INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Ariana

Inverse Problems in Earth Observation and Cartography

Sophia Antipolis - Méditerranée

THEME COG

Activity Report

2007

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2. Overall Objectives

2.1. Introduction

Ariana is a joint project team of INRIA, CNRS, University of Nice-Sophia Antipolis, via the Computer Science, Signals and Systems Laboratory (I3S) in Sophia Antipolis (UMR 6070). It has been created in 1998.

The Ariana project aims to provide image processing tools to aid in the solution of inverse problems arising in a wide range of concrete applications, mainly in Earth observation and cartography, for example cartographic updating, land management, and agriculture, while at the same time advancing the state of the art in the image processing methods used to construct those tools. Another application concerns biological imaging using the same tools as in remote sensing.

2.2. Highlights of the year

- The associated team SHAPES was created on january 1st 2007 (http://www-sop.inria.fr/ariana/Projets/Shapes/index.html). This project is dedicated to the use of statistical shape theory to improve algorithms for analysing aerial and high-resolution satellite images. It will strongly enhance the collaboration between Ariana project-team and the Vision Group of Florida State University
- Josiane Zerubia has been nominated "Associate Editor-European Space Organizations and Industries, Space Signal and Image Processing" of the electronic journal Earthzine (http://www.earthzine.org/) which supports the international Global Earth Observation System of Systems (GEOSS) initiative.

3. Scientific Foundations

3.1. Probabilistic approaches

Following a Bayesian methodology as far as possible, probabilistic models are used within the Ariana project-team, as elsewhere, for two purposes: to describe the class of images to be expected from any given scene, and to describe prior knowledge about the scene in the absence of the current data. The models used fall into the following three classes.

3.1.1. Markov random fields

Markov random fields were introduced to image processing in the Eighties, and were quickly applied to the full range of inverse problems in computer vision. They owe their popularity to their flexible and intuitive nature, which makes them an ideal modelling tool, and to the existence of standard and easy-to-implement algorithms for their solution. In the Ariana project-team, attention is focused on their use in image modelling, in particular of textures; on the development of improved prior models for segmentation; and on the lightening of the heavy computational load traditionally associated with these techniques, in particular via the study of varieties of hierarchical random field.

3.1.2. Wavelets

The development of wavelets as an alternative to the pixel and Fourier bases has had a big impact on image processing due to their spatial and frequency localization, and the sparse nature of many types of image data when expressed in these bases. In particular, wavelet bases have opened up many possibilities for probabilistic modelling due to the existence of not one but two natural correlation structures, intra- and inter-scale, leading to adaptive wavelet packet models and tree models respectively. In Ariana, attention is focused on the use of tree models for denoising and deconvolution; adaptive wavelet packet models for texture description; and on the use of complex wavelets for their improved translation invariance and directional selectivity.

3.1.3. Stochastic geometry

One of the grand challenges of computer vision and image processing is the expression and use of prior geometric information. For satellite and aerial imagery, this problem has become increasingly important as the increasing resolution of the data results in the necessity to model geometric structures hitherto invisible. One of the most promising approaches to the inclusion of this type of information is stochastic geometry, which is a new and important line of research in the Ariana project-team. Instead of defining probabilities for different types of image, probabilities are defined for configurations of an indeterminate number of interacting, parameterized objects located in the image. Such probability distribution are called ‘marked point processes’. For instance, two examples that have been developed in Ariana use interacting cuboids of varying length, width, height and orientation for modelling buildings; and interacting line segments of varying length and orientation for modelling road and other networks.

3.2. Variational approaches

3.2.1. Regularization and functional analysis

The use of variational models for the regularization of inverse problems in image processing is long-established. Attention in Ariana is focused on the theoretical study of these models and their associated algorithms, and in particular on the Γ-convergence of sequences of functionals and on projection algorithms. Recent research concerns the definition of and computation in a function space containing oscillatory patterns, a sort of dual space to BV space, which captures the geometry of the image. These variational methods are applied to a variety of problems, for example image decomposition.

3.2.2. Contours and regions

In addition to the regularization of inverse problems, variational methods are much used in the modelling of boundaries in images using contours. In Ariana, attention is focused on the use of such models for image segmentation, in particular texture segmentation; on the theoretical study of the models and their associated algorithms, in particular level set methods; and on the incorporation of prior geometric information concerning the regions sought using higher-order active contour energies.

3.2.3. Wavelets

Wavelets are important to variational approaches in two ways. They enter theoretically, through the study of Besov spaces, and they enter practically, in models of texture for segmentation, and in the denoising of the oscillatory parts of images.

3.3. Parameter estimation

One of the most important problems studied in the Ariana project-team is how to estimate the parameters that appear in the models. For probabilistic models, the problem is easily framed, but is not necessarily easy to solve, particularly in the case when it is necessary to extract simultaneously from the data both the information of interest and the parameters. For variational models, there are few methods available, and the problem is consequently more difficult.

4. Application Domains

4.1. Denoising and deconvolution

These are perhaps the most basic of the applications with which Ariana is concerned, and two of the most studied problems in image processing. Yet progress can still be made in these problems by improving the prior image models used, for example, by using hidden Markov trees of complex wavelets or by decomposing the image into several components. Ariana is also interested in blind deconvolution.

Figure 1. Left: denoising; middle: a degraded (blurred and noisy) image; right: its restoration.

4.2. Segmentation and classification

Many applications call for the image domain to be split into pieces, each piece corresponding to some entity in the scene, for example, forest or urban area, and in many cases for these pieces to be assigned the appropriate label. These problems too are long-studied, but there is much progress to be made, in particular in the use of prior geometric information.

4.3. Extraction of structures

As the resolution of remote sensing imagery increases, so the full complexity of the scene comes to the fore. What was once a texture is now revealed to be, for example, an arrangement of individual houses, a road network, or a number of separate trees. Many new applications are created by the availability of this data, but efficient harvesting of the information requires new techniques.

4.4. 3D modelling

Earth observation and cartography is not solely concerned with 2D images. One important problem is the construction of 3D digital elevation models (DEMs) from high-resolution stereo images produced by satellites or aerial surveys. Synthetic aperture radar (SAR) imagery also carries elevation information, and allows the production of more accurate DEMs thanks to interferometry techniques, for example.

Figure 2. Left: a satellite image; right: its classification.

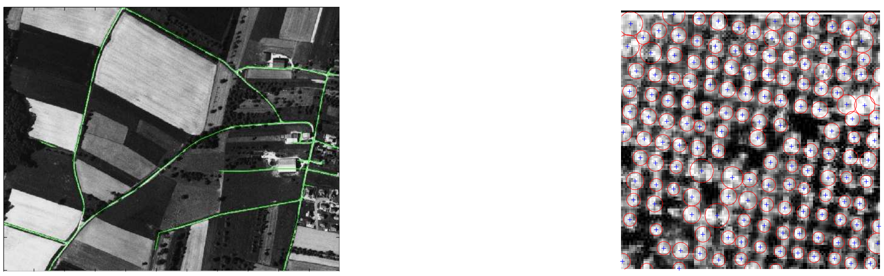


Figure 3. Left: road network extraction; right: tree extraction.

Figure 4. Left: DEM; right: interferometry.

4.5. Information mining and database retrieval

Every day, vast quantities of data are accumulated in remote sensing data repositories, and intelligent access to this data is becoming increasingly problematic. Recently, the problem of retrieval from large unstructured remote sensing image databases has begun to be studied within the project.

Figure 5. Image registration for the evaluation of retrieval systems. Left: mosaicked aerial image data; right: registered ground truth classification.

5. Software

5.1. ORCHARD

Keywords: *birth and death algorithm*, *marked point process*, *orchard*, *tree crown extraction*.

Participants: Stig Descamps, Xavier Descombes, Josiane Zerubia [contact].

Software for tree crown extraction from orchards using a marked point process model based on circles. It finds the positions of the trees. Deposited with the APP. This software has been transferred to the Joint Research Centre of the European Commission in Ispra, Italy.

5.2. FLAMINGO

Keywords: *birth and death algorithm*, *flamingo detection*, *marked point process*.

Participants: Stig Descamps, Xavier Descombes, Josiane Zerubia [contact].

Software for detecting flamingos in order to count them, using a marked point process model based on ellipses. Deposited with the APP. This is free software distributed under the CECILL C license. It has already been transferred to two ecological centres (Tour du Valat in Camargue, France and in Tunisia) and to the French Space Agency (CNES).

5.3. PhaseCircle

Keywords: *gas of circles*, *higher-order active contour*, *phase field*, *tree crown extraction*.

Participants: Peter Horvath, Ian Jermyn, Josiane Zerubia [contact].

Software to extract circular tree crowns from panchromatic or colour infrared aerial images. The software is based on the 'gas of circles' phase field model. Deposited with the APP and transferred to the Joint Research Centre (JRC) of the European Commission in Ispra, Italy and to the Hungarian Central Agricultural Office, Forestry Administration (CAO, FA) in Budapest, Hungary.

5.4. Exzum

Keywords: *Markov random fields*, *urban area extraction*.

Participants: Xavier Descombes, Josiane Zerubia [contact].

This software was deposited with the APP in 1999 (V1.0 with Anne Lorette, Ph.D. student, as co-author) and in 2003 (V2.0 with Osca Viveros-Cancino, Ph.D. student, as co-author). It has previously been transferred to the French Space Agency (CNES) and to Alcatel, and was transferred in 2007 to IRD, Earth Observation Division, in Montpellier.

6. New Results

6.1. Probabilistic models

6.1.1. *Tree crown extraction*

Keywords: *marked point process*, *tree crown extraction*.

Participants: Neismon Fahé, Xavier Descombes, Josiane Zerubia [contact].

This work is funded by the French National Forest Inventory (IFN) [http://www.ifn.fr/]. It has been done in collaboration with Guillaume Perrin, a former PhD student of Ariana (see the 2005 and 2006 activity reports).

Forests have been the subject of many studies because of their key role in the Earth's life cycle, particularly in the equilibrium of ecosystems and the balance of CO_2 in the biosphere. Consequently, it is important to have good tools for monitoring the evolution of forest resources in the current climatic and industrial context. An increasing number of the methods being developed are based on remote sensing techniques. Forestry science uses remote sensing high resolution images for photo-interpretation, in order to establish inventories and maps, comparing this information with that acquired in the field. The work described here proposes different methods, based on a probabilistic approach, for extracting information from Colour InfraRed (CIR) aerial images. Two models for tree crown extraction, based on object processes, have already been studied in Ariana (see the 2005 and 2006 activity reports). In dense areas, an ellipse process is used, while in sparse zones, an ellipsoid process gives more information. As a result, we can obtain the number of trees, their position, their height, and the diameters of the crowns for sparse areas. The models have been tested on high resolution CIR aerial images provided by the French National Forest Inventory (IFN). The software GRENAT, developed in Ariana, implements the algorithms of these models, and many other specific tools, with an easy-to-use interface. This year, we worked on a user interface defined in collaboration with the French National Forest Inventory (IFN) for use by their operators.

6.1.2. *A new birth and death algorithm for road detection*

Keywords: *diffusion*, *marked point process*, *road detection*.

Participant: Xavier Descombes [contact].

This study was partially supported by CNRS and INRIA and has been conducted in collaboration with Prof. E. Zhizhina, IIPT Moscow (Russian Academy of Sciences) within the Poncelet Laboratory [http://www.mccme.ru/lifr/].

We have generalized our previous continuous birth and death dynamics [42] to the case of road network extraction. We previously defined a continuous birth and death process which, after discretization, can be interpreted as a multiple birth and death algorithm. Each iteration is divided into three steps. The first step consists in generating a configuration of objects which is added to the current configuration. In the second step, the different objects are sorted into a list according to the value of the data term. Finally, in the death step, each object, taken in list order, is killed with a probability depending on the posterior model. This scheme improves on the classical RJMCMC algorithm in term of computational time, for counting simple geometric objects (trees, flamingos). We have generalized this framework to the context of road network detection. The dynamic has been enlarged by including a specific birth rate that depends on the interaction. This new possibility has to be compared to the 'birth and death in a neighbourhood' perturbation previously defined for the RJMCMC scheme (see the 2004, 2005, and 2006 activity reports). This work is still in progress.

Figure 6. Some results obtained with the software GRENAT. (© IFN/INRIA)

6.1.3. Parameter estimation for marked point processes

Keywords: *EM*, *MCMCML*, *marked point processes*, *parameter estimation*, *pseudo-likelihood*, *remote sensing*.

Participants: Florent Chatelain, Xavier Descombes, Josiane Zerubia [contact].

This study was partially supported by the French Space Agency (CNES).

Marked point processes are useful for image processing problems such as object extraction from remote sensing images. The advantage of these processes is that they allow the inclusion of strong geometrical constraints on the objects to be detected. In our applications, a marked point process is defined by a density function with respect to the Poisson measure. Within the framework of Gibbs point process, this density is expressed as a combination of several energy terms: firstly, a data energy term, which controls the localization of the objects with respect to the data; secondly, prior information about the objects is given by internal energy terms corresponding to geometrical constraints on the objects. The weights associated with each internal energy are the so-called 'hyperparameters'. These 'hyperparameters' used to be calibrated by hand. As their values depend on the kind of images studied, the calibration step is often long. In order to develop fully unsupervised detection procedures, an estimation of these hyperparameters has to be performed. First of all, an estimation strategy is studied in the case of complete data, for which the configuration, *i.e.* the set of marked points corresponding to the objects, is known. In this case, several estimators such as maximum likelihood or pseudo-likelihood estimators may be derived. However, since the normalizing constant of the process density is not tractable, maximum likelihood estimators cannot be derived directly. The likelihood is, rather, computed using an importance sampling method. This implies the simulation of importance weights using MCMC methods. MCMCML estimators are then numerically obtained by maximizing the resulting estimated likelihood. Another estimation method is based on the pseudo-likelihood, which is a combination of valid likelihoods associated with conditional events. Pseudo-likelihood estimators are then obtained by maximizing the corresponding pseudo-likelihood. The interest of this last procedure is that one avoids the simulation step, since the normalizing constant does not appear in the pseudo-likelihood. Of course, these estimators are sub-optimal, and their performance has to be compared to MCMCML estimators. Finally, in the more general framework of missing data, *i.e.* when the configuration is unknown, there is in general no tractable closed form expression for the density associated with the observations. To tackle this problem, estimation methods such as the Expectation-Maximization (EM) can be used. This work is in progress.

6.1.4. Flamingo detection using a multiple birth and death algorithm

Keywords: *diffusion*, *flamingo detection*, *marked point process*.

Participants: Stig Descamps, Xavier Descombes, Josiane Zerubia [contact].

This study was partially supported by the COLORS Flamants project and was conducted in collaboration with Arnaud Béchet from La Tour du Valat [http://www-sop.inria.fr/ariana/personnel/Xavier.Descombes/Flamants.html].

This work addresses the problem of detecting and counting breeding greater flamingos in aerial images of their colonies [41]. We consider a stochastic approach based on object processes, also called marked point processes. Here, the objects represent flamingos, which are represented by ellipses. The density associated with the ellipse process is defined with respect to the Poisson measure. Thus, the problem is reduced to energy minimization, where the energy is composed of a regularizing term (prior density), which introduces some constraints on the objects and their interactions, and a data term, which links the objects to the features to be extracted in the image. Then, we sample the process to extract the configuration of objects minimizing the energy by a new and fast birth-and-death dynamics [42], leading to the total number of birds. This approach gives counts with good precision when compared to manual counts. Additionally, this approach does not need image pre-processing or supervision of the extraction, thus considerably reducing the overall processing time required to get the count. The algorithms were tested on images provided by the Tour du Valat. Two of them are presented in figure 7.

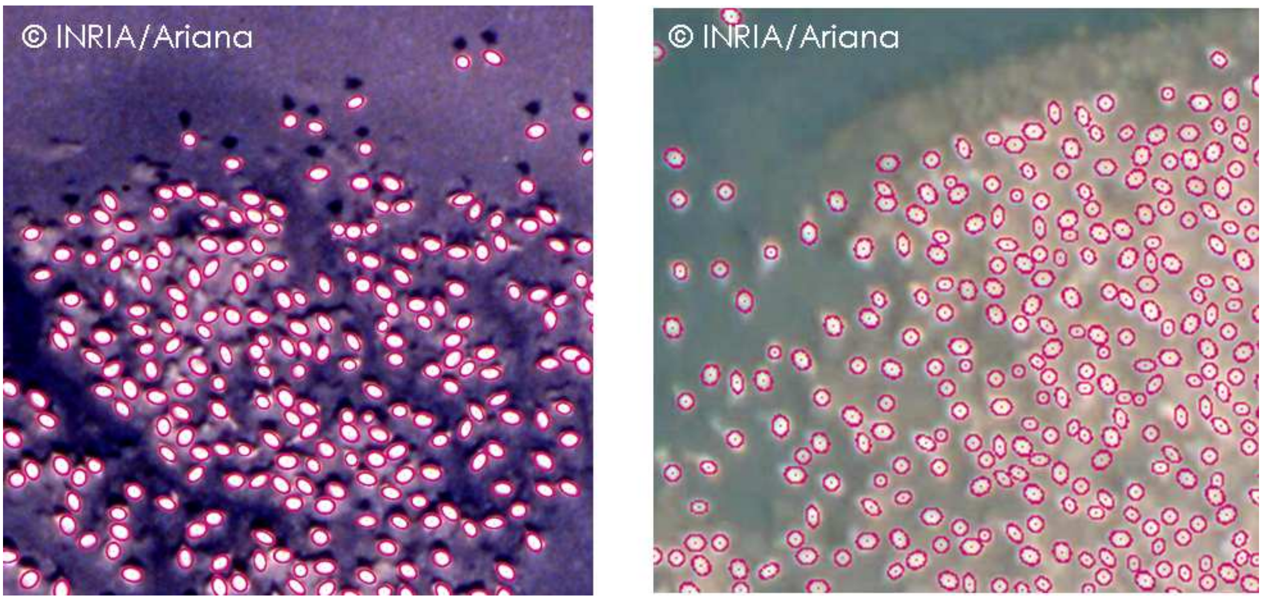


Figure 7. Left: result on a colony of flamingos in Turkey; right: result on a colony of flamingos in France.

6.1.5. Shape recognition for scene analysis

Keywords: *colour infrared aerial images*, *geodesic path*, *shape space*, *tree crowns*.

Participants: Maria S. Kulikova, Xavier Descombes, Josiane Zerubia [contact].

This Ph.D. was funded by an MESR grant and by INRIA/FSU Associated Team 'SHAPES' [http://www-sop.inria.fr/ariana/Projets/Shapes/]. This work was conducted in collaboration with Prof. Srivastava from Florida State University, and Prof. E. Zhizhina and Prof. R. Minlos from the Institute of Information Transmission (IITP Russian Academy of Sciences, Russia).

The goal of this research work is to develop a generic model for extracting geometric shapes from an image [26]. The first applications we address concern tree crown and building extraction. The challenge is to find an appropriate shape representation and then a measure of shape similarity on the so-called shape space. This will allow us to define statistics on the shape space and then to sample shapes. The resulting statistical models will form part of the prior distribution of a probabilistic model for object extraction.

This year, we have studied a new representation, the so-called ‘q-representation’. This representation, in contrast to previous representations defined by the angle function, allows us to take into account not only shape bending but also shape compression and stretching in constructing geodesics between shapes.

Figures 8 and 9 show some examples in which one can see the difference between the geodesics for tree crown and building shapes constructed using the different approaches. Looking at the shapes along the geodesics, one notices that the branches of the tree crowns (Fig. 8) and the angles of the buildings (Fig. 9) are better preserved along the geodesic path using the new shape representation. This property is important for the calculation of the shape statistics, in particular the average shape, which will be more representative of the shape class.

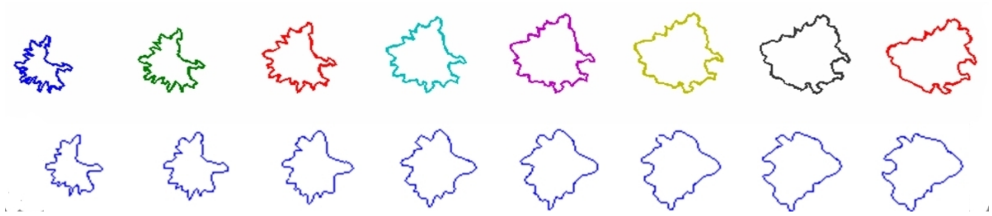


Figure 8. Geodesic between two tree shapes. In colour: old approach using angle function representation; in blue: new approach using q-representation.

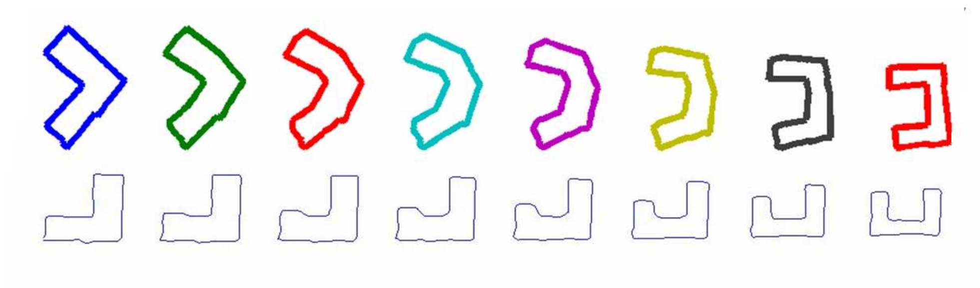


Figure 9. Geodesic between two building shapes. In colour: old approach using angle function representation; in blue: new approach using q-representation.

6.1.6. 3D city modelling using a structural approach

Keywords: *3D reconstruction*, *DEM*, *RJMCMC*, *building*, *marked point process*, *simulated annealing*.

Participants: Florent Lafarge, Xavier Descombes, Josiane Zerubia [contact].

This Ph.D. is co-supervised by Marc-Pierrot Deseilligny, chief scientist of the technical management of French National Geographic Institute (IGN). The data (satellite images of urban areas) were provided by French Space Agency (CNES).

Three dimensional models of urban areas are very useful for many kinds of applications, for example urban planning, radiowave reachability tests for wireless communications, and disaster recovery. However, 3D building reconstruction is a difficult problem, mainly due to the complexity of urban scenes.

We have developed a method for the 3D reconstruction of buildings from satellite images based on a stochastic approach [7]. It consists in reconstructing buildings by assembling simple urban structures extracted from a library of 3D parametric models, rather like the toy Lego[Registered] Trade Mark. Such a method is particularly well adapted to data of average quality such as satellite images. The approach is based on a density formulation defined within a Bayesian framework. The configuration that maximizes this density is found using an RJMCMC sampler, which solves the multiple parametric object recognition problem. Figure 10 presents results on typical French town centres.

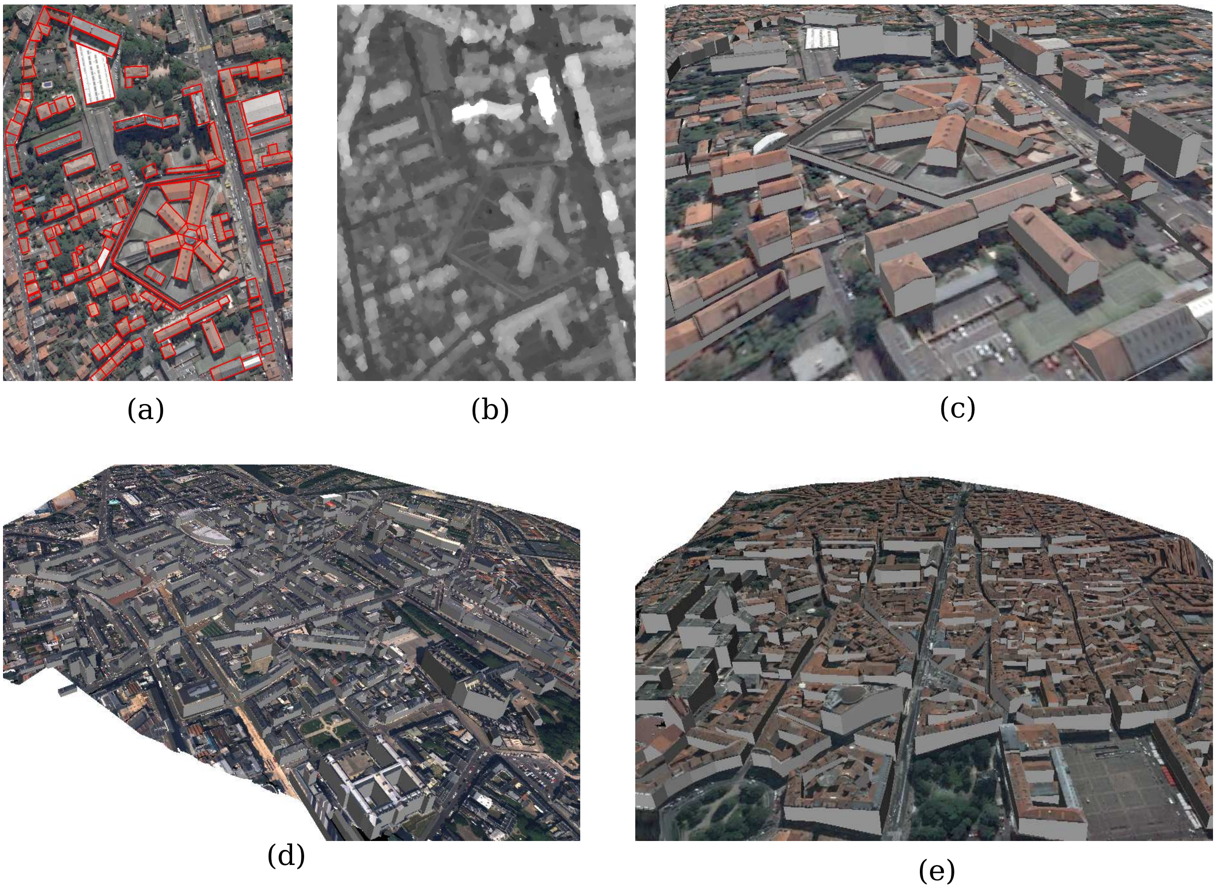


Figure 10. a) PLEIADES images of the Toulouse area; b) the associated DEM; c) the 3D result obtained; d) 3D reconstruction of Amiens town centre; e) 3D reconstruction of Toulouse town centre. (All images © CNES/IGN.)

6.1.7. Target change detection in high resolution images

Keywords: *change detection*, *entropy K-means*, *remote sensing*, *target detection*.

Participants: Alexandre Fournier, Xavier Descombes, Josiane Zerubia [contact].

This Ph.D. is partially funded by a DGA/MRIS grant.

This work addresses the problem of target change detection in high resolution remotely sensed images [18]. Its particularity is to take advantage of the data and differences available in image pairs of the same area taken at different times, rather than single images. In our previous work, we performed a first rough detection of changed areas based on an iterative Principal Component Analysis (PCA). This was followed by clustering based on an Entropy K-means algorithm. Both were based on radiometric data, although spatial dependence was introduced through a Markov random field regularization. This year, the research work has involved designing a polygonal approximation algorithm in order to extract geometrical data from the previously clustered zones. This algorithm is designed to minimize the Lebesgue measure of the symmetric difference between a contour and its Polygonal Approximation. As figure 11 shows, this criterion is robust to outliers of the detected shape. Figure 12 shows the convergence result on an aeroplane shape. Figure 13 shows how building shadows (which qualify as changes) present particular directions that are eventually matched after algorithm convergence. Once obtained, the orientations of all the segments are classified in order to find a new criterion for discriminating changes (shadows and city street directions). Work in progress includes creating a model merging both geometric and radiometric data for the detected objects. Then a connectivity model defining relationships between the objects should improve the classification.

Figure 11. Left: naive initialization on a square shadow. Right: Result after convergence. The outliers do not influence the final result.

Figure 12. Naive initialisation (left) and convergence (right) of the polygonal approximation algorithm on the shadow of an aeroplane.

6.1.8. Damage assessment after forest fires from satellite image

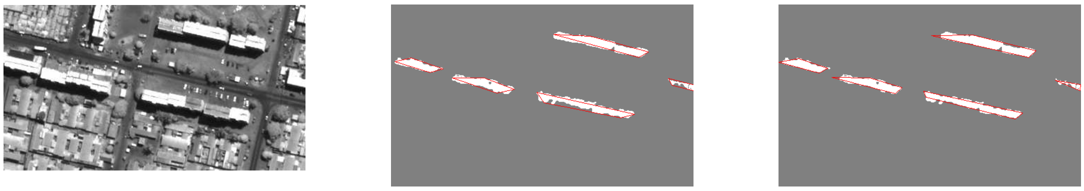


Figure 13. One of the image pairs (left); naive initialization on the 'shadow' class (middle); and convergence (bottom) to fit the shadow directions (right).

Keywords: *burnt area*, *classification*, *entropy K-means*, *forest fire*, *support vector machine*.

Participants: Olivier Zammit, Xavier Descombes, Josiane Zerubia [contact].

This Ph.D. was partly funded by SILOGIC and INRIA. We particularly thank Commandant Poppi (Fire brigade member and director of the cartography service, SDIS83 Draguignan) for interesting discussions.

Several studies have shown the effectiveness of using several coarse-resolution images to detect burnt areas. But these methods require at least two satellite images which are expensive. This work addresses the problem of burnt area mapping after forest fires from a single high-resolution post-fire image. It consists of delineating burnt areas from the radiometric information given by the different sensors of SPOT 5.

To discriminate burnt from unburnt areas, we use Support Vector Machines (SVM) [45], a supervised learning algorithm which provides high classification accuracy and good generalization capacity. Finally, we improve the classification by regularizing it with either a classical Markov model or mathematical morphology techniques.

SVM requires a set of observations (*i.e.* a labelled training set) to predict the classification of unlabelled samples. To avoid the manual selection of this training set, we have proposed an automatic selection process combining an entropy K-means algorithm and SVM [38].

The classification methods (the simple SVM and the combination of K-means and SVM) are applied to several SPOT 5 images of Southern France (PACA and Corsica regions) containing various types of vegetation to test their efficiency [39], and are compared with classical algorithms such as K-means and K-Nearest neighbours [45]. The extracted burnt areas are also compared to the corresponding ground truth provided by CNES, Infoterra-ESA, ONF-AM, and the SDIS3 and SDIS2B.

6.1.9. The Fisher-Rao metric and Bayesian shape classification from point sets using joint models on shape and sampling

Keywords: *Fisher-Rao*, *Shape*, *classification*, *metric*, *point set*, *prior*, *sampling*.

Participant: Ian Jermyn [contact].

This work was supported by and performed as part of INRIA Associate Team 'Shapes' in collaboration with Prof. Srivastava of Florida State University [http://www-sop.inria.fr/ariana/Projets/Shapes/].

The Fisher-Rao (FR) metric is the unique metric on spaces of probability measures to be invariant to push-forward by Markov mappings, and in particular, diffeomorphisms [53]. Its expression in terms of half-densities is particularly simple: it is Euclidean, revealing that in the FR metric, spaces of probability measures are orthants of the unit sphere in spaces of measures. This enables the analytical computation of geodesics between probability measures, which previously required numerical computation.

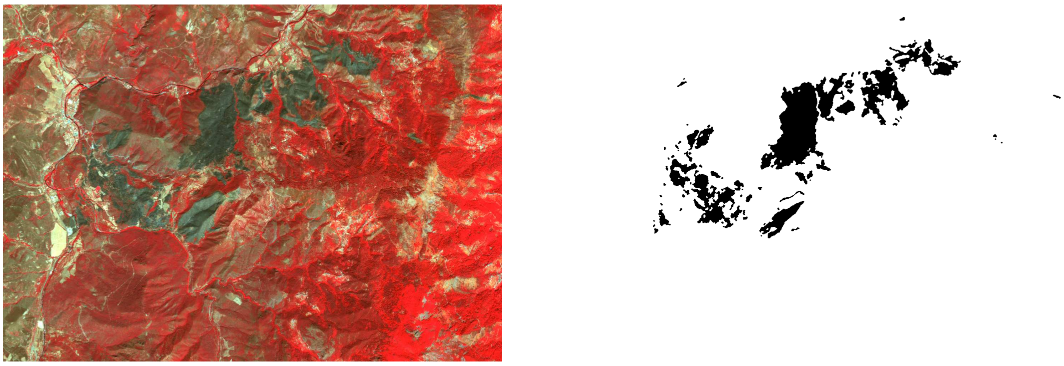


Figure 14. Left: SPOT 5 image (© CNES 2003, Distribution SPOT Image). Right: results using a combination of K-means and SVM classification.

The space of 1D diffeomorphisms of $[0,1]$, $\mathrm{Diff}([0,1])$, is isomorphic to the space of probability densities on $[0,1]$, and the FR metric can thus be used to measure distances between such diffeomorphisms. This enables the creation of 'Gaussian' probability distributions on $\mathrm{Diff}([0,1])$. Different samplings of curves can be described by the action of $\mathrm{Diff}([0,1])$ on a fixed sampling (*e.g.* uniform), and probability distributions on $\mathrm{Diff}([0,1])$ can thus be pushed forward to the space of samplings.

Certain types of imaging modality or the outputs of certain types of image processing (*e.g.* edge detection) lead to images that are essentially point sets, where some of the points correspond to the border of an object, while others are 'noise'. Combining probability distributions on shapes with probability distributions on samplings of curves, and an image formation model, enables the classification of objects from such images, as illustrated in figure 15, and described in [25].

6.1.10. An efficient representation for computing geodesics between n-dimensional elastic shapes

Keywords: *classification*, *curve*, *distance*, *geodesic*, *higher dimension*, *metric*, *prior*, *shape*.

Participant: Ian Jermyn [contact].

This work was supported by and performed as part of INRIA Associate Team 'Shapes' in collaboration with Prof. Srivastava, Prof. E. Klassen, and S. Joshi of Florida State University [http://stat.fsu.edu/]

The Fisher-Rao metric is defined on spaces of densities, and hence pushes forward to $\mathrm{Diff}([0,1])$. These can be viewed as curves in one dimension. The question arises as to whether there is a natural generalization to spaces of vector-valued densities, or equivalently to curves in higher dimensions: the derivative of a parameterized curve transforms as a vector-valued density under the action of $\mathrm{Diff}([0,1])$. There is in fact a one-parameter family of generalizations, and these metrics can be used to compute distances and geodesics between parameterized curves, or projected to compute distances between 'shapes', *i.e.* parameterized curves modulo $\mathrm{Diff}([0,1])$, translation, rotations, scalings, etc. In 2D, all the members of the family are flat, and Euclidean coordinates can be found. For higher dimensions, all members of the family are conformally flat, but only for one value of the parameter does the metric have zero curvature. Euclidean coordinates can be found, and these facilitate the computation of geodesics between shapes in any number of dimensions. This also opens the way to computing distances and geodesics between 'decorated' shapes, *i.e.* with texture features attached to each point of the curve. The first row of figure 16 shows a geodesic between two 3D curves from two points of view, while the second row shows the results of clustering American Sign Language shapes using geodesic distances computed from this metric. Further details are available in [23], [24].

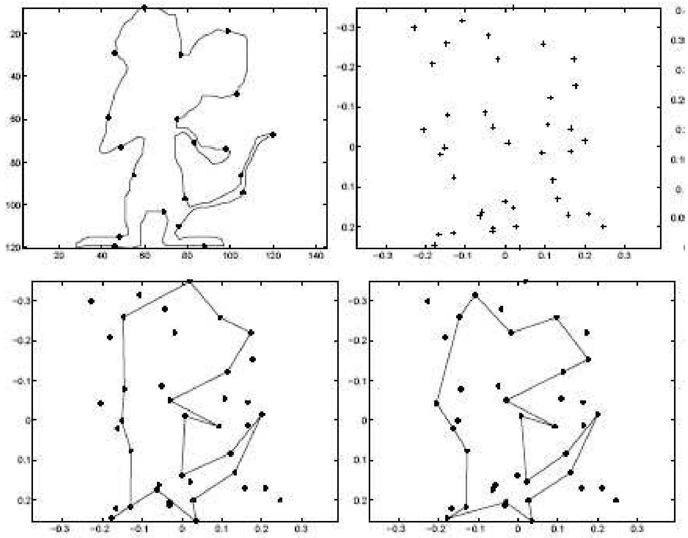


Figure 15. Top left: original shape and a sampling; top right: the sampled points plus Poisson noise; bottom row: two samples from the posterior distribution, estimating the points that come from the original shape.

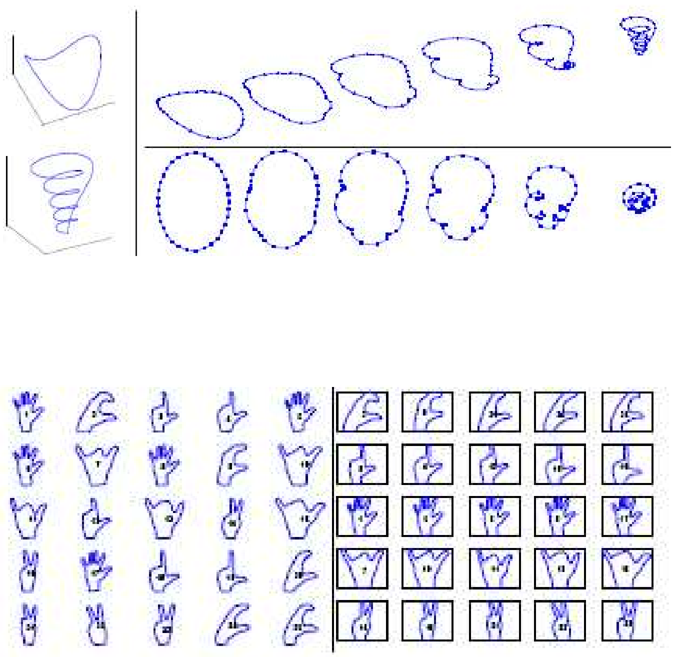


Figure 16. Top row: two 3D shapes, and the geodesic between them, from two points of view. Bottom row: 25 different American Sign Language shapes and the results of clustering them using geodesics distances.

6.2. Variational models

6.2.1. Satellite image reconstruction from irregular sampling

Keywords: *TV regularization*, *irregular sampling*, *remote sensing*, *variational approach.*

Participants: Eric Bughin, Laure Blanc-Féraud, Josiane Zerubia [contact].

This work was partially funded by CS-Toulouse.

The problem of reconstructing an image from a random set of irregular samples is a problem of great interest in various domain such as satellite imaging. In this work, we are interested in solving a problem of image restoration with different aspects: reconstruction from irregular samples, deconvolution, and denoising. The context is a satellite stereoscopic acquisition of a scene. Thus we have two regular acquisitions of the same scene. By applying the disparities between the two images to the reference image, we get an irregularly sampled new image which should be identical to the second image of the stereopsis pair (apart from some details due to moving objects during the time between the acquisitions of the stereoscopic pair). As a matter of fact, the second image can be considered as an irregularly sampled acquisition (in comparison to the reference image) and the problem of reconstructing the reference image from the second image knowing the disparities between the two images can be considered as an irregular sampling problem. We also consider at the same time the deconvolution problem, by considering the point spread funstion (PSF) of the acquisition system. The noise considered here has two different parts: the first is due to the acquisition system, and can be considered to be white Gaussian noise, while the second is due to errors in the computation of the disparities between the two images of the stereoscopic pair. Such an error may have disastrous effects in urban images: poor estimation of the position of a sample located on the top of a building may place this sample in a place where there should be some shadow. As a matter of fact, some errors in the estimation of irregular samples may completely change the value of a pixel, which can be seen as impulsive noise. We reconstruct and restore the image by minimizing a functional with an l^1-norm on the data term in order to take into account the impulsive noise and a standard TV regularizing term. We use a smoothed approximation of the l^1-norm around zero, and we minimize the functional using a gradient descent algorithm. We have shown that using an l^1-norm on the data term is more robust to impulsive noise (see figure 17).

6.2.2. Super-resolution in satellite imaging

Keywords: *TV regularization*, *remote sensing*, *super-resolution*, *variational approach.*

Participants: Gregory Loeb, Laure Blanc-Féraud, Josiane Zerubia [contact].

This work was partially funded by Astrium/EADS Toulouse.

The problem addressed in this work is the reconstruction of a high resolution image from several low resolution images. In the context of remotely sensed images, this can be applied to geostationary satellites, for example, whose resolution is low due to the high altitude of the satellite. We assume that we know the shift between the low resolution observed images. At the same time, we address the problems of noise removal and deconvolution in order to remove the effect of the point spread function (PSF) of the acquisition system. The problem is formulated as an inverse problem, and we regularize it by minimizing a functional composed of the data term and a TV regularization term. In order to be robust to small errors in the shift estimation, which can induce high intensity errors at borders of objects, and which can be viewed as impulsive noise, we propose to minimize a functional with an l^1-norm in the data term to be increase robustness. As the l^1-norm is not differentiable at zero, we use a smooth approximation of it for both terms, and minimize the functional by using a gradient descent procedure. Tests have been made on images provided by Astrium/EADS, comparing the results obtained with the l^2-norm and the l^1-norm in the data term, as well as comparing to other recent methods in the literature (see figure 18). When there are no errors in the shift, we can use the functional with the l^2-norm. In this case, very fast algorithms can be derived. In the other case, faster algorithms are still to be developed.

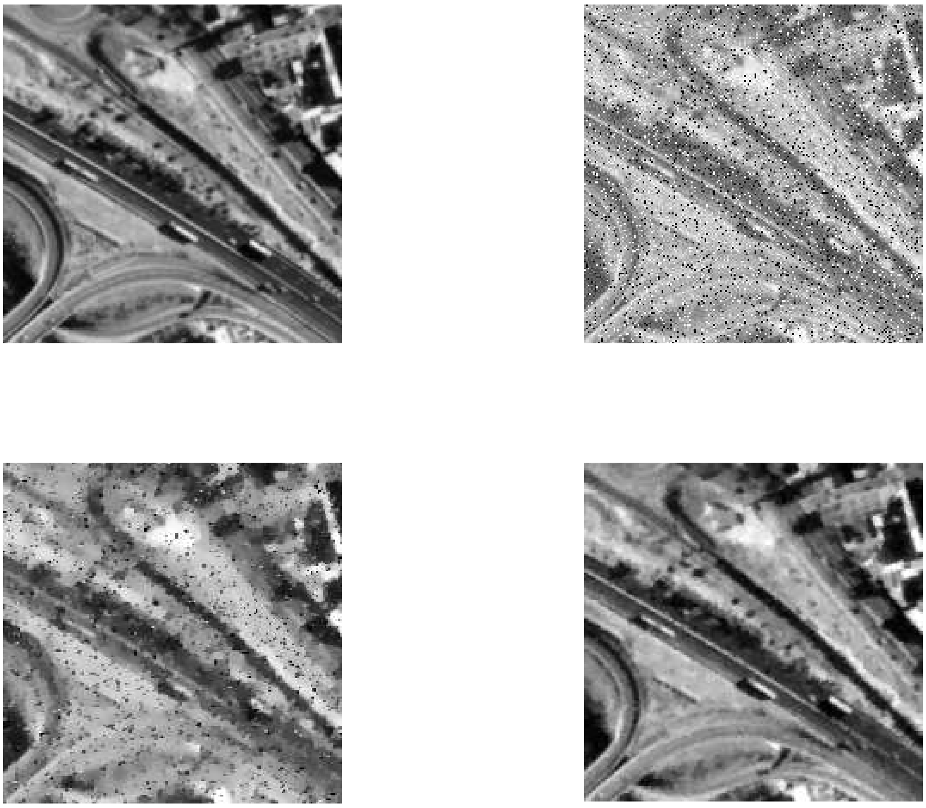


Figure 17. Robustness to noise: top left: reference image (© CNES); top right: input (irregularly sampled) with additive Gaussian noise ($RSB = 15.5$dB) and 10% of impulse noise; bottom left: result of the algorithm of Almansa et al. (regular sampling + denoising with an l^2-norm on the data term); bottom right: result of our algorithm (regular sampling + denoising with an l^1-norm on the data term).

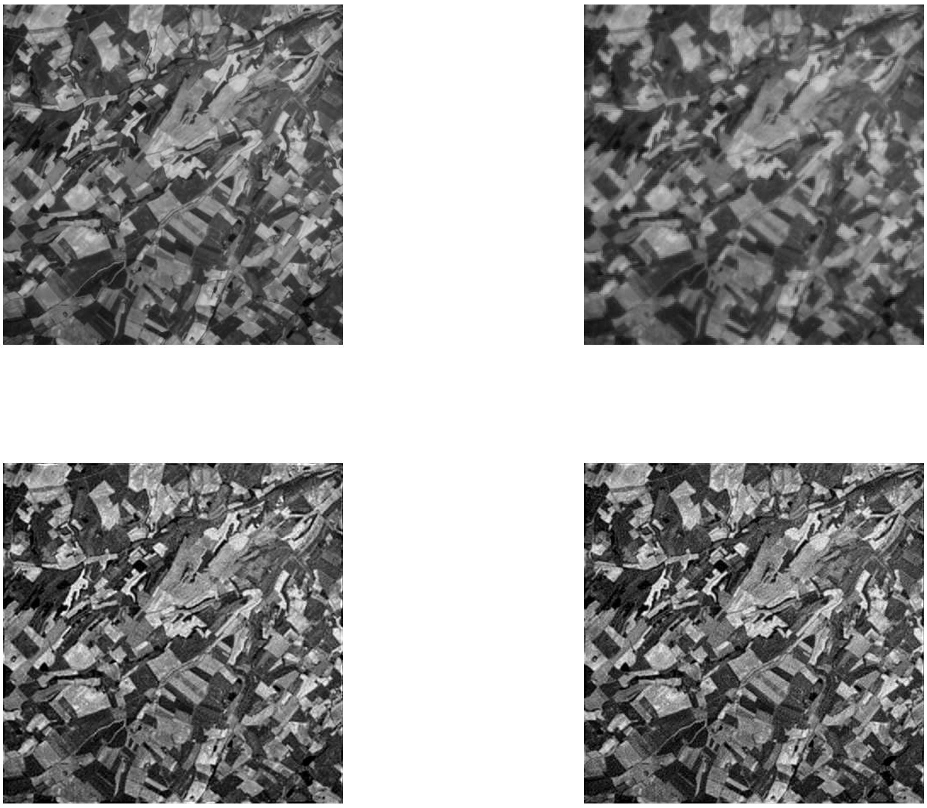


Figure 18. Top left: ground truth (© ASTRIUM/EADS); top right: a low resolution image; bottom left: reconstruction of the high resolution image using an l^2-norm in the data term; bottom right: reconstruction of the high resolution image using an l^1-norm in the data term.

6.2.3. Efficient schemes for total variation minimization in image processing

Keywords: *Nesterov scheme*, *decomposition*, *duality*, *geometry*, *l 1 norm minimization*, *texture*, *total variation*.

Participants: Weiss Pierre, Laure Blanc-Féraud [contact].

This Ph.D. is co-supervised by Gilles Aubert, professor of the J.-A. Dieudonné Mathematics Laboratory of the University of Nice Sophia Antipolis [http://math1.unice.fr/].

We have developed new algorithms [44] to minimize total variation and more generally l^1-norms under a general convex constraint. The algorithms [37] are based on a recent advance in convex optimization proposed by Yurii Nesterov. Depending on the regularity of the data fidelity term, we solve either a primal problem or a dual problem.

First, we show that standard first-order schemes allow solutions of precision ϵ in $O(\frac{1}{\epsilon^2})$ iterations at worst. For a general convex constraint, we propose a scheme that allow solutions of precision ϵ in $O(\frac{1}{\epsilon})$ iterations. For a strongly convex constraint, we solve a dual problem with a scheme that requires $O(\frac{1}{\sqrt{\epsilon}})$ iterations to obtain a solution of precision ϵ.

Thus, depending on the regularity of the data term, we gain from one to two orders of magnitude in the theoretical convergence rates with respect to standard schemes. We perform some numerical experiments which confirm the theoretical results for various problems. Compared to standard optimization procedures, computing times are reduced by a factor ranging from 4 to 20.

Figure 19 shows the results of a new texture/cartoon decomposition algorithm. The image on the right shows the decrease of the cost function with the number of iterations for two different sets of parameters and two different algorithms. The proposed algorithm clearly outperforms (here by a factor of 4), a standard gradient descent with optimal step.

Figure 19. Left: original image; middle: cartoon part of the decomposition; right: cost function for a projected gradient descent with optimal step, and the proposed Nesterov approach.

6.2.4. Variational models for road network updating in dense urban areas from very high resolution optical images

Keywords: *GIS*, *active contour*, *dense urban area*, *higher-order*, *multiscale*, *nonlocal*, *phase field*, *road network*, *very high resolution*.

Participants: Ting Peng, Ian Jermyn, Josiane Zerubia [contact].

This Ph.D. is co-supervised by Baogang Hu, from LIAMA/CASA, Chinese Academy of Sciences [http://liama.ia.ac.cn], and by Véronique Prinet from the same laboratory. The data (Quickbird images and GIS of Beijing urban areas) were respectively provided by DigitalGlobe [http://www.digitalglobe.com] and the Beijing Institute of Survey and Mapping [http://www.bism.cn]. This work is partially supported by Thales Alenia Space.

The problem addressed in this work is the extraction of the region containing the road network from very high resolution (~ 0.5m) satellite images. In our initial work [32], a phase field higher-order active contour was used to model the network region and its relation to the image, and thus to extract the main road network in dense urban areas from a single QuickBird panchromatic image (see figure 20). At $1/8$ resolution, the complete main road network is successfully retrieved (see figure 20). However, at the original resolution, the detail in the image results in errors along the boundary of the roads and in the detection of spurious regions in the background (see figure 20).

The prior energy used was *generic*: it incorporates constraints on the form of the road network region that are true of any road network. To improve the results at the original resolution, we developed a *specific* prior energy, linking the extracted road network region to a GIS map of the road network [31]. The GIS map was obtained a few years earlier than the satellite images, and thus represents a slightly different road network. To test the method, we introduced further artificial errors in order to increase the difficulty of the problem (see figure 20). The additional prior energy measures the difference between the network region in the GIS map and the extracted network. Its main effect is to reduce false detections in the background. Experiments show that at the original resolution, our model is able to keep the unchanged roads, to correct the mistakes, and to extract new roads (see figure 20). In order to free the method from the need for a GIS map, we replaced the GIS map by the result obtained with our previous method at a lower resolution. The results show little change, showing that a GIS map, although useful, is not necessary.

We then turned to the extraction of secondary roads. These are far harder to deal with because their radiometric properties are very similar to those of the background, and because small roads are often occluded by shadows and trees. To deal with these difficulties, we developed a new nonlinear nonlocal prior energy term. This is a new type of higher-order active contour/phase field term. It allows the interaction between points on the same side of a road to be stronger and of longer range than the interaction between points on opposite sides of a road. The preliminary results at $1/4$ and $1/2$ resolution are extremely promising, clearly outperforming the old model (see figure 21).

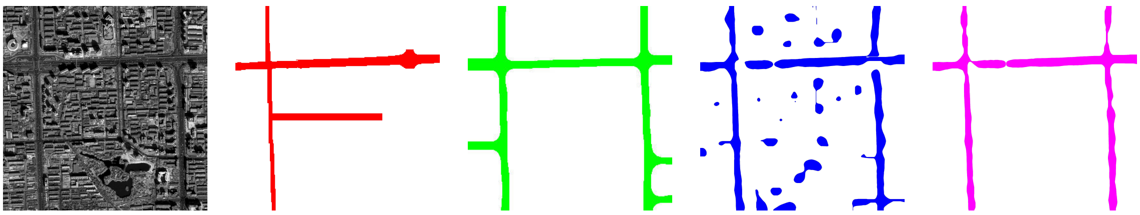


Figure 20. Left to right: QuickBird image, $0.61m$ (© DigitalGlobe); deliberately 'damaged' ground truth, to simulate an earlier GIS map; the result at $1/8$ resolution; the result at the original resolution without specific prior; the result at the original resolution with specific prior from GIS.

6.2.5. Higher-order active contours for tree detection

Keywords: *active contour*, *aerial imaging*, *gas of circles*, *higher order*, *phase field*, *shape modelling*, *tree detection*, *variational methods*.

Participants: Peter Horvath, Ian Jermyn, Josiane Zerubia [contact].

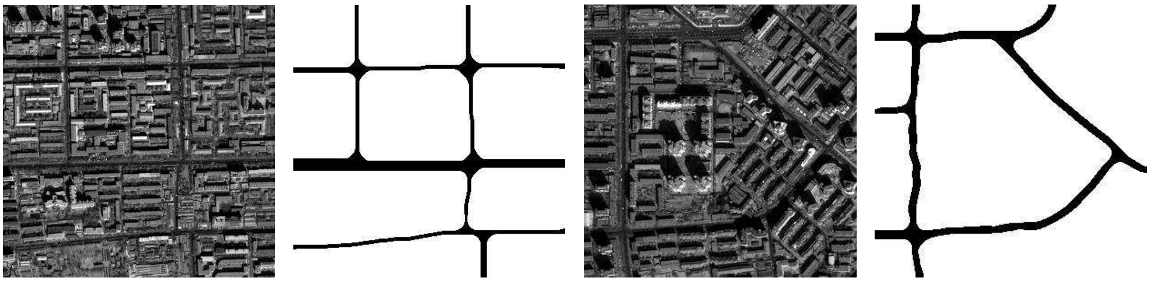


Figure 21. Images (© DigitalGlobe) and results obtained with the new nonlinear nonlocal prior energy at $1/4$ *resolution.*

This Ph.D. is co-supervised by Zoltan Kato, Assistant Professor at the University of Szeged, Hungary. The data (aerial images of French forests) were provided by the French National Forest Inventory (IFN).

In this work, we propose a phase field version [20], [21] of our earlier higher-order active contour (HOAC) 'gas of circles' model [47], [48], and develop a multispectral data term for colour infrared aerial images [19].

The HOAC 'gas of circles' model is an effective tool for modelling circular shapes. Nevertheless there are some difficulties. It is complicated to express the space of regions in the contour representation, and consequently difficult to work with a probabilistic formulation. In addition, from the algorithmic point of view, the current model does not allow enough topological freedom, and the implementation of the HOAC model is difficult and computationally expensive. However, it is possible to create an alternative formulation of HOAC models, based on the 'phase field' framework much used in physics to model regions and interfaces [51]. In order to make use of the stability analyses developed for the HOAC models, we computed, as a function of the HOAC energy parameters, the phase field energy parameters that produce an equivalent model. This means that we can adjust the phase field parameters to ensure stable circles of a given radius [20]. We extended the phase field 'gas of circles' model to the case of an inflection point rather than a minimum in the circle energy at the desired radius [21]. The use of the phase field framework cuts execution times by one or two orders of magnitude.

We have also introduced a data model using all three bands of the colour infrared (CIR) images [19]. We studied the quality of the extraction results produced by modelling the three bands as independent or as correlated. We have shown that, even at the level of maximum likelihood, the inclusion of 'colour' information, and in particular, interband correlations, can improve the results, and in conjunction with the region prior, the full model is considerably better than that based on one band alone. We use the models to extract tree crowns from aerial images, but the models are not restricted to forest management: they can be applied to the detection of any circular objects.

Figure 22(a) shows a CIR image of a plantation, with a field in its upper part, while figure 22(b) shows the segmentation result obtained using the multispectral 'gas of circles' model. Figure 22(c) shows a panchromatic aerial image with sparsely planted poplars, while figure 22(d) shows the result obtained using the phase field 'gas of circles' model.

6.3. EU Project MUSCLE

6.3.1. Phase diagram of a higher-order active contour energy

Keywords: *active contour*, *higher-order*, *phase diagram*, *road network*, *stability analysis*, *tree crown*.

Participants: Aymen El Ghoul, Ian Jermyn, Josiane Zerubia [contact].

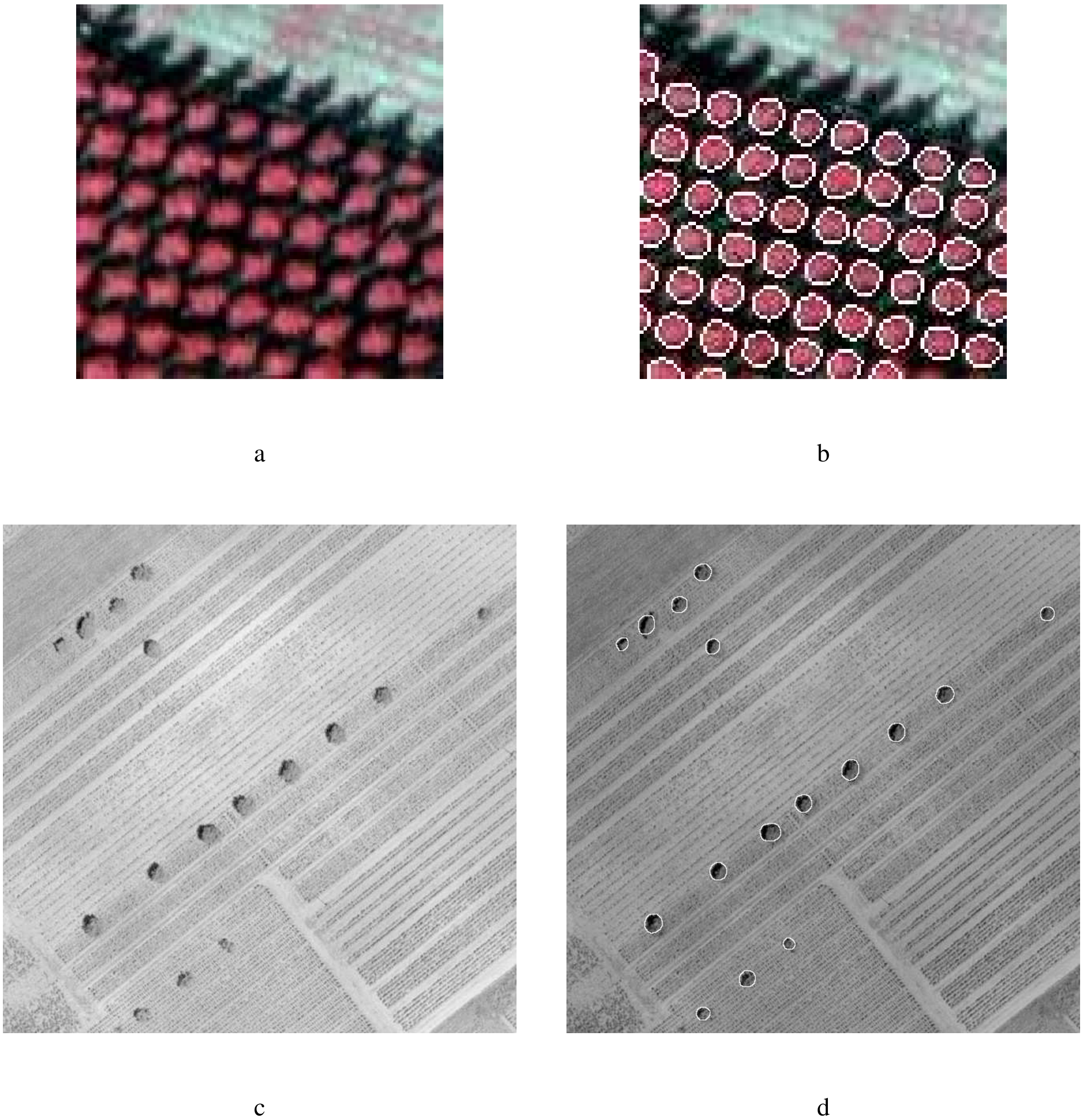


Figure 22. a: an aerial image of a plantation (© IFN); b: the extraction result with the HOAC 'gas of circles' model; c: a second image (© Hungarian Central Agricultural Office, Forestry Administration (CAO, FA)); d: the extraction result obtained with the phase field 'gas of circles' model.

This work was partially funded by EU Network of Excellence MUSCLE.

Higher-order active contours (HOACs) are models of regions containing sophisticated prior geometric knowledge about region shape introduced via long-range interactions between region boundary points [50], [52]. They have been used to extract road networks [50], [52] and tree crowns [49], [47] from remote sensing images using models of network shapes and a 'gas of circles' respectively.

The shapes modelled by a given energy can vary considerably with the model parameters. In particular, the same energy is used for the two applications mentioned above, only with different parameter values. In order to set the parameters of the model for a given application, we therefore need to know which shapes are modelled in which parameter ranges. The aim of this work is thus to determine the 'phase diagram' of the basic HOAC model, *i.e.* to determine the parameter ranges leading to stable circles and/or stable bars (a bar is a simplified network).

The stability analysis for both configurations (bar and circle) is based on a functional Taylor series expansion of the energy up to second order around the shape whose stability we wish to analyse. The first functional derivative must be zero and the second functional derivative non-negative definite in order for the shape to be stable, which places strong constraints on the model parameters, allowing us to reduce the effective dimension of the parameter space, in some cases to one dimension. Figure 23 shows two pieces of the phase diagram resulting from these analyses, corresponding to circles (left) and bars (right). The coloured zones of the diagrams represent the parameter ranges leading to stable circles or stable bars respectively. The upper part of each zone corresponds to circles with negative energy per circle, or negative energy per unit length of bar, while the lower parts correspond to positive energies. This division is important as it has a dramatic influence on the behaviour of the model: if the energy of a circle is negative then as many circles as possible will be created, while if the energy per unit length of a bar is negative then the bar will lengthen without limit. The corresponding Gibbs distributions are then not normalizable. This work will be published in RFIA 2008.

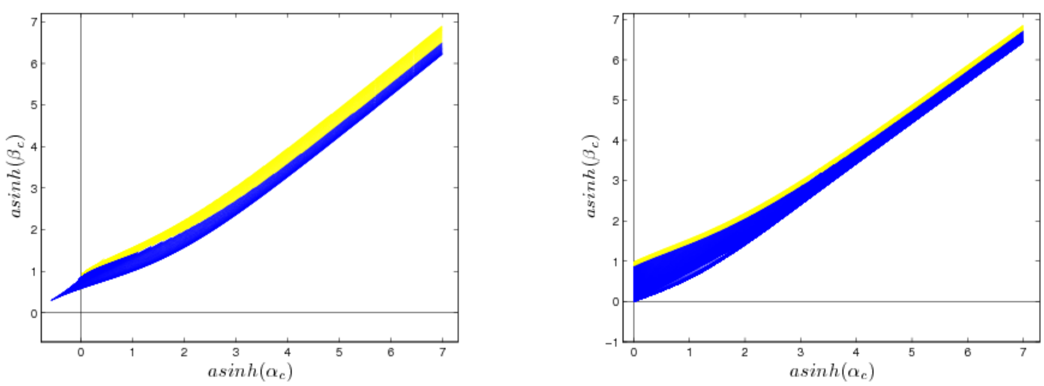


Figure 23. Left: zone of phase diagram corresponding to stable bars; right: zone of phase diagram corresponding to stable circles. Blue and yellow regions correspond respectively to a positive and negative energy of the local minimum.

6.3.2. Land classification using a Tree Structured MRF and Mean Shift

Keywords: *Markov random fields*, *image segmentation*, *land classification*, *mean shift*, *remote sensing*, *tree structured*.

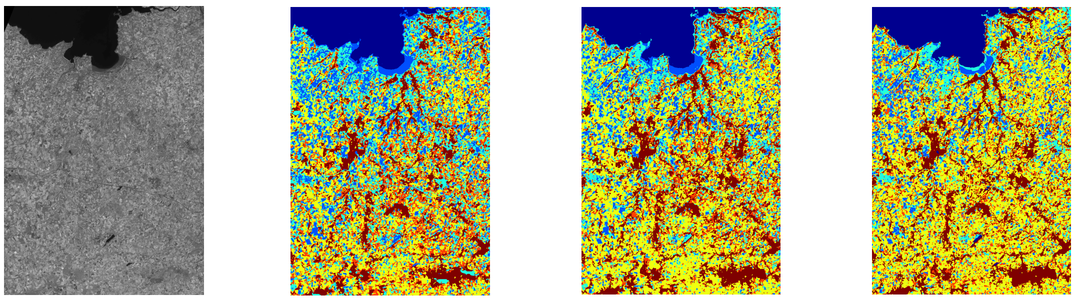
Participants: Raffaele Gaetano, Josiane Zerubia [contact].

This study is part of a Ph.D. funded by the University 'Federico II' of Naples, Italy, and was partially supported by EU Network of Excellence MUSCLE, and conducted in collaboration with Prof. G. Scarpa (University of Naples).

This work addresses the problem of land classification via pixel-based image segmentation of low- and mid-resolution multispectral satellite images. Unsupervised segmentation is here pursued using a particular class of Markov random fields, namely tree structured MRFs (TS-MRFs). These models allow the hierarchical representation of a 2D field by the use of a sequence of nested MRFs, each corresponding to an internal node of the tree. Consequently, the segmentation algorithm can perform optimization of such models by recursively working on a single internal node at a time, from the root to the leaves, with a significant reduction in complexity.

In our former work on TS-MRFs, only binary tree structures were used, but such a constraint can be too tight when attempting to fit arbitrarily structured data within a hierarchical tree representation. In this work, we propose a variation to our unsupervised segmentation algorithm that allows the use of generic tree structures, providing dynamic dimensionality selection for MRFs located at each node of the tree, and therefore a new structure evolution strategy, based on Mean-Shift analysis applied to the joint spatial/spectral feature space. Mean-shift is also used to provide initial conditions for the optimization of each MRF.

Results (see figure 24) have been obtained that outperform the old version of the algorithm both on synthetic data and real SPOT satellite images of Lannion Bay (France), showing that in both cases a more coherent tree structure is provided and that consequently segmentation quality is improved. These improvements are confirmed by classification quality assessment, showing lower average error rates.



(a) (b) (c) (d)

Figure 24. Unsupervised segmentation of a SPOT image of Lannion Bay, France (size 1480 × 1024*, 3 channels, © SPOTImage/CNES): (a) source image (XS3 channel); (b) 6-class map retrieved using the original TS-MRF algorithm (classification rate 77.5%); (c) 6-class map retrieved using the modified TS-MRF/Mean Shift algorithm (classification rate 86.0%); (d) corresponding 6-class map from the supervised TS-MRF based segmentation, for comparison.*

6.4. ACI MULTIM

6.4.1. Mathematical methods for multi-channel image restoration

Keywords: *multi-channel image processing*, *restoration*, *stochastic methods*, *variational methods*.

Participants: Pierre Weiss, Laure Blanc-Féraud [contact], Xavier Descombes, Josiane Zerubia.

This work is being done as part of the ACI MULTIM [http://www-syscom.univ-mlv.fr/ACI].

An important evolution in image processing is the passage from scalar data to multi-channel data, with the development of multi- and hyper-spectral cameras, particularly for astronomical and satellite imaging. A crucial problem in this context is the restoration of these data, *i.e.* the removal of degradations introduced during the acquisition procedure. An important aspect is to take into account the dependency of the channels in the restoration procedure. The aim of this ACI is to develop mathematical models for multi-spectral image restoration, mainly using variational and PDE multidimensional methods.

6.5. ACI Masses de Données QuerySat

6.5.1. Indexing of remote sensing images using road networks

Keywords: *database retrieval*, *graph matching*, *remote sensing*, *road network*, *skeleton*.

Participants: Avik Bhattacharya, Ian Jermyn, Xavier Descombes, Josiane Zerubia [contact].

This Ph.D. is co-supervised by Henri Maître, deputy director of École Nationale Supérieure des Télécommunications (ENST), Paris [http://www.tsi.enst.fr] and Michel Roux, Assistant Professor at ENST. This work has been done as part of ACI QuerySat [http://www.tsi.enst.fr/QuerySat/], and is partly funded by the French Space Agency (CNES).

Remote sensing image databases have grown enormously with recent advances in image acquisition technologies. These images offer a huge amount of potentially useful information, but retrieving this information from such large volumes of data using indices of relevance to applications is an extremely difficult problem. In this work, we take a novel approach to this problem. Instead of using correlations between low-level image features (representing short-range pixel dependencies) and semantic content to retrieve images, we use correlations between one type of semantic content (representing long-range pixel dependencies) and another. Specifically, we use the fact that the properties of road networks vary from one type of geographical environment to another to identify and retrieve these environments. This presupposes that we can find automatically the road network in an image; we test various methods for this task in order to evaluate the robustness of the method to errors in the network. To describe the properties of road networks, we use various statistics computed from a graphical representation of the extracted network to quantify properties such as density, curvature, spatial variation, and so on [46]. In order to deal with the failure of the extraction methods in dense urban areas, a second set of features computed from a segmentation of these areas is used [4]. We use the extracted features to classify large satellite images at a coarse scale using a one-vs-rest probabilistic Gaussian kernel support vector machine. An sample result is shown in figure 25.

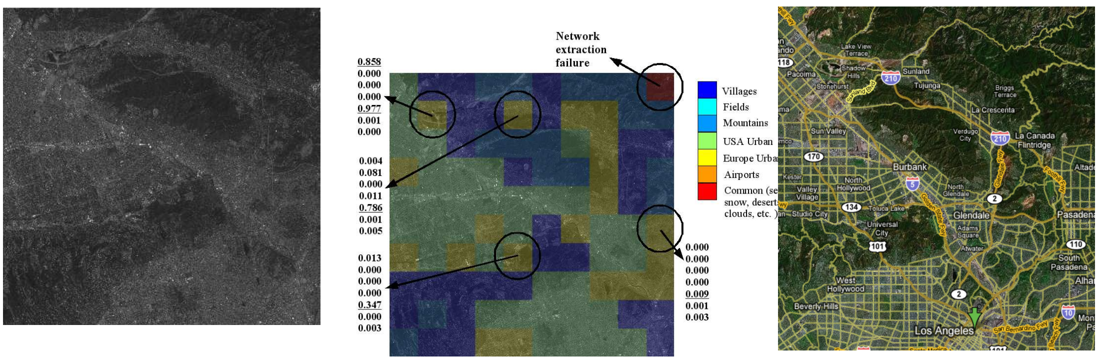


Figure 25. Large image classification. Left: original image (© CNES); middle: superimposed image; right: ground truth (Google Maps).

6.6. Applications to biology

6.6.1. 3D confocal image deconvolution

Keywords: *3D image*, *Poisson noise*, *confocal microscopy*, *deconvolution*, *restoration*, *wavelet*.

Participants: Caroline Chaux, Laure Blanc-Féraud, Josiane Zerubia [contact].

This research was partly supported by the P2R Franco-Israeli Collaborative Program [http://www-sop.inria.fr/ariana/Projets/P2R/] and by post-doc fellowship funded by INRIA.

In this work, we propose an iterative algorithm for 3D confocal microcopy image restoration. The image quality is limited by the diffraction-limited nature of the optical system, which causes blur, and the reduced amount of light detected by the photomultiplier leading to noise having Poisson statistics. Wavelets have proved to be very effective in image processing and have gained much popularity. Indeed, they allow the efficient denoising of images by applying a thresholding to the coefficients. Moreover, they are used in algorithms as a regularizing term and seem to preserve textures and small objects.

We propose here a 3D iterative wavelet-based algorithm [16] and make some comparisons with state-of-the-art methods for restoration. More precisely, we compare three methods:

1. Method 1: denoising (wavelet thresholding) then deconvolution (Richardson-Lucy);
2. Method 2: deconvolution (PSF inversion) then denoising (estimation of the noise and then wavelet thresholding);
3. Method 3: combine denoising and deconvolution.

We plan to use pre-processing similar to the Anscombe transform or the Fisz transform in order to stabilize the noise variance and consequently apply more conventional methods developed for Gaussian noise.

Different tests were made on synthetic images, real images, and phantom images (*i.e.* the object put under the microscope is known). The latter class of images allows the numerical and visual evaluation of the methods. Figure 26 shows a result on a phantom image of a shell. The objective here is to recover the initial shell dimension. We know that the thickness lies between 0.5 and 0.7μm.

Figure 26. Restoration of an image of a shell. Left: raw data; centre: restored images using method 1 (denoising + deconvolution); right: restored images using method 3 (combined approach).

Looking at figure 26, method 3 seems to lead to the best results. If we look at the intensity profiles of the images (see figure 27), we can see that method 3 allows a more accurate recovery of the real thickness of the shell.

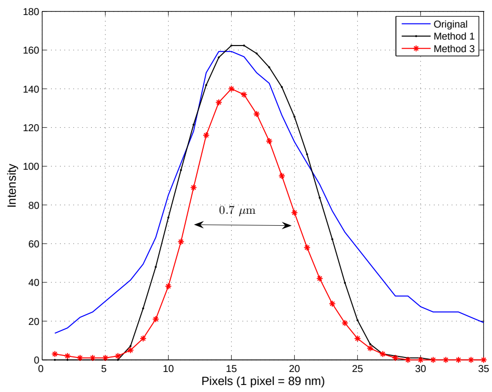


Figure 27. Intensity profile of the 3 images represented in figure 26. One pixel represents 89nm.

6.6.2. Parametric Blind Deconvolution in Confocal Laser Scanning Microscopy (CLSM)

Keywords: *3D image*, *Bayesian restoration*, *Richardson-Lucy (RL)* , *Total-Variation (TV)* , *blind deconvolution*, *confocal microscopy*, *parameter estimation*.

Participants: Praveen Pankajakshan, Laure Blanc-Féraud, Josiane Zerubia [contact].

This Ph.D. was funded by an INRIA CORDI Fellowship. It forms part of the P2R Franco-Israeli project [http://www-sop.inria.fr/ariana/Projets/P2R/].

This work addresses the problem of blind deconvolution for fluorescence microscopy. An iterative method can restore fluorescence Confocal Laser Scanning Microscopy (CLSM) images and parametrically estimate the acquisition system point spread function (PSF). The CLSM is an optical fluorescence microscope that scans a specimen in 3D and uses a pinhole to reject most of the out-of-focus light. However, the quality of the images suffers from two basic physical limitations. The diffraction-limited nature of the optical system and the reduced amount of light detected by the photomultiplier cause blur and photon counting noise respectively. These images can hence benefit from post-processing restoration methods based on deconvolution. An efficient method for parametric blind image deconvolution [30] involves the simultaneous estimation of the specimen 3D distribution of fluorescent sources and the microscope PSF [11]. By using a model for the microscope image acquisition physical process, we reduce the number of free parameters describing the PSF and introduce constraints. The parameters of the PSF may vary during the course of experimentation, and so they have to be estimated directly from the observed data. A prior model of the specimen is further applied to stabilize an alternate minimization algorithm and to converge to the solution.

The model was previously tested on 2D images and the restoration process was very effective. However, extending it to 3D images poses a new challenge because the sampling is different for the radial and the axial plane. Another important obstacle is that the amount of spread in the intensity is higher in the Z direction than in the XY plane. Hence direct extension from 2D to 3D case is not obvious. Additional changes to the parametric estimation algorithm ensured a more robust estimation of the parameters of the PSF without imposing any constraints on the estimation step size. The results obtained on some 3D synthetic images are as shown in figure 28.

6.6.3. Segmentation and Deconvolution of 3D images

Keywords: *3D image*, *confocal microscopy*, *deconvolution*, *filament*, *segmentation*, *variational method*.

Participants: Alexis Baudour, Laure Blanc-Féraud [contact].

This Ph.D. is co-supervised by Gilles Aubert, professor of the J.-A. Dieudonné Mathematics Laboratory of the University of Nice Sophia Antipolis [http://math1.unice.fr/] and is conducted within the ANR Detectfine in collaboration with the Pasteur Institute.

We propose a new model to detect locally thin filaments in 2D or 3D confocal microscopy images [12], [13]. This model uses an approximation of the PSF by a Gaussian function G_σ and take into consideration the effect of the discretization due to the CCD sensors and additive Gaussian noise b.

First, we show that the observed image of a linear filament passing through a point x with an intensity A and a direction v at pixel y_i, without additive Gaussian noise b, is given by:

$$I(y_i) = \int_C (y_i) A e^{-\frac{(Vxy.Vv^{\perp})^2}{\sigma}} \tag{1}$$

We look for pairs (F, b) where F is a filament with parameters (x, Vv, A) compatible with the model 1 above, and b is a Gaussian with a minimum L^2 norm. We use a gradient descent method in order to obtain these pairs.

The examples in figure 29 show the results of the proposed method on a synthetic 2D image.

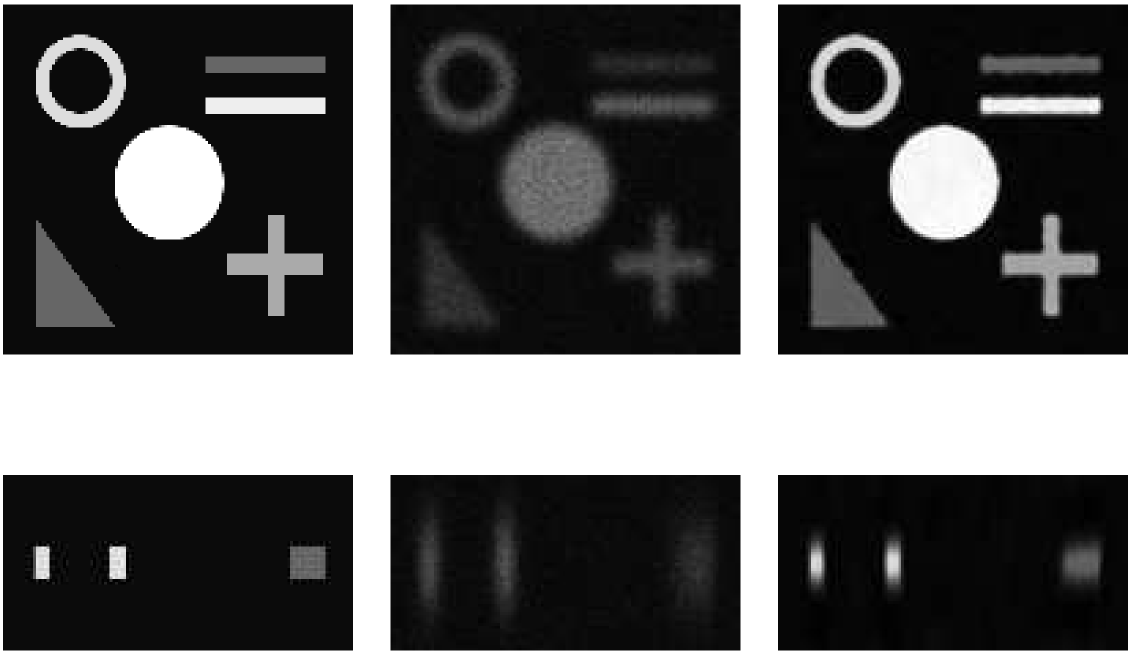


Figure 28. Left: phantom object to be imaged; middle: observed image from a Confocal Laser Scanning Microscopy (CLSM) ; right: estimated object using the Parametric Blind Deconvolution (PBD) . (Images © INRIA.)

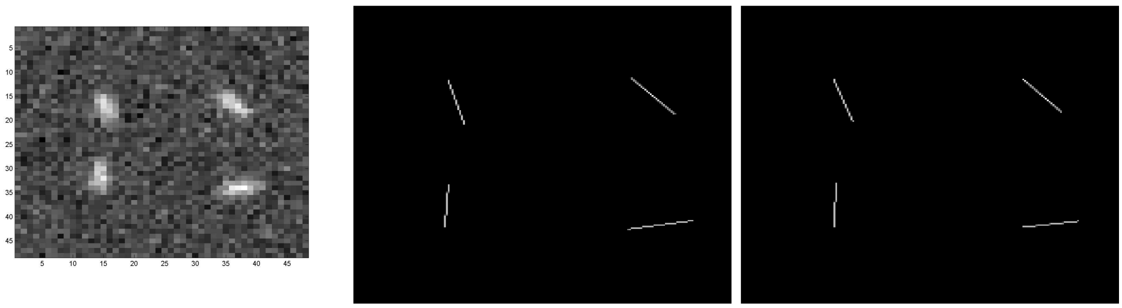


Figure 29. Left: original synthetic image; middle: ground truth; right: detected filaments.

7. Contracts and Grants with Industry

7.1. Industrial

7.1.1. CNES Toulouse

Participants: Avik Bhattacharya, Ian Jermyn, Xavier Descombes, Josiane Zerubia [PI].

Extraction and characterization of line networks in satellite images for retrieval from image databases. Contract #293

7.1.2. CNES Toulouse

Participants: Florent Chatelain, Xavier Descombes, Josiane Zerubia [PI].

Parameter estimation for marked point processes for object extraction from high resolution satellite images. Contract #2150, part 1.

7.1.3. CNES, Toulouse

Participants: Aymen El Ghoul, Ian Jermyn, Josiane Zerubia [PI].

Higher-order active contours with application to the extraction of networks (roads and rivers) from high-resolution satellite images. Contract #2150, part 2.

7.1.4. CS Toulouse

Participants: Eric Bughin, Laure Blanc-Féraud, Josiane Zerubia [PI].

Satellite image reconstruction from irregular sampling. Contract #2104.

7.1.5. Astrium/EADS Toulouse

Participants: Gregory Loeb, Laure Blanc-Féraud, Josiane Zerubia [PI].

Super-resolution for satellite imaging. Contract #2402.

7.1.6. SILOGIC Toulouse

Participants: Olivier Zammit, Xavier Descombes, Josiane Zerubia [PI].

Evaluation of the damage after a forest fire from high resolution satellite images. Contract #1156.

7.1.7. Thales Alenia Space Cannes

Participants: Ting Peng, Ian Jermyn, Josiane Zerubia [PI].

Road network updating in dense urban areas from very high resolution optical images. Contract #1675.

7.1.8. IFN Nogent sur Vernisson

Participants: Neismon Fahe, Xavier Descombes, Josiane Zerubia [PI].

Semi-automatic methods for forestry cartography using aerial and high resolution satellite images. Contract #1467.

7.1.9. DGA/CTA Arcueil

Participants: Alexandre Fournier, Xavier Descombes, Josiane Zerubia [PI].

Target detection through texture perturbation analysis. Grant from the DGA and CNRS.

7.1.10. JRC Ispra, Italy

Participants: Stig Descamp, Peter Horvath, Ian Jermyn, Xavier Descombes, Josiane Zerubia [PI].

Tree detection and counting in orchards. Contract #2576.

7.1.11. IRD Montpellier

Participants: Xavier Descombes, Josiane Zerubia [PI].

Urban area extraction from SPOT5 images. Contract #2713.

8. Other Grants and Activities

8.1. Regional

8.1.1. INRIA COLORS project 'FLAMANTS'

Participants: Stig Descamps, Nadia Belhadj Arfani, Xavier Descombes [PI], Josiane Zerubia.

Detection of flamingos in aerial images. In collaboration with the Tour du Valat (Sansouire Foundation) in Arles (Arnaud Béchet) (http://www-sop.inria.fr/ariana/personnel/Xavier.Descombes/Flamants.html)

8.2. National

8.2.1. ANR programme blanc: project 'DETECFINE'

Participants: Alexis Baudour, Laure Blanc-Féraud [PI].

In collaboration with the J.-A. Dieudonné Laboratory of CNRS/UNSA (G. Aubert, L. Almeida), the Pasteur Institute in Paris (J-C Olivo-Marin, C. Zimmer), SAGEM DS at Argenteuil (D. Duclos, Y. Le Guilloux), and ENS Cachan (J.F. Aujol).

8.2.2. ANR programme blanc: project 'Micro-Réseaux'

Participant: Xavier Descombes [Ariana PI].

In collaboration with IMFT (F. Plouraboue (PI), L. Risser), CERCO (C. Fonta), and ESRF (P. Cloetens, G. LeDuc).

8.2.3. ACI NIM: project 'MULTIM'

Participants: Xavier Descombes, Laure Blanc-Féraud [Ariana PI], Josiane Zerubia.

In collaboration with Paris 6 (P. Combettes (PI)), Paris 5 (L. Moisan), Ecole Polytechnique (A. Chambolle), J.-A. Dieudonné Laboratory of CNRS/UNSA (G. Aubert), University of Paris Est-Marne La Vallée (JC. Pesquet), Observatoire Midi-Pyrénées (S. Roques). Website: http://www-syscom.univ-mlv.fr/ACI.

8.2.4. ACI Masse de Données: project 'QuerySat: Heterogeneous and multi-scale descriptors for retrieval from remote sensing image databases'

Participants: Avik Bhattacharya, Aymen El Ghoul, Ian Jermyn, Xavier Descombes [Ariana PI], Josiane Zerubia.

In collaboration with the Signal and Image Processing laboratory of ENST (M. Campedel, Y. Kyrgyzov, B. Luo, H. Maître, M. Roux (PI)), INRIA project-team IMEDIA (O. Besbes, S. Boughorbel, N. Boujemaa, M. Crucianu, M. Ferecatu, V. Gouet) and URISA of Sup'Com Tunis (Z. Belhadj, A. Ben Azza, R. Tebourbi). Website: http://www.tsi.enst.fr/QuerySat/.

8.3. European

8.3.1. EU project MUSCLE

Participants: Avik Bhattacharya, Aymen El Ghoul, Peter Horvath, Ting Peng, Ian Jermyn [Ariana PI], Josiane Zerubia.

The Ariana project-team is a participant in the European Union Sixth Framework Network of Excellence MUSCLE (Multimedia Understanding through Semantics, Computation and Learning), contract FP6-507752, in collaboration with 41 other participants around Europe, including four other INRIA project-teams. Web site: http://www.muscle-noe.org.

8.4. International

8.4.1. P2R Franco-Israeli project

Participants: Caroline Chaux, Praveen Pankajakshan, Laure Blanc-Féraud, Josiane Zerubia [Ariana PI].

In collaboration with the Pasteur Institut (Bo Zhang, Jean-Christophe Olivo-Marin [PI]), the Weizmann Institute (Zvi Kam) and Technion (Arie Feuer [PI]). Website: http://www-sop.inria.fr/ariana/Projets/P2R.

8.4.2. INRIA/FSU Associated team 'SHAPES'

Participants: Maria S. Kulikova, Ian Jermyn, Xavier Descombes, Josiane Zerubia [PI].

In collaboration with the Vision Group of Florida State University (A. Srivastava (PI), V. Patrangenaru, S. H. Joshi, and W. Liu). Website: http://www-sop.inria.fr/ariana/Projets/Shapes.

8.4.3. PRA Project

Participant: Xavier Descombes [Ariana PI].

In collaboration with LIAMA (V. Prinet) and the VISTA/IRISA project-team (J.F. Yao, P. Bouthemy).

9. Dissemination

9.1. Conferences, Seminars, Meetings

- The members of the Ariana project-team participated actively in GdR ISIS and GdR MSPCV.
- Members of the Ariana project-team participated in the Fête de la Science at EAI CERAM in October.
- The Ariana project-team organized numerous seminars in image processing during 2007. Eighteen researchers were invited from the following countries: Belgium, Canada, China, the Czech Republic, France, Hungary, Ireland, Israel, the Netherlands, Spain, Switzerland, the UK, and the USA. For more information, see the Ariana project-team web site.
- Members of the Ariana project-team participated actively in the visits to INRIA Sophia Antipolis of students from the Grandes Écoles (École Polytechnique, ENS Cachan, ENPC, Sup'Aéro) and from John Hopkins University, USA; helped students of the Classes Préparatoires with TIPE in France; and gave information on remote sensing image processing to high school students in Mauritius.
- The work of the Ariana project-team was reported in Interstices (special topic on tree detection in aerial images), in Code Source for the 40$^{\text{th}}$ anniversary of INRIA, and in LISA in May (special issue dedicated to the environment).
- The Ariana project-team presented demos to visitors from the Association Aéronautique et Aérospatiale Francaise (AAAF) in March.
- All the members of the Ariana project-team participated in a 'brain-storming' session in Sospel in June.
- Avik Bhattacharya gave a cross-seminar (Ariana/Maestro) in May at INRIA Sophia Antipolis. He presented a paper at the Fifth International Workshop on Content-Based Multimedia Indexing (CBMI 2007), Bordeaux. He presented a poster at the 1st Symposium of the CNES/DLR/ENST Competence Centre on Information Extraction and Image Understanding for Earth Observation, Paris, in June, and an oral presentation at the DLR centre in Oberpfaffenhofen in March. He gave a talk at the ACI Masses de Données QuerySat meeting at ENST, Paris.

- Alexis Baudour presented a poster at SSVM, Ischia, Italy in May. He gave a talk at SMAI, Praz-sur-Arly, France, in June. He presented a poster at GRETSI, Troyes, France, in September.
- Caroline Chaux presented a paper at the SPIE Wavelet XII conference in August in San Diego, California, USA. She presented a seminar at CEA Saclay in September.
- Stig Descamps gave a seminar for the GdR ISIS meeting in July at Télécom Paris, France.
- Aymen El Ghoul gave a seminar at LIAMA in July in Beijing, China. He presented his Masters project in June at the Ecole Supérieure des Télécommunications de Tunis, Tunisia.
- Alexandre Fournier and Olivier Zammit attended the workshop ‘Utilisation des drones pour la prévention et la lutte contre les feux de forêt’ organized by the ‘Pôle de Compétitivité Pegase’, and the ‘Pôle Risques’, in May in Gardanne, France.
- Alexandre Fournier presented a paper at the TAIMA conference in Hammamet, Tunisia, and gave a seminar at Sup’Com in Tunis, Tunisia, both in May. He gave a seminar at the CNES-DLR workshop in March in Oberpfaffenhofen, Germany. He also presented the work of the Ariana project-team in Spanish to an official delegation from Valencia, Spain.
- Peter Horvath gave a cross-seminar (Ariana/Odyssée) in May at INRIA Sophia Antipolis. He presented his work at ACIVS in August in Delft, the Netherlands, and at EUSIPCO in September in Poznan, Poland. He gave a talk at University of Szeged in Hungary in September and at ETH Zurich in November.
- Maria Kulikova presented a poster at the ‘Shape Day’ workshop in the Department of Statistics of Florida State University, Tallahassee, Florida, USA in April. She participated at The International Summer School on Pattern Recognition in July, where she also presented a poster. She presented a paper at EUSIPCO, Poznan, Poland in September.
- Florent Lafarge gave talks at the “Atelier PNTS: la très haute résolution spatiale en télédétection” in September in Nantes, France, and at the EURANDOM workshop on image analysis and inverse problems in Eindhoven, The Netherlands. He presented papers at ICIP in San Antonio, USA, at EUSIPCO in Poznan, Poland, and at PIA in Munchen, Germany, all in September.
- Praveen Pankajakshan presented a paper at the International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) in August in Lyon, France. He presented his work at the first P2R Franco-Israeli joint meeting in February, at the Pasteur Institute, Paris, France. He presented his work at the second P2R Franco-Israeli joint meeting in October, at Sophia Antipolis and gave a cross-seminar at ED STIC in November.
- Ting Peng participated in the Summer School on Statistical Learning, Microsoft Research Asia, Beijing, China, in July. She participated in EMMCVPR in EZhou, Hubei, China, in August. She presented a paper at BMVC, Warwick, UK, in September. She participated in the THRS TU Workshop of PNTS, Nantes, France, in September.
- Pierre Weiss, presented a poster at CODE in April in Paris, France. He gave a talk at SMAI, Praz-sur-Arly, France, in June. He gave a talk at GRETSI, Troyes, France, in September.
- Olivier Zammit made a presentation at the INTECH seminar in June in Sophia Antipolis, France. He presented a paper at IGARSS in July in Barcelona, Spain. He presented another paper at the GRETSI Colloquium in September in Troyes, France. He attended the ‘Observation et télédétection pour une meilleure gestion des risques’ conference organized by POPSUD in March in Aix en Provence, France, and the Drones conference organized by the ‘Pôle de Compétitivité Pegase’ and the ‘Pôle Risques’ in Valabre in May.
- Laure Blanc-Féraud gave an invited talk at the Workshop ‘An interdisciplinary approach to Textures and Natural Images Processing’ in January in Paris, France. She gave a seminar at the Pierre et Marie Curie University in April in Paris, France. She gave an invited tutorial talk at the ORASIS conference in June in Obernai, France. She attended the conference SSVM in May in Italy and GRETSI, Troyes, France, in September. She participated in the P2R meetings at the Pasteur Institute in Paris in February and at Sophia Antipolis in October. She organized and attended ANR meetings, one in Paris in March and one in Nice in September.

- Xavier Descombes gave an invited talk at the Workshop ‘An interdisciplinary approach to Textures and Natural Images Processing’ in January in Paris, France. He visited the Department of Statistics of Florida State University for a week in April, and gave an invited talk as part of the ‘Shape Day’ workshop organized at FSU. He gave a seminar at IITP in Moscow in November. He presented a paper at VISAPP in Barcelona in March. He took part in two ANR ‘Micro-Réseaux’ meetings. He gave a seminar organized by the Geometrica project-team at INRIA Sophia Antipolis. He took part in two meetings with CNES where he gave talks.
- Ian Jermyn gave an invited talk at CNES in Paris as part of the ORFEO Accompaniment Programme day in January. In March, he took part in a meeting with CNES, at which he gave a talk, and also gave a seminar to the INRIA APICS project-team. He visited the Department of Statistics of Florida State University for a week in April, and gave an invited talk as part of the ‘Shape Day’ workshop organized at FSU. Also in April, he gave a paper at URBAN in Paris. In May, he presented his work to a representative of the European Commission Joint Research Centre at INRIA Sophia Antipolis. In June, he attended a meeting of the CNES/DLR/ENST Centre of Competence in Paris. In July, he attended a meeting of ACI QuerySat in Paris, and gave a talk; he attended the Journée Pôle IMA-SIG-SYS and gave a talk; and he presented his work to the company CS. In August, he gave a paper at CAIP in Vienna. In September, he took part in a meeting with CNES in Toulouse, and gave a talk. In November, he visited the University of Szeged, Hungary for a week; he attended the COST GTRI Equipe Associées evaluation meeting in Paris; and he took part in a plenary meeting of the MUSCLE Network of Excellence, at which he gave a talk. In December, he took part in a meeting with the management of Total.
- Josiane Zerubia made presentations of the work of the Ariana project-team in January to Astrium/EADS and Infoterra France in Toulouse, and to the Director of the French Forest Inventory (IFN) in Sophia Antipolis. In May, she presented Ariana’s work to a representative of the European Commission Joint Research Centre in Sophia Antipolis and to the CEO of Noveltis in Toulouse. Also in May, she helped evaluate CNES as a member of the CERT, attended the GMES day organized by CNES in Toulouse, and presented Ariana’s work to the Director of ONERA in Salon de Provence in relation with the ‘Pôle de Compétitivité Pegase’. In June, she gave a seminar on risk management as part of INTECH day, and organized the Ariana Brain Storming meeting, which took place over three days in Sospel. In September, she presented Ariana’s work at CNES in Toulouse, and visited Sanofi Aventis and presented a paper at EUSIPCO, Poznan, Poland. In October, she organized a one-day international workshop on confocal and wide-field microscopy at the Hotel Mercure in Sophia Antipolis, as well as the P2R Franco-Israeli meeting on confocal and wide-field microscopy in Sophia Antipolis. In November, she presented Ariana’s work at Silogic in Toulouse and to the Rotary Club of Antibes Juan les Pins, visited Sanofi Aventis for a second time, and attended the MUSCLE EU Network of Excellence plenary meeting in Paris. In December, she organized the visit to the Ariana project-team of a Hungarian delegation from the University of Szeged and SZTAKI, and a delegation from Total management.

9.2. Refereeing

- C. Chaux was a reviewer for IEEE TCAS, IEEE TSP, and IEEE TIP.
- P. Pankajakshan was a reviewer for the SPIE journal on Optical Engineering.
- P. Weiss was a reviewer for SITIS’07.
- Laure Blanc-Féraud is a regular reviewer for the journals IEEE TIP and IJCV, and for the conferences Eusipco’07, EMBS’07, GRETSI’07. She is reviewer for the ANR (programme blanc and jeunes chercheurs), she was a referee for the Scientific Commission of the EPFL (Swiss Federal Institute of Technology, Lausanne) for awarding Doctoral Fellowships in Imaging Technology for Biology and Medicine. She is a member of the jury for the Ph.D. award of Club EEA, Signal and Image section. She is a member of the INRIA Committee in charge of assigning Ph.D. and postdoctoral grants (CORDI programme). She was a reviewer for one Ph.D. thesis and one HdR, and attended one Ph.D. defence.

- Xavier Descombes is a regular reviewer for the journals IEEE TIP, IEEE Medical Imaging, and IEEE TPAMI, and for IJCV. He was a reviewer for Gretsi'07, RFIA'07, ICCV'07 and CVPR'07. He is reviewer for the ANR (programme blanc and jeunes chercheurs). He was a reviewer for five Ph.D. theses and was on one Ph.D. committee. He is also an expert for the DDRT program on 'Jeunes Entreprises Innovantes'.
- Ian Jermyn was a regular reviewer for the IEEE TSP, IEEE TIP, and IEEE TPAMI, for the ISPRS Journal of Photogrammetry and Remote Sensing, and for the Journal of Mathematical Imaging and Vision. He was a reviewer for ECCOMAS'07, EUSIPCO'07, and ICIP'07. He was on two Ph.D. committees.
- Josiane Zerubia was a reviewer for four Ph.D. theses and one HdR, and a member of three Ph.D. committee. She was a reviewer for IJCV, and SFPT (Revue Française de Photogrammétrie et de Télédétection). She was a reviewer or a program committee member for ICASSP'07, ISBI'07, ICIP'07, SPIE-ISPRS'07 ('Image and Signal Processing for Remote Sensing'), ICCV'07, MICCAI'07, SISP'07, GRETSI'07, and TAIMA'07.

9.3. Organization

- Laure Blanc-Féraud was vice-director of the I3S Laboratory of CNRS and the University of Nice Sophia Antipolis until September. She is vice-director of the Gdr ISIS in charge of the imaging theme. She is a member of the GRETSI association and of its desk. She is a member of the scientific committee of the École Doctorale STIC of UNSA. She is a member of the organizing committee of the summer school Peyresq organized every year in July. She has organized four days of training on image processing for Sagem DS in Argenteuil in October. She is part of the ANR Scientific Committee for STIC ('Sciences et Technologies de l'Information et de la Communication').
- Xavier Descombes is a member of the scientific committee of the 'Pôle de compétitivité Optitec', and a member of the strategic committee of PopSud. He is also a member of the expert committee 'Multi' of CNRS. He is computer systems coordinator for the Ariana project. He was coordinator of the collaboration COLORS 'Flamants' between Ariana and the Sansouire Foundation ('Station Biologique de la Tour Valat'). He is the Ariana coordinator for the ACI 'QuerySat'.
- Ian Jermyn is a member of the Comité de Suivi Doctoral at INRIA Sophia Antipolis, and, since October, of the COST Groupe de Travail Relations Internationales of INRIA. He is co-computer systems coordinator for the Ariana project. He is the coordinator of the Ariana project-team's efforts within the EU Network of Excellence MUSCLE. He was a member of the program committees for EUSIPCO'07 and ECCOMAS'07.
- Josiane Zerubia is an IEEE Fellow. She is a member of the Biological Image and Signal Processing Technical Committee of the IEEE Signal Processing Society. She is an Associate Editor of the collection 'Foundation and Trends in Signal Processing' (http://www.nowpublishers.com/sig). She is a member of the Editorial Boards of IJCV and the Revue Française de Photogrammétrie et de Télédétection of SFPT. She is an Associate Editor of the electronic journal Earthzine [http://www.earthzine.org/]. She was a member of the organizing committee of the GEOSS workshop in Honolulu in April. She was a member of the CERT Committee, as one of 30 experts nominated by the Director of the French Space Agency (CNES) to evaluate the future research and development of CNES. She was a member of the evaluation boards for the Dutch Research Council (NWO), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Cosmo-Skymed program of the Italian Space Agency. She is principal investigator for the P2R Franco-Israeli collaborative programme. She is also principal investigator for the eleven current industrial contracts and grants of the Ariana project-team. She is a member of the ORFEO group (CNES) and of the 3D working group of CNES. She is a member of the scientific committee of TechforFood and participated in the organization of the TechforFood day at the 'Salon de l'Agriculture' in Paris in March. She is a consultant for Sanofi-Aventis Research in Toulouse.

9.4. Teaching

- Alexis Baudour was lab instructor for ‘Mathematics for digital images’ (64h), at the IUT of Nice Sophia Antipolis.
- Alexandre Fournier was an advisor for Image Processing projects (21h) at Poly’Tech Nice-Sophia Antipolis.
- Maria Kulikova was teaching assistant for the course ‘Games and Strategies’ (64h) at Poly’Tech Nice-Sophia Antipolis (UNSA).
- Florent Lafarge was course instructor for ‘Image processing’ (8h) at ENSG (Marne-La Vallée).
- Pierre Weiss was lab instructor for ‘Digital signal processing’ (32h), and for ‘Mathematics’ (40h) at Poly’Tech Nice-Sophia Antipolis (UNSA).
- Laure Blanc-Féraud taught at Sagem DS (6 hours) and at Poly’Tech Nice-Sophia Antipolis (6 hours).
- Xavier Descombes taught at Sup’Aero (20h), at Poly’Tech Nice-Sophia Antipolis (UNSA) (9h) and at SAGEM DS (6h).
- Ian Jermyn taught ‘Image analysis’ (6h) at Poly’Tech Nice-Sophia Antipolis (UNSA), and ‘Filtering and segmentation of space imagery’ (2.5h) at Sup’Aéro.
- Josiane Zerubia taught the module ‘MRF models in image processing’ for the Masters 2 course IGMMV at the University of Nice-Sophia Antipolis (3h). She was director of the course ‘Filtering and segmentation of space imagery’ at Sup’Aéro (40h, of which 20h taught), where she also taught as part of the course ‘Variational methods for image processing’ (2.5h). She also taught 3 hours at SAGEM DS.

9.5. PhDs

9.5.1. In progress

1. Alexis Baudour: ‘Segmentation and deconvolution of 3D images’, University of Nice-Sophia Antipolis. Defence expected in 2008.
2. Aymen El Ghoul: ‘Champs de Phase pour l’extraction de réseaux à partir d’images de télédétection’, University of Nice-Sophia Antipolis. Defence expected in 2010.
3. Alexandre Fournier: ’Détection de cibles par une analyse des perturbations de la texture’, École Nationale Supérieure de l’Aéronautique et de l’Éspace, Toulouse. Defence expected in 2008.
4. Maria S. Kulikova: ‘Reconnaissance de formes pour l’analyse de scènes’, University of Nice-Sophia Antipolis. Defence expected in 2009.
5. Praveen Pankajakshan: ‘Blind biological image deconvolution’, University of Nice-Sophia Antipolis. Defense expected in 2009.
6. Ting Peng: ‘Variational models for road network updating in dense urban areas from very high resolution optical images’, CASIA, Chinese Academy of Sciences, Beijing, China and University of Nice-Sophia Antipolis. Defence expected in 2008.
7. Pierre Weiss: ‘Multispectral image processing with PDEs’, University of Nice-Sophia Antipolis. Defence expected in 2008.
8. Olivier Zammit: ‘Forest fire damage assessment from satellite images’, University of Nice-Sophia Antipolis. Defence expected in 2008.

9.5.2. Defended in 2007

1. Avik Bhattacharya: ‘Indexing of satellite images with structural information’, École Nationale Supérieure des Télécommunications, Paris. Defended on December 14.

2. Peter Horvath: ‘The “gas of circles” model and its application to tree crown extraction’, University of Szeged, Hungary, and University of Nice-Sophia Antipolis. Defended on December 3.
3. Florent Lafarge: ’Modèles stochastiques pour la reconstruction d’environnements urbains’, École Nationale Supérieure des Mines, Paris. Defended on October 2.

10. Bibliography

Year Publications

Doctoral dissertations and Habilitation theses

[1] A. BHATTACHARYA. *Indexing of satellite images with structural informations*, Ph. D. Thesis, Ecole Nationale Supérieure des Télécommunications, Paris, dec 2007.

[2] P. HORVATH. *The ‘gas of circles’ model and its application to tree crown extraction*, Ph. D. Thesis, University of Nice-Sophia Antipolis, France and University of Szeged, Hungary, dec 2007.

[3] F. LAFARGE. *Modèles stochastiques pour la reconstruction tridimensionnelle d’environnements urbains*, Ph. D. Thesis, Ecole des Mines de Paris, oct 2007.

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