)
Carvalho et al. (2009)	Bayesian	Local peak search	Optical (sim)	n/a	TP (%) FP (%)	67.41%/56.41%/82.95% 9.6%/8.62%/8.19%
Torrent et al. (2010)	Matched filtering	Thresholding	Radio (real)	601	TP FP	505 (455,473) 96 (474,n/a)
Broos et al. (2010)	Multi-scale	Local peak search	X-ray (real)	100	TP FP	89 11

5. Discussion

As we have seen, several strategies are used to face up the astronomical source detection. Most of them coincide in focus the detection on the intensity of the image pixels, whether in the pre-processing steps in order to enhance the sources with respect to the background, or in the detection process, choosing those pixels with an intensity value which suggests that they are likely to be part of an object. We have seen that all the different pre-processing and detection steps are used indistinctly in all types (all frequency bands) of astronomical images, although there are techniques which are more commonly used in some particular bands. An overview of the different techniques reviewed with their strengths and weaknesses is shown in the Table 2.

Table 2. Overview of the different techniques with their advantages and drawbacks.

Step	Description	Strengths	Weaknesses
Pre-processing			
Basic pre-processes	Basic pre-processing steps as filtering, profile fitting or morphological operators	Intuitive, fast and easy Slightly emphasise sources Correct background variations Reduce noise	Limited May blur and twinkle the image Often need more pre-processing steps
Bayesian approaches	Methodologies based on Bayesian inference	Emphasise sources Good results with source variability Reduce background variability and noise	Computational cost Need prior knowledge
Matched filtering	Methods based on filters with the profile of the objects to find	Rather emphasise sources Reduce background variability and noise	Need prior knowledge Different filters for different sources
Multi-scale approaches	Approaches that decompose the image in several scales	Reduce noise and delete background Good results with source variability Allow working with different scales Implicitly performs source detection Can deblend sources	Quite slow Often need combinations of transforms
Detection criterion			
Thresholding	Pixels above a certain threshold are considered as part of the object	Good results with all sources Good results with inhomogeneous background Good results with high contrast and SNR	Difficult to select the optimal threshold Not suitable for faint sources
Local peak search	Search pixels that are maximums in a neighbourhood	Good results with point sources Good results with noisy images	Need an additional detection process Not suitable for extended sources
Other methods	Other innovative detection methods	Similar results than the other two methods	Still not have enough acceptance

Acknowledgments. The authors acknowledge support by EMED - Ministerio de Educación y Ciencia (MEC) and EMCI - Ministerio de Ciencia e Innovación under grants AYA2007-68034-C03-03 and AYA2010-21782-C03-02. M. Masias holds a FI grant 2011FI_B 00081.

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