



Activity Report 2011

Team GALEN

Organ Modeling through Extraction,
Representation and Understanding of Medical
Image Content

RESEARCH CENTER
Saclay - Île-de-France

THEME
Computational Medicine and Neuro-
sciences

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Team GALEN

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2. Overall Objectives

2.1. GALEN@Ecole-Centrale

Computational vision is one of the most challenging research domains in engineering sciences. The aim is to reproduce human visual perception through intelligent processing of visual data. The application domains span from computer aided diagnosis to industrial automation & robotics. The most common mathematical formulation to address such a challenge is through mathematical modeling. In such a context, first the solution of the desired vision task is expressed in the form of a parameterized mathematical model. Given such a

model, the next task consists of associating the model parameters with the available observations, which is often called the model-to-data association. The aim of this task is to determine the impact of a parameter choice to the observations and eventually maximize/minimize the adequacy of these parameters with the visual observations. In simple words, the better the solution is, the better it will be able to express and fit the data. This is often achieved through the definition of an objective function on the parametric space of the model. Last, but not least given the definition of the objective function, visual perception is addressed through its optimization with respect to the model parameters. To summarize, computation visual perception involves three aspects, a task-specific definition of a parametric model, a data-specific association of this model with the available observations and last the optimization of the model parameters given the objective and the observations.

Such a chain processing inherits important shortcomings. The curse of dimensionality is often used to express the importance of the model complexity. In simple words, the higher the complexity of the model is, the better its expressive power will be with counter effect the increase of the difficulty of the inference process. Non-linearity is another issue to be addressed which simply states that the association between the model and the data is a (highly) non-linear function and therefore direct inference is almost infeasible. The impact of this aspect is enforced from the curse of non-convexity that characterizes the objective function. Often it lives in high-dimensional spaces and is ill posed making exact inference problematic (in many cases not possible) and computationally expensive. Last, but not least modularity and scalability is another important concern to be addressed in the context of computational vision. The use of task-specific modeling and algorithmic solutions make their portability infeasible and therefore transfer of knowledge from one task to another is not straightforward while the methods do not always scale well with respect either to the dimensionality of the representation or the data.

GALEN aims at proposing innovative techniques towards automatic structuring, interpretation and longitudinal modeling of visual data. In order to address these fundamental problems of computational perception, GALEN investigates the use of discrete models of varying complexity. These methods exhibit an important number of strengths such as their ability to be modular with respect to the input measurements (clinical data), the nature of the model (certain constraints are imposed from computational perspective in terms of the level of interactions), and the model-to-data association while being computationally efficient.

2.2. Highlights

- **ICCV Participation:** GALEN has participated in the 2011 International Conference in Computer Vision (ICCV'11) conference, the most selective conference in the field of computer vision and medical image analysis with five papers (acceptance rate %20).
- **CVPR Participation:** GALEN has participated in the 2011 annual IEEE Conference in Computer Vision and Pattern Recognition (CVPR'11) conference, the leading event in the field of computer vision and medical image analysis with five papers (double blind full submissions, acceptance rate %25) including one oral presentation (out of a 60).
- **MICCAI Participation:** GALEN has participated in the 2011 annual Medical Image Computing and Computer Assisted Intervention (MICCAI'11) conference one of the leading events in the field of medical image analysis with four (double blind full submissions, acceptance rate %30).
- **ISBI Participation:** GALEN has participated in the 2011 International Symposium of Biomedical Imaging (ISBI'11) conference, one of the notable events in the field of medical image analysis with four papers (acceptance rate %40) including three oral presentations.
- **IEEE Fellow & BMVC Plenary Speaker:** N. Paragios was promoted to the IEEE Fellow grade and was one of the plenary speakers of the 22nd edition of the British Machine Vision Conference.

3. Scientific Foundations

3.1. Discrete Computational Perception

A wide variety of tasks in medical image analysis can be formulated as discrete labeling problems. In very simple terms, a discrete optimization problem can be stated as follows: we are given a discrete set of variables \mathcal{V} , all of which are vertices in a graph \mathcal{G} . The edges of this graph (denoted by \mathcal{E}) encode the variables' relationships. We are also given as input a discrete set of labels \mathcal{L} . We must then assign one label from \mathcal{L} to each variable in \mathcal{V} . However, each time we choose to assign a label, say, x_{p_1} to a variable p_1 , we are forced to pay a price according to the so-called *singleton* potential function $g_p(x_p)$, while each time we choose to assign a pair of labels, say, x_{p_1} and x_{p_2} to two interrelated variables p_1 and p_2 (two nodes that are connected by an edge in the graph \mathcal{G}), we are also forced to pay another price, which is now determined by the so called *pairwise* potential function $f_{p_1 p_2}(x_{p_1}, x_{p_2})$. Both the singleton and pairwise potential functions are problem specific and are thus assumed to be provided as input.

Our goal is then to choose a labeling which will allow us to pay the smallest total price. In other words, based on what we have mentioned above, we want to choose a labeling that minimizes the sum of all the MRF potentials, or equivalently the MRF energy. This amounts to solving the following optimization problem:

$$\arg \min_{\{x_p\}} \mathcal{P}(g, f) = \sum_{p \in \mathcal{V}} g_p(x_p) + \sum_{(p_1, p_2) \in \mathcal{E}} f_{p_1 p_2}(x_{p_1}, x_{p_2}). \quad (1)$$

The use of such a model can describe a number of challenging problems in medical image analysis. However these simplistic models can only account for simple interactions between variables, a rather constrained scenario for high-level medical imaging perception tasks. One can augment the expression power of this model through higher order interactions between variables, or a number of cliques $\{C_i, i \in [1, n] = \{p_{i^1}, \dots, p_{i^{|C_i|}}\}\}$ of order $|C_i|$ that will augment the definition of \mathcal{V} and will introduce hyper-vertices:

$$\arg \min_{\{x_p\}} \mathcal{P}(g, f) = \sum_{p \in \mathcal{V}} g_p(x_p) + \sum_{(p_1, p_2) \in \mathcal{E}} f_{p_1 p_2}(x_{p_1}, x_{p_2}) + \sum_{C_i \in \mathcal{E}} f_{p_1 \dots p_n}(x_{p_{i^1}}, \dots, p_{x_{i^{|C_i|}}}). \quad (2)$$

where $f_{p_1 \dots p_n}$ is the price to pay for associating the labels $(x_{p_{i^1}}, \dots, p_{x_{i^{|C_i|}}})$ to the nodes $(p_1 \dots p_{i^{|C_i|}})$. Parameter inference, addressed by minimizing the problem above, is the most critical aspect in computational medicine and efficient optimization algorithms are to be evaluated both in terms of computational complexity as well as of inference performance. State of the art methods include deterministic and non-deterministic annealing, genetic algorithms, max-flow/min-cut techniques and relaxation. These methods offer certain strengths while exhibiting certain limitations, mostly related to the amount of interactions which can be tolerated among neighborhood nodes. In the area of medical imaging where domain knowledge is quite strong, one would expect that such interactions should be enforced at the largest scale possible.

3.2. Machine Learning & Structure Prediction

The foundation of statistical inference is to learn a function that minimizes the expected loss of a prediction with respect to some unknown distribution

$$\mathcal{R}(f) = \int \ell(f, x, y) dP(x, y), \quad (3)$$

where $\ell(f, x, y)$ is a problem specific loss function that encodes a penalty for predicting $f(x)$ when the correct prediction is y . In our case, we consider x to be a medical image, and y to be some prediction, e.g. the segmentation of a tumor, or a kinematic model of the skeleton. The loss function, ℓ , is informed by the costs associated with making a specific misprediction. As a concrete example, if the true spatial extent of a tumor is encoded in y , $f(x)$ may make mistakes in classifying healthy tissue as a tumor, and mistakes in classifying diseased tissue as healthy. The loss function should encode the potential physiological damage resulting from erroneously targeting healthy tissue for irradiation, as well as the risk from missing a portion of the tumor.

A key problem is that the distribution P is unknown, and any algorithm that is to estimate f from labeled training examples must additionally make an implicit estimate of P . A central technology of empirical inference is to approximate $\mathcal{R}(f)$ with the empirical risk,

$$\mathcal{R}(f) \approx \widehat{\mathcal{R}}(f) = \frac{1}{n} \sum_{i=1}^n \ell(f, x_i, y_i), \quad (4)$$

which makes an implicit assumption that the training samples (x_i, y_i) are drawn i.i.d. from P . Direct minimization of $\widehat{\mathcal{R}}(f)$ leads to overfitting when the function class $f \in \mathcal{F}$ is too rich, and regularization is required:

$$\min_{f \in \mathcal{F}} \lambda \Omega(\|f\|) + \widehat{\mathcal{R}}(f), \quad (5)$$

where Ω is a monotonically increasing function that penalizes complex functions.

Equation (5) is very well studied in classical statistics for the case that the output, $y \in \mathcal{Y}$, is a binary or scalar prediction, but this is not the case in most medical imaging prediction tasks of interest. Instead, complex interdependencies in the output space leads to difficulties in modeling inference as a binary prediction problem. One may attempt to model e.g. tumor segmentation as a series of binary predictions at each voxel in a medical image, but this violates the i.i.d. sampling assumption implicit in Equation (4). Furthermore, we typically gain performance by appropriately modeling the inter-relationships between voxel predictions, e.g. by incorporating pairwise and higher order potentials that encode prior knowledge about the problem domain. It is in this context that we develop statistical methods appropriate to structured prediction in the medical imaging setting.

3.3. Self-Paced Learning with Missing Information

Many tasks in artificial intelligence are solved by building a model whose parameters encode the prior domain knowledge and the likelihood of the observed data. In order to use such models in practice, we need to estimate its parameters automatically using training data. The most prevalent paradigm of parameter estimation is supervised learning, which requires the collection of the inputs x_i and the desired outputs y_i . However, such an approach has two main disadvantages. First, obtaining the ground-truth annotation of high-level applications, such as a tight bounding box around all the objects present in an image, is often expensive. This prohibits the use of a large training dataset, which is essential for learning the existing complex models. Second, in many applications, particularly in the field of medical image analysis, obtaining the ground-truth annotation may not be feasible. For example, even the experts may disagree on the correct segmentation of a microscopical image due to the similarities between the appearance of the foreground and background.

In order to address the deficiencies of supervised learning, researchers have started to focus on the problem of parameter estimation with data that contains hidden variables. The hidden variables model the missing information in the annotations. Obtaining such data is practically more feasible: image-level labels ('contains car', 'does not contain person') instead of tight bounding boxes; partial segmentation of medical images. Formally, the parameters \mathbf{w} of the model are learned by minimizing the following objective:

$$\min_{\mathbf{w} \in \mathcal{W}} R(\mathbf{w}) + \sum_{i=1}^n \Delta(y_i, y_i(\mathbf{w}), h_i(\mathbf{w})). \quad (6)$$

Here, \mathcal{W} represents the space of all parameters, n is the number of training samples, $R(\cdot)$ is a regularization function, and $\Delta(\cdot)$ is a measure of the difference between the ground-truth output y_i and the predicted output and hidden variable pair $(y_i(\mathbf{w}), h_i(\mathbf{w}))$.

Previous attempts at minimizing the above objective function treat all the training samples equally. This is in stark contrast to how a child learns: first focus on easy samples (‘learn to add two natural numbers’) before moving on to more complex samples (‘learn to add two complex numbers’). In our work, we capture this intuition using a novel, iterative algorithm called self-paced learning (SPL). At an iteration t , SPL minimizes the following objective function:

$$\min_{\mathbf{w} \in \mathcal{W}, \mathbf{v} \in \{0,1\}^n} R(\mathbf{w}) + \sum_{i=1}^n v_i \Delta(y_i, y_i(\mathbf{w}), h_i(\mathbf{w})) - \mu_t \sum_{i=1}^n v_i. \quad (7)$$

Here, samples with $v_i = 0$ are discarded during the iteration t , since the corresponding loss is multiplied by 0. The term μ_t is a threshold that governs how many samples are discarded. It is annealed at each iteration, allowing the learner to estimate the parameters using more and more samples, until all samples are used. Our results already demonstrate that SPL estimates accurate parameters for various applications such as image classification, discriminative motif finding, handwritten digit recognition and semantic segmentation. We will investigate the use of SPL to estimate the parameters of the models of medical imaging applications, such as segmentation and registration, that are being developed in the GALEN team. The ability to handle missing information is extremely important in this domain due to the similarities between foreground and background appearances (which results in ambiguities in annotations). We will also develop methods that are capable of minimizing more general loss functions that depend on the (unknown) value of the hidden variables, that is,

$$\min_{\mathbf{w} \in \mathcal{W}, \theta \in \Theta} R(\mathbf{w}) + \sum_{i=1}^n \sum_{h_i \in \mathcal{H}} \Pr(h_i | x_i, y_i; \theta) \Delta(y_i, h_i, y_i(\mathbf{w}), h_i(\mathbf{w})). \quad (8)$$

Here, θ is the parameter vector of the distribution of the hidden variables h_i given the input x_i and output y_i , and needs to be estimated together with the model parameters \mathbf{w} . The use of a more general loss function will allow us to better exploit the freely available data with missing information. For example, consider the case where y_i is a binary indicator for the presence of a type of cell in a microscopical image, and h_i is a tight bounding box around the cell. While the loss function $\Delta(y_i, y_i(\mathbf{w}), h_i(\mathbf{w}))$ can be used to learn to classify an image as containing a particular cell or not, the more general loss function $\Delta(y_i, h_i, y_i(\mathbf{w}), h_i(\mathbf{w}))$ can be used to learn to detect the cell as well (since h_i models its location).

4. Application Domains

4.1. Application Domains

- **Large Scale Urban Modeling:** The use of satellite imaging along with range data towards large scale image-driven reconstruction. The aim is to produce scalable representations of 3D models that are compact, modular and able to provide realistic 3D representations of real visual data.
- **Objet Recognition:** The use annotated data-bases towards learning class-specific visual and geometric object characteristics to perform recognition.
- **MR & Muscular Diseases:** The use of MR and Diffusion Tensor Imaging are investigated in collaboration with the Henri Mondor University Hospital and Institut of Myology towards automatic quantification of muscular mass loss and non-invasive biopsy. The aim is to provide tools that could be used to automatically analyze MR imaging and extract useful clinical measurements (Insitut of Myology), and assess the potential impact of diffusion tensor imaging towards automatic quantification either of muscular diseases progression.
- **MR Brain Imaging towards Low-Gliomas Tumor Brain Understanding:** The use of contrast enhanced imaging is investigated in collaboration with the Montpellier University Hospital towards better understanding of low-gliomas positioning, automatic tumor segmentation/identification and longitudinal (tumor) growth modeling.

5. Software

5.1. Deformable Registration Software

Participants: Nikos Paragios [Correspondant], Ben Glocker, Aristeidis Sotiras, Nikos Komodakis.

DROP is a deformable registration platform in C++ for the medical imaging community (publicly available at <http://www.mrf-registration.net>) developed mainly at Ecole Centrale, Technical University of Munich and University of Crete. This is the first publicly available platform which contains most of the existing metrics to perform registration under the same concept. The platform is used for clinical research from approximately 3,000 users worldwide.

5.2. Fast Primal Dual Strategies for Optimization of Markov Random Fields

Participants: Nikos Komodakis [Correspondant], Nikos Paragios, George Tziritas.

FASTPD is an optimization platform in C++ for the computer vision and medical imaging community (publicly available at <http://www.csd.uoc.gr/~komod/FastPD/>) developed mainly at Ecole Centrale and University of Crete. This is the most efficient publicly available platform in terms of a compromise of computational efficiency and ability to converge to a good minimum for the optimization of generic MRFs. The platform is used from approximately 1,500 users worldwide.

5.3. imaGe-based Procedural Modeling Using Shape Grammars

Participants: Olivier Teboul [Correspondant], Iasonas Kokkinos, Panagiotis Koutsourakis, Loic Simon, Nikos Paragios.

GRAPES is a generic image parsing library based on re-inforcement learning. It can handle grammars (binary-split, four-color, Hausmannian) and image-based rewards (Gaussian mixtures, Randomized Forests) of varying complexity while being modular and computationally efficient both in terms of grammar and image rewards. The platform is used from approximately 500 users worldwide.

5.4. Texture Analysis Using Modulation Features and Generative Models

Participants: Iasonas Kokkinos [Correspondant], Georgios Evangelopoulos.

TEXMEG is a front-end for texture analysis and edge detection platform in Matlab that relies on Gabor filtering and image demodulation (publicly available at <http://cvsp.cs.ntua.gr/software/texture/>). Includes frequency- and time- based definition of Gabor- and other Quadrature-pair filterbanks, demodulation with the Regularized Energy Separation Algorithm and Texture/Edge/Smooth classification based on MDL criterion. The platform is used from approximately 250 users worldwide.

6. New Results

6.1. Reconstruction

Participants: Panagiotis Koutsourakis, Helene Langet, Loic Simon, Olivier Teboul, Gilles Fleury, Elisabeth Lahalle, Yves Troussset, Cyril Riddell, Nikos Paragios.

- **Image-based Procedural Modeling of Urban environments:** In [20] we develop a multiple hypotheses testing algorithm for image-based/grammar-driven building modeling. Shape grammars are used to express the variation of the observed architecture. Such a model is coupled with the observations through a maximum likelihood principle where the aim is to maximize the posterior segmentation probability in the image plane given the partition being determined from the grammar derivation. The unknown parameters of the process involve the grammar derivation tree and the associated parameters. Such a mixed continuous/discrete problem is solved through a hill climbing approach that involves joint perturbations in the derivation and parameter space. Promising results demonstrated the potentials of such a formulation for complex Parisian architectures. This idea was further extended in [40] where reinforcement learning was used as optimization principle. 2D Image-based grammar parsing was expressed as a Markov decision process where an agent ought to take actions in an environment so as to maximize some notion of cumulative reward. Performance in particular computational gain over [20] demonstrated the extreme potentials of such a formulation. In order to cope with multi-view geometry, the grammar was further derived to include 3D components and the optimization process was amended to deal with multiple views. An evolutionary computation process (based on consistent mutation and recombination of partial grammar trees) was proposed to fuse image and depth-based information. The use of the Pareto frontier between the two concurrent components of the objective function provides a principle way to determine the optimal solution of the designed objective function.
- **Compressed Sensing Digital Subtraction Rotational Angiography:** in [39] we develop an extension of iterative filtered backprojection method for reconstruction of three-dimensional vascular structures from two spins. Our contribution refers to an approach that improves the reconstruction quality of non-sparse volumes when there exists a sparse combination of these volumes. This is achieved through a joint reconstruction of the mask and contrast volumes via $\ell_1 - \ell_1$ -minimization of sparse priors. These ideas were further explored to address three-dimensional reconstruction in interventional radiology in [30] through a regularized extension of the iterative filtered backprojection algorithm. To this end the conventional TV-norm was replaced from a new sparsity constraint that relies on the $\ell_1 - \ell_1$ -minimization-norm and the positivity constraint. The use of such a constraint allows for removing most of the subsampling artifacts while preserving background structures.

6.2. Matching/Segmentation

Participants: Haithem Boussaid, Iasonas Kokkinos, Chaohui Wang, Bo Xiang, Ahmet Besbes, Ben Glocker, Nikos Komodakis, Nikos Paragios.

- **Rapid Deformable Part Model Detection:** in [27] we introduce a Branch-and-Bound technique which efficiently finds the most promising configuration of a pictorial structure model given an image. The fastest previously known techniques are linear in the image size; our technique has a best-case complexity that is logarithmic in the image size. When evaluated on standard datasets (Pascal benchmark) our technique gives a 5- to 15-fold speedup. Moreover, when evaluated in the multi-object detection problem our technique's complexity scales sublinearly also in the number of objects, resulting in 20- to 100- fold speedups when evaluated with 20 object categories.
- **Segmentation with Deformable Graph-based Priors:** in [22] we have introduced a novel formulation to address deformable segmentation using graph-based priors while being able to handle partial-correspondences. Segmentation was formulated as a matching task, where candidate correspondences were determined using boosting, and the assignment problem was solved using MAP inference constrained by a graph-based deformable prior. The notion of missing/erroneous correspondences was introduced in the process leading to state-of-the art results once compared with prior art in the field. The same prior was used in the context of the segmentation of tagging MR heart images [37]. The main contribution of this paper was the exact estimation of the region-based probability likelihood within a pair-wise MRF through the use of Stokes theorem and integral images.

- **Deformable Model-based 3D reconstruction:** in [23] we introduce a model-based optimization approach to the 3D reconstruction of Femur images using a small set of low-dose X-Ray images. We use a parametric deformable model of the Femur surface and fit it to the acquired data by optimizing its parameters. We incorporate in our optimization criterion multiple aspects of the problem, namely the 3D surface- to 2D plane projection, region-based statistics, and edge-based terms. Our evaluation includes both in vitro and in vivo experiments, where our method is shown to yield promising results, while alleviating the need for time demanding, manual annotations.
- **Pose-invariant Higher Order Graph-based Priors:** in [36] we have introduced a novel method for 3D model inference from 2D images in the absence of camera pose parameters. The method exploits higher (fourth) order priors, which alleviate the need of the estimation of the camera parameters. Furthermore, the proposed formulation couples 3D model inference with 2D correspondences and results on a single shot solution for both problems in the absence of knowledge of the observer internal and external parameters.

6.3. Fusion/Registration

Participants: Stavros Alchatzidis, Nicolas Honnorat, Fabrice Michel, Aristeidis Sotiras, Chaohui Wang, Alex Bronstein, Michael Bronstein, Christos Davatzikos, Ben Glocker, Nikos Komodakis, Yangming Ou, Dimitris Samaras, Regis Vaillant, Yun Zeng, Nikos Paragios.

- **Intrinsic Dense 3D Surface Matching:** in [38] a probabilistic tracking framework for registering two 3D shape that relies on accurate correspondences between all points across the two frames was proposed. The definition of the matching cost is done using the "uniformization" theory that is combined with regularization terms that enforce spatial and temporal motion consistencies, into a maximum a posteriori (MAP) problem which we approximate using a Markov Random Field (MRF).
- **Optimal Linear Registration:** in [26] we proposed a novel formulation to address linear registration of volumetric images (translation, rotation and scale) that guarantees the optimality of the obtained solution. This was achieved through the approximation of the volumetric data using a sparse representation and the expression of the registration criterion in the form of a difference of convex functions. Cutting plain algorithms in the high-dimensional space were used to provide the optimal solution of the registration problem.
- **Quasi-real Time Registration:** in [21] we proposed a novel message-passing based optimization method to for pair-wise Markov Random Fields models and their applications in medical imaging and computer vision. Such a method was integrated to the deformable registration paradigm introduced in [12]. Such an optimization framework was combined with efficient use of modern architectures (Graphics Processing Units) leading to a speed up of at least one order of magnitude with respect to [12] making quasi-time deformable registration feasible.
- **Metric Learning:** in [31] we extend prior work on similarity sensitive hashing to address multimodal 3D registration. The method consists of combining invariant to translation/rotation/scale features defined at the Gabor space with a machine learning/boosting method that aims to projection corresponding visual patterns to binary vectors with minimal Hamming distance while maximizing the distance between no corresponding samples.
- **Symmetric Deformable Fusion:** in [9] a novel graph-based formulation combining image and geometric terms was proposed for deformable registration. The method aimed at constraining iconic registration using a set of landmark correspondences that are sparse, do not inherit redundancy and are symmetric. The central idea was to simultaneously deform the target and the source image using two symmetric flows such that the similarity criterion is reaching its lowest potential. This was achieved through the use of composite symmetric deformation fields. This formulation was expressed as a graph-based optimization problem leading to promising experimental results.

- **Deformable registration of gene expression data:** in [28] the combined iconic/geometric registration framework introduced in [9] was extended to deal with gene expression data. Similarity Sensitive Hashing was used to establish costs for landmark correspondences, and a graph-based formulations with unknowns the deformation vectors was adopted for the objective function. Such an idea was extended to deal with combined segmentation/registration approach through an atlas in [29] where subdivision surfaces were considered to represent the deformation grid.

6.4. Physiological Modeling & Spatio-Temporal Analysis

Participants: Nicolas Honnorat, Sarah Parisot, Stephane Chemouny, Hugues Dufaut, Regis Vaillant, Nikos Paragios.

- **Low Gliomas Brain Map:** in [33] we introduce a graph-based modeling approach towards spatial position interpretation of low gliomas brain tumors. This was achieved through unsupervised clustering from exemplars, where spatial and geometric proximity of tumors were used to determine the strength connectivity of a graph. Towards automatic estimation of the lowest rank graph that is able to express the observed variation of tumors, an LP problem was solved that determines automatically the number of clusters and their centers while associating the training exemplars with them. Promising results that are well aligned with observations from neuro-sciences demonstrate the potentials of the proposed formulation.
- **Coupled Iconic/Geometric Spatio-temporal Segmentation:** in [25] we have introduced a combined elongated structures segmentation/tracking approach that was based on a two-layer graphical model. The image layer was exploiting the visual space and was seeking to minimize a data-driven cost while the geometric layers was seeking to establish temporal correspondences of the deforming structure. These two layers were coupled through a common set of variables acting on the deformation of the control points representing the elongated structure. Guide-wire segmentation [24] and tracking in low signal-to-noise ratio interventional images demonstrated the extreme potentials of our approach.

7. Contracts and Grants with Industry

7.1. Contracts with Industry

- **Intrasene:** spatio-temporal modeling of low gliomas brain tumors [PhD thesis S. Parisot: 2010-2013]
- **General Electric HealthCare**
 - Compressed Sensing Digital Subtraction Rotational Angiography [PhD thesis H. Langet: 2009-2012]
 - Guide-wire Segmentation and Tracking of in interventional Imaging [PhD thesis N. Honnorat: 2008-2011]
- **Microsoft:** Image-based Procedural Modeling of Large Scale Urban Environments [PhD thesis O. Teboul: 2008-2011]
- **Siemens:** Muscle Segmentation in MR Imaging [PhD thesis P-Y. Baudin: 2009-2012]

8. Partnerships and Cooperations

8.1. Regional Initiatives

- **SubSample:** A chair proposal was submitted to DIGITEO in collaboration with the PARIETAL group (B. Thirion) from Pr. Dimitris Samaras (StonyBrook) aiming understanding correlations between imaging and gene expressions data. The proposal was accepted and Pr. Samaras will be spending for the next four years, three months per year at Ecole Centrale. In parallel a PhD student will be co-supervised between B. Thirion and D. Samaras.
- **sterEOS+:** MEDICEN excellence cluster supported a regional initiative towards the creation of the new generation clinical orthopedic work-station. This was a collaborative project consisting of EOS-Imaging (hardware provide/low dose X-ray Imaging), Global Imaging on Line (software provider - Picture archiving and communication system), the Arts et Métiers ParisTech (image-based biomechanical modeling), the GALEN group (medical image processing) and the leading clinical and university hospitals in the greater Paris area
- **ADOC:** MEDICEN excellence cluster supported a regional initiative towards an imaging scanner providing guided diagnosis for cancer surgery. This translational research project will be conducted in collaboration between public partners (Inria, The Curie Institut and Hopital Tenon) and private companies (LLtech, Intrasure). A new imaging scanner allowing real time digital histology will be developed to assist the surgeon. The digital images will be used to give an indication to the surgeon, after a pathologist' validation, on whether the surgical procedure shall be continued or stopped.

8.2. European Initiatives

8.2.1. Collaborations in European Programs, except FP7

Program: European Research Council

Project acronym: DIOCLES

Project title: Discrete bIOimaging perCeption for Longitudinal Organ modEling and computEr-aided diagnosis

Duration: mois année début - mois année fin 9/2011-8/2016

Coordinator: N. Paragios

Abstract: Recent hardware developments from the medical device manufacturers have made possible non-invasive/in-vivo acquisition of anatomical and physiological measurements. One can cite numerous emerging modalities (e.g. PET, fMRI, DTI). The nature (3D/multi-phase/vectorial) and the volume of this data make impossible in practice their interpretation from humans. On the other hand, these modalities can be used for early screening, therapeutic strategies evaluation as well as evaluating bio-markers for drugs development. Despite enormous progress made on the field of biomedical image analysis still a huge gap exists between clinical research and clinical use. The aim of this proposal is three-fold. First we would like to introduce a novel biomedical image perception framework for clinical use towards disease screening and drug evaluation. Such a framework is expected to be modular (can be used in various clinical settings), computationally efficient (would not require specialized hardware), and can provide a quantitative and qualitative anatomo-pathological indices. Second, leverage progress made on the field of machine learning along with novel, efficient, compact representation of measurements toward computer aided diagnosis. Last, using these emerging multi-dimensional signals, we would like to perform longitudinal modeling and understanding the effects of aging to a number of organs and diseases that do not present pre-disease indicators such as brain neurological diseases, muscular diseases, certain forms of cancer, etc. Such a challenging and pioneering effort lies on the interface of medicine (clinical context), biomedical imaging (choice of signals/modalities), machine learning (manifold representations of heterogeneous multivariate variables), discrete optimization (computationally efficient inference of higher-order models), and biomedical image inference (measurements extraction and multi-modal data fusion of heterogeneous information sources). The expected results of such an approach are societal and scientific. The societal impact can be tremendous since we aim to provide novel means of using emerging biomedical

signals to help physicians diagnose, select, customize and follow up therapeutic strategies for life-threatening diseases. Concerning scientific impact, this framework could influence and introduce novel means of re-thinking old, unsolved problems in a number of areas such as bioinformatics, geometric modeling, robotics, computer vision, multimedia, etc.

8.2.2. Major European Organizations with which you have followed Collaborations

Partner 1: Technical University of Munich, Chair for Computer Aided Medical Procedures & Augmented Reality - Computer Science Department (Germany)

Mono and Multi-modal image fusion using discrete optimization and efficient linear programming.

Partner 2: University of Crete, Computer Vision Group - Computer Science Department, (Greece)

Linear Programming, relaxations and efficient optimization of pair-wise and higher order Markov Random Fields.

Partner 3: Eidgenössische Technische Hochschule (ETH) - Zürich, Seminar für angewandte Mathematik - Mathematics Department, (Switzerland)

Sparse Representations and Optimal Linear Registration of Volumetric Medical Image Data.

8.3. International Initiatives

8.3.1. INRIA Associate Teams

Galen Team along with the Machine Learning Group (DAGS) of the Computer Science Department of Stanford University have proposed the creation of the SPLENDID — Self-Paced Learning for Exploiting Noisy, Diverse or Incomplete Data associate team. The proposal was among the ones accepted in the 2011 INRIA campaign.

8.3.2. INRIA International Partners

- **Department of Diagnostic Radiology, University of Pennsylvania:** The GALEN and the Section of Biomedical Image Analysis - SBIA group (Pr. C. Davatzikos) have an established collaboration during the past three years in the area of deformable image fusion. In this context, PhD candidates of the GALEN group spend time visiting the SBIA group, while Pr. Paragios participates at a National Institute Health grant led by SBIA. Such a collaboration led to a number of outstanding rank journal and conference publications [19].
- **Department of Computer Science, Stony Brook, State University of New York:** The GALEN and the Image Analysis Lab - CBL (Pr. D. Samaras) have an established collaboration during the past three years in the area of graph-based methods in medical imaging and computer vision. Pr. Samaras holds a research professor position (DIGITEO chair) at Ecole Centrale de Paris. Such a collaboration led to a number of outstanding rank conference publications during the last year [38], [32].
- **Department of Computer Science, University of Houston:** The GALEN and the Computational Biomedicine Lab - CBL (Pr. I. Kakadiaris) have an established collaboration during the past three years in the area of medical image segmentation and gene expressions imaging processing. Pr. Paragios holds a research professor position at the Computer Science Department of the University of Houston. Such a collaboration led to a number of outstanding rank conference publications [19] during the last year [36], [28].
- **Chang Gung Memorial Hospital – Linkou, Taiwan:** In the context of France-Taiwan program sponsored from the French Science Foundation, GALEN (in collaboration with the department of radiology of Henri Mondor University Hospital), a project (ADAMANTIUS) was initiated with the Chang Gung Memorial Hospital – Linkou that is the largest private hospital in Taiwan. The aim of the project is to study the Automatic Detection And characterization of residual Masses in pAtients with lymphomas through fusioN of whole-body diffusion-weighted mri on 3T and 18F-flUorodeoxyglucoSe pet/ct.

8.3.3. Visits of International Scientists

- **Rafeef Abugharbieh:** Jan-Jun. 2011, University of British Columbia - CA.
- **Ghassan Hamarneh:** Jan-Jun. 2011, Simon Fraser University - CA.
- **Dimitris Samaras:** Oct. 2011, State University of New York - StonyBrook, US.

8.3.3.1. Internship

- **Avinash Singh Bagri:** Indian Institute of Technology - New Delhi, IN - Message Passing Methods on Graphics Processing Units towards Real-time Deformable Image Fusion .
- **Krishna Nand Keshava Murthy:** University of British Columbia, CA - Iconic/Geometric Deformable Registration of Diffusion Tensor Images.
- **Thanos Papadopoulos:** Technical University of Athens, GR - Iconic/Geometric Atlas-based Segmentation of Liver Volumetric Images.
- **Jose Carlos Rubio:** Universitat Autònoma de Barcelona, ES - HyperGraph Representations and Matching towards Scene Understanding.
- **Stavros Tsogkas:** Technical University of Athens, GR - Learning-based Symmetry Detection.

9. Dissemination

9.1. Animation of the scientific community

- **Matthew Blaschko**
 - **Guest Editorships:** International Journal of Computer Vision: Special Issue on Structured Prediction and Inference
 - **Conference Committee:** IEEE International Conference on Computer Vision, IEEE Computer Vision and Pattern Recognition, Artificial Intelligence and Statistics (area chair), Neural Information Processing Systems, Robotics: Science and Systems, International Conference on Robotics and Automation
 - **Workshop & Tutorials Organization:** British Machine Vision Conference Tutorial on Structured Prediction, Twentieth Annual Computational Neuroscience Meeting CNS*2011 Tutorial on Machine Learning and Kernel Methods
 - **Journal Reviewing Services:** IEEE Transactions on Pattern Analysis and Machine Intelligence, Journal of Machine Learning Research, PLoS ONE.
 - **Invited Seminars/Presentations:** Max Planck Institutes, Tübingen; Royal Academy of Engineering; Gatsby Computational Neuroscience Unit, University College London; University of Sheffield; Radboud Universiteit Nijmegen; University of Birmingham; Toyota Technological Institute at Chicago; University of Illinois at Chicago; Winter Intelligence Conference, Future of Humanity Institute, University of Oxford
 - **Distinctions:** Newton International Fellow, Best Reviewer Award IEEE International Conference on Computer Vision.
- **Iasonas Kokkinos**
 - **Editorial Activities:** Image and Vision Computing Journal.
 - **Conference Committee:** IEEE International Conference on Computer Vision, IEEE Computer Vision and Pattern Recognition, Artificial Intelligence and Statistics, IEEE Workshop in Stochastic Image Grammars Workshop, Energy Minimization Methods in Computer Vision and Pattern Recognition.

- **Journal Reviewing Services:** IEEE Transactions on Pattern Analysis and Machine Intelligence, IEEE Transactions on Image Processing, IEEE Transactions on Systems Man and Cybernetics, Part B., Computer Vision and Image Understanding.
 - **PhD Committee Participation:** Olivier Teboul - Ecole Centrale de Paris - FR.
 - **Master Committee Participation:** Stavros Tsogkas - National Technical University of Athens -GR.
 - **Invited Seminars/Presentations:** Symmetry Detection in Real World Images Workshop, in conjunction with the IEEE Conference in Computer Vision and Pattern Recognition - US, Visual Geometry Group, Oxford University - UK, Visual Computing Lunch, ETH Zurich - CH, Computer Science Department, Università della Svizzera Italiana - CH.
- **Pawan Kumar**
 - **Conference Committee:** IEEE Conference on Computer Vision and Pattern Recognition, IEEE International Conference on Computer Vision, International Conference on Machine Learning, Advances in Neural Information Processing Systems.
 - **Journal Reviewing Services:** IEEE Transactions on Pattern Analysis and Machine Intelligence, Journal of Machine Learning Research.
 - **Workshop & Tutorials Organization:** IEEE International Conference in Computer Vision tutorial on *Learning with Inference for Discrete Graphical Models*, IEEE Computer Vision and Pattern Recognition Workshop on *Inference in Graphical Models with Structured Potentials*.
 - **Invited Seminars/Presentations:** Mysore Park Workshop on Computer Vision - IN, Ecole Normale Supérieure - FR, Ecole Centrale de Paris - FR, Kungliga Techniska Hogskolan, SE.
 - **Distinctions:** Best Reviewer Award, IEEE Conference in Computer Vision and Pattern Recognition.
 - **Nikos Paragios**
 - **Editorial Activities:** IEEE Transactions on Pattern Analysis and Machine Intelligence, International Journal of Computer Vision, Medical Image Analysis, Computer Vision and Image Understanding, Image and Vision Computing Journal, Machine Vision and Applications, SIAM Journal in Imaging Sciences.
 - **Guest Editorships:** Computer Vision and Image Understanding, Image and Vision Computing Journal, Special issue on Optimization for vision, graphics and medical imaging: Theory and applications [15].
 - **Conference Committee:** IEEE International Conference in Computer Vision, IEEE Computer Vision and Pattern Recognition, Medical Image Computing and Computer Assisted Intervention (area chair), Information Processing in Medical Imaging, IEEE International Symposium on Biomedical Imaging, IEEE Mathematical Methods in Biomedical Image Analysis, International Symposium on Visual Computing.
 - **Workshop & Tutorials Organization:** IEEE International Conference in Computer Vision tutorial on *Learning with Inference for Discrete Graphical Models*.
 - **Journal Reviewing Services:** IEEE Transactions on Image Processing.
 - **PhD Committee Participation:** Daniel Pescia - Ecole Centrale de Paris - FR, Yangming Ou - University of Pennsylvania - US, Olivier Teboul - Ecole Centrale de Paris - FR, Benjamin Glocker - Technical University of Munich - DE, Loic Simon - Ecole Centrale de Paris - FR, Chaohui Wang - Ecole Centrale de Paris - FR, Maélène Lohezic - University of Nancy - FR, Aristeidis Sotiras - Ecole Centrale de Paris - FR, Hiep Hoang Vu - Ecole des Ponts-ParisTech - FR, Christophe Avenel - Univeristy of Rennes - FR.

- **Invited Seminars/Presentations:** British Machine Vision Conference - UK, Isaac Newton Institute for Mathematical Sciences, Analytic and Geometric Methods in Medical Imaging - UK.
- **Distinctions:** IEEE Fellow.

9.2. Teaching

Participants: Nikos Paragios, Iasonas Kokkinos.

Master : Introduction to Signal Processing, 36, M1, Ecole Centrale de Paris, France [I. Kokkinos]

Master : Introduction to Computer Vision, 36, M1, Ecole Centrale de Paris, France [I. Kokkinos]

Master : Pattern Recognition, 24, M2, Ecole Centrale de Paris/Ecole Normale Supérieure-Cachan, France [I. Kokkinos]

Master : Advanced Mathematical Models in Computer Vision, 24, M2, Ecole Centrale de Paris/Ecole Normale Supérieure-Cachan, France [N. Paragios]

N. Paragios is in charge of the option Medical Imaging, Machine Learning and Computer Vision at the Department of Applied Mathematics of Ecole Centrale de Paris. This option consists of 6 classes in the above mentioned fields, 180 hours of teaching and is associated with the M.Sc. (M2) program of the ENS-Cachan in Applied Mathematics, Machine Learning and Computer Vision.

PhD: Daniel Pescia[7], Segmentation des tumeurs du foie sur des images de scanner CT, Ecole Centrale de Paris, 15/01/2011, Nikos Paragios

PhD: Aristeidis Sotiras [9], Discrete Image Registration: a Hybrid Paradigm, Ecole Centrale de Paris, 6/11/2011, Nikos Paragios

PhD: Chaohui Wang[11], Distributed and Higher-Order Graphical Models: towards Segmentation, Tracking, Matching and 3D Model Inference, Ecole Centrale de Paris, 29/09/2011, Nikos Paragios

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Major publications by the team in recent years

- [1] B. GLOCKER, A. SOTIRAS, N. KOMODAKIS, N. PARAGIOS. *Deformable Registration: Setting the State of the Art with Discrete Methods*, in "Annual Reviews on Biomedical Engineering", 2011, p. 219-244.
- [2] I. KOKKINOS, A. YUILLE. *Inference and Learning with Hierarchical Shape Models*, in "International Journal in Computer Vision", 2011, p. 201-225.
- [3] N. KOMODAKIS, N. PARAGIOS, G. TZIRITAS. *MRF Energy Minimization and Beyond via Dual Decomposition*, in "IEEE Trans. Pattern Anal. Mach. Intell.", 2011, vol. 33, n^o 3, p. 531-552.
- [4] P. KUMAR, V. KOLMOGOROV, P. TORR. *An Analysis of Convex Relaxations for MAP Estimation of Discrete MRFs*, in "Journal of Machine Learning Research", 2009, p. 71-106.
- [5] C. H. LAMPERT, M. B. BLASCHKO, T. HOFMANN. *Efficient Subwindow Search: A Branch and Bound Framework for Object Localization*, in "IEEE Trans. Pattern Anal. Mach. Intell.", 2009, vol. 31, n^o 12, p. 2129-2142.

- [6] L. SIMON, O. TEBOUL, P. KOUTSOURAKIS, N. PARAGIOS. *Random Exploration of the Procedural Space for Single-View 3D Modeling of Buildings*, in "International Journal of Computer Vision", 2011, vol. 93, n^o 2, p. 253-271.

Publications of the year

Doctoral Dissertations and Habilitation Theses

- [7] D. PESCIA. *Segmentation des tumeurs du foie sur des images de scanner CT*, Ecole Centrale Paris, Jan 2011.
- [8] L. SIMON. *Procedural Reconstruction of Buildings: Towards Large Scale Automatic 3D Modeling of Urban Environments*, Ecole Centrale Paris, Jul 2011.
- [9] A. SOTIRAS. *Discrete Image Registration: a Hybrid Paradigm*, Ecole Centrale Paris, Nov 2011.
- [10] O. TEBOUL. *Shape Grammar Parsing: Application to Image-based Modeling*, Ecole Centrale Paris, Jun 2011.
- [11] C. WANG. *Distributed and Higher-Order Graphical Models: towards Segmentation, Tracking, Matching and 3D Model Inference*, Ecole Centrale Paris, Sep 2011.

Articles in International Peer-Reviewed Journal

- [12] B. GLOCKER, A. SOTIRAS, N. KOMODAKIS, N. PARAGIOS. *Deformable Registration: Setting the State of the Art with Discrete Methods*, in "Annual Reviews on Biomedical Engineering", 2011, p. 219-244.
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- [14] I. KOKKINOS, A. YUILLE. *Inference and Learning with Hierarchical Shape Models*, in "International Journal in Computer Vision", 2011, p. 201-225.
- [15] N. KOMODAKIS, G. LANGS, H. BISCHOF, N. PARAGIOS. *Special issue on Optimization for vision, graphics and medical imaging: Theory and applications*, in "Computer Vision and Image Understanding", 2011, vol. 115, n^o 12, 1597.
- [16] N. KOMODAKIS, N. PARAGIOS, G. TZIRITAS. *MRF Energy Minimization and Beyond via Dual Decomposition*, in "IEEE Trans. Pattern Anal. Mach. Intell.", 2011, vol. 33, n^o 3, p. 531-552.
- [17] G. LANGS, N. PARAGIOS, P. DESGRANGES, A. RAHMOUNI, H. KOBEITER. *Learning deformation and structure simultaneously: In situ endograft deformation analysis*, in "Medical Image Analysis", 2011, vol. 15, n^o 1, p. 12-21.
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