Efficient morphological tools for astronomical image processing

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Chapter 9

Summary and Outlook

9.1 Summary

In this thesis, tools and new methods in the frame of Mathematical Morphology suitable for image processing of astronomical datasets and remote sensing imagery are explored and developed. Given the sheer number and the high bit depths of data collected by modern instruments, especially in the field of astronomy, automatic segmentation of the objects of interest is required. In Mathematical Morphology, connected filters work by preserving or removing sets of pixels that have the same intensity and that are path-wise connected, namely *connected components*. Size or shape connected filters, used for image filtering or object segmentation, are not enough to catch the huge heterogeneity that astronomical objects have. Moreover, many of the structures that astronomers are interested into to understand the evolution and classify the morphology of galaxies are very faint, often diffused and close to the level of noise. Even a human observer could not be able to spot them promptly in many cases.

In this thesis, a new connected filter is proposed, based on the statistical distribution of the noise present in astronomical datasets. Filtering is implemented on the max-tree structure. This structure is a hierarchical representation of the image connected components and it allows image filtering and segmentation in an efficient way. Clustering masks, to be used within the second-generation connectivity theory, are studied as a way to preserve the fainter, diffused structures in galaxies. To deal with resolutions in the order of gigapixels or gigavoxels, parallel algorithms to build max-trees have been sought in recent years. A new parallel method to build a max-tree structure is proposed, enabling the processing of 2D images and 3D volumes that was prohibitive before. Run times are about 20 times better than the fastest sequential algorithm and the usability of morphological filtering techniques benefits from that. Experiments regarding classification of astronomical objects are performed. The goal is to separate two classes: mergers from projected galaxies. Connected pattern spectra computed for every identified object are used as feature vectors to be fed to a classifier: a classification precision of about 80% is reached. Finally, in the framework of hyperconnectivity, a new algorithm is introduced to perform filtering of hyperconnected components belonging to a particular hyperconnectivity class: the goal is to address the leakage problem, typical issue in standard connectivity and connected filters.

Throughout the chapters, the theory and explanations referring to the new proposed algorithms are accompanied with pseudo-code snippets. Experiments and comparisons to other methods, when possible, are reported. Advantages and limitations of the proposed solutions are stated and the reader can genuinely understand their usability and applicability to his particular field of research. More in detail, all the work summarised above breaks down to six chapters, as follows.

In Chapter 2, a new second-generation connectivity is introduced and a method is proposed to preserve the faint structures of astronomical objects. The goal is to allow extended, dim structures, broken up by noise, to be clustered together. At the same time, compact and bright sources (stars) that are close to each other should not by grouped as a single object. Experiments are carried out showing how connectivity masks defined by *viscous* closings can achieve such selective clustering, by testing a range of parameter settings that drive the amount of clustering performed. In this task, viscous operators work better than the structural closing. However, even when better clustering is achieved, object segmentation remains by no means trivial. A max-tree based segmentation method is proposed in Chapter 3. It combines connected filtering of image components, in standard connectivity, with the statistical knowledge of the noise present in the astronomical images. The new method uses a statistical test based on the *power* attribute, proportional to the integrated square intensity of an image component, for each node of the max-tree. Sets of connected components are selected so that it is not likely that they belong to the background (noise), given the expected distribution of the power attribute in presence of noise components. This solution improves the fixed threshold mechanism used in Source Extractor, a widely used state-of-the-art software for astronomical image processing. In fact, Source Extractor, often fails to detect the faint extended sources. The method benefits also from a background estimate that reduces the object bias, with respect to Source Extractor. Sections of the image devoid of objects are identified and the background parameters are estimated from those. Performance and results are discussed, using the Sloan Digital Sky Survey Data Release 7 as a testbed.

In Chapter 4, it is shown that given the high resolution and the dynamic range of astronomical or remote sensing images, there is a real need of parallelizing the construction of the max-tree structure: existing parallel solutions are tested and it is demonstrated that they work effectively only up to 16 bits per pixel. A shared-memory parallel algorithm is proposed that combines the root-to-leaf flooding and leaf-to-root merging approaches in a two-step process. The algorithm is thoroughly tested with simulated and real-world data, both with 2D images and 3D volumes. The parallel algorithm and the statistical max-tree based segmentation method are used together in Chapter 5. Experiments on the segmentation of high-resolution 3D radio volumes containing measures of the emission of galaxies, as they would be observed by the WSRT (Westerbork Synthesis Radio Telescope) are performed. Limited but promising results are presented, encouraging to explore further the use of max-trees and statistical filters on this kind of data.

Object classification is also investigated. The task at hand is to distinguish galaxies showing an actual interaction (mergers) from galaxies that just looks close to each other (projected). The use of collections of local 2D pattern spectra as feature vectors suitable for classification of astronomical object looks promising. Pattern spectra are univariate or multivariate histograms of the image structures, in which each bin denotes how much image content lies in a particular size or shape class. Pattern spectra and their parallel computation are introduced in Chapter 6, in a remote sensing scenario. Computation times decrease from several minutes to 8 and 15 seconds on the gigapixel images tested. Rather then computing a pattern spectrum on the entire image, in Chapter 7 the concept of *local* pattern spectra is introduced. A pattern spectrum is computed for every segmented object, not for the image as a whole. The method proposed in Chapter 6 is adapted to calculate local 2D pattern spectra. A 2D pattern spectrum of area versus image moment invariants is generated for every galaxy and fed as feature vector to a classifier. Using a C4.5 tree classifier with bagging, the percentage of correctly classified instances is about 80%.

As an extension to the hyperconnectivity framework, a novel algorithm to perform attribute filtering of *viscous*-hyperconnected components is proposed in Chapter 8. It addresses the leakage problem typical of connected filters: often, noise or unwanted structures link objects of interest, creating path-wise connected sets of among the pixels of structures that should be separate. The viscous-hyperconnectivity class presented allows for connected components to overlap thus stopping the leakage from happening through the image structures narrower than a given input structuring element. A novel algorithm to perform hyperconnected attribute filtering on viscous-hyperconnected components is proposed. Initially, the max-tree of the image eroded by a structuring element is built with any algorithm. The attributes of its nodes are updated at a later stage with the contribution from the pixels that lie between the eroded image and its dilate. While this last topic is not directly linked to astronomical image processing, it could open up different ways of filtering. More application fields ought to be investigated.

The work presented in this thesis contributes to a better understanding of how methods and approaches coming from Mathematical Morphology can be applied to solve problems in the domain of image segmentation and classification, with a focus on astronomical images. Many of the analysed techniques and proposed new methods proved a legitimate applicability for this theory to the application areas that are discussed.

9.2 Outlook

The presented work could be extended in several directions. A few suggestions of topics for future research are put forward in the following.

Alpha-trees (Ouzounis and Soille, 2012) are structures used nowadays especially in remote sensing image analysis for the identification of human settlements and building footprints. In Soille (2008), $\alpha-$connected components are defined as path-wise connected components in which two adjacent elements along a path do not differ more than a certain threshold value on a given a dissimilarity measure. Alpha-trees describe within a compact representation the complete hierarchy of the whole set of $\alpha-$connected components in an image. As a matter of fact, dissimilarity metrics often present floating point values. The alpha-tree building algorithm is based on the Tarjan's union-find method, that is used for both the labelling and the merging of the $\alpha-$connected components. Being able to deal with union-find sets and high bit depth data, a shared-memory parallel algorithm for the alpha-trees could be based on the same premises as the algorithm described in Chapter 4: a parallel building algorithm based on union-find, seen as a refinement process on a support tree, previously built on quantized dissimilarity values.

The segmentation of astronomical objects could be improved by finding better ways to separate (deblend) linked objects, especially for the sources whose brightness profile deviates from Gaussian. In fact, for interconnected or nested sources, even if it is mostly ambiguous where the exact boundary of an object is, the results in Chapter 3 showed that in many cases too many pixels are assigned to one object. A strength of the segmentation algorithm is also its modularity that can be exploited by investigating other datasets and plugging in different noise models or types of connectivity. An experiment in that direction is already proposed in Chapter 5, where the method is adapted to support 3D radio volumes, using a noise model different from the one originally designed for the Sloan 2D optical dataset. Along these lines, a recent Master thesis performed at the Intelligent Systems group at the University of Groningen (Arnoldus, 2015) tried to combine the clustering approach through connectivity masks introduced in Chapter 2 with the connected filtering algorithm based on noise statistics. The idea is to build the max-tree of a mask image that allows for clustering: however, the pixel values used for attribute computation in the max-tree are taken from the original image and not from the mask image. Clustering of broken up and faint structures is achieved through masks obtained by applying higher smoothing on the lower intensities. Both intensity-driven and gradient-magnitude-driven (Perona-Malik) diffusion are tried when generating a mask. Experiments were performed again on the 3D radio volumes of Chapter 5 and the shared-memory algorithm was used to build the tree. After realizing that this radio dataset contained correlated noise, and not uncorrelated as it was thought initially, ways to exploit other attributes than the power attribute in Chapter 3 and other statistical distributions were explored. The segmentation achieved at this point is similar to other state-of-the art techniques. However, the versatile max-tree structure can be easily extended to compute other kinds of attributes. That could be potentially useful, because specific attributes are used by astronomers to define feature spaces in which objects look better separated from noise, as in Serra et al. (2012). A segmentation based on both statistical filtering and a combination of relevant attributes could be the way forward to improve from state-of-the-art techniques.

The parallel max-tree algorithm proposed in Chapter 4 works on shared-memory hardware. To avoid memory limitation in case of images with size in the order of terabytes or petabytes, distributed-memory algorithms should be designed. A starting point to adapt the parallel algorithm could be the review work in Iverson et al. (2015) about connected component labelling on distributed memory systems. Five parallel algorithms are reported, mostly based on the union-find approach. The problem when dealing with hierarchical image representations, like max-tree, is that just labelling the components is not enough: the nesting relationships among components at different intensity levels must be also computed. Maintaining the updated correct parent pointers with the same shared-memory approach in a distributed environment would result in a large communication overhead.

In Chapter 8, an effective way to perform viscous hyperconnected attribute filtering to stop the leakage effect is proposed. A drawback of that method is that the edge preserving property of connected filters does not hold any more: it would be desirable to restore it. While a possible solution has been put forward in Chapter 8, its feasibility is currently under study. As for the applicability of this kind of filtering, the focus should go on finding application fields that would benefit from viscous hyperconnectivity. When segmenting medical images, often the narrow and elongated structures that belong to the background undesirably interconnect objects of interest, such as bacteria or cell membranes. These unwanted structures could be excluded from the segmentation using hyperconnectivity: leakage that links those to the actual objects would be prevented from happening in the narrower structures. Another application could be found also in the field of astronomical image processing: two connected objects seen as one, such as a galaxy and its companion or two near stars linked by their halo, could be separate at the location at which the interconnecting structure becomes smaller than a given criterion.