INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team GALEN

OrGAn ModeLing through Extraction, Representation and UnderstaNding of Medical Image Content

Saclay - Île-de-France

Theme : Computational Medicine and Neurosciences

Activity Report

2009

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1. Team

Faculty Member

Nikos Paragios [Team Leader, Professor, Ecole Centrale de Paris, HdR]
Iasonas Kokkinos [Associate Professor, Ecole Centrale de Paris]

External Collaborator

Nikos Komodakis [Research Scientist, University of Crete]
Ben Glocker [PhD Candidate, Technical University of Munich]

Technical Staff

Pascale Beliveau

PhD Student

Pierre-Yves Baudin [SIEMENS CIFRE, starting on 01/08/2009]
Ahmed Besbes [MENESR Grant]
Xiang Bo [MENESR Grant, starting on 01/12/2009]
Salma Essafi [AFM Grant]
Katerina Gkirtzou [Centrale-Paris Grant, starting on 01/05/2009]
Nicolas Honnorat [GE-HealthCare CIFRE, starting on 01/02/2009]
Fabrice Michel [MEDICEN Stereos+ Grant]
Radhouene Neji [Centrale-Paris/Supelec Grant]
Daniel Pescia [Intrasense CIFRE]
Mickael Savinaud [BiospaceLab CIFRE]
Aristeidis Sotiras [Centrale-Paris Grant]

Post-Doctoral Fellow

Samuel Kadoury

Visiting Scientist

Ioannis Emiris [Professor, University of Athens, from 15/04/2009 to 15/06/2009]
Christos Davatzikos [Professor, University of Pensylvania, from 15/08/2009 to 15/09/2009]
Michael Bronstein [Postdoctoral Associate, Technion University, from 10/10/2009 to 25/10/2009 & 01/12/2009 to 15/12/2009]
Dimitris Samaras [Associate Professor, State University of New York-Stony Brook, from 01/01/2009 to 31/01/2009]
Rola Harmouche [PhD candidate, Ecole Polytechnique de Montreal, from 01/01/2009 to 30/07/2010]

Administrative Assistant

Christine Biard

2. Overall Objectives

2.1. Galen@Ecole-Centrale

The Galen team was created at Ecole Centrale in November 2005, and became part of INRIA-Saclay Ile-de-France on February, 2008.

Computer-aided diagnosis aims at developing mathematical models and their computational solutions to assist data interpretation in a clinical setting. In simple words, one would like to be able to provide a formal answer to a clinical question using the available measurements. The development of mathematical models for automatic clinical interpretation of multi-modalities [42][1] is a great challenge. The mathematical formulation of clinical data interpretation aims to introduce a compact set of parameters that are to be inferred from the data and answer the clinical question. Such a task requires a consensus between physicians and applied mathematicians, towards the definition of a feasible, clinically-interesting model. Once this model has been defined, the next task consists in associating it with the available observations, which in turn requires the establishment of an anatomical/physiological interpretation of the model components with respect to the measurements. Last, one has to computationally solve the inference problem and recover the set of model parameters which optimally interpret the data.

GALEN aims at proposing innovative techniques towards automatic structuring, interpretation and longitudinal modeling of medical measurements through the analysis of anatomical and functional images. In order to address these fundamental problems of biomedical 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 computational efficient. Successful completion of the above efforts will lead to better understanding of organ evolution due to aging and will provide novel means of diagnosis, follow up, and therapy treatment evaluation. Long-term modeling and understanding the effects of aging is critical to a number of organs and diseases that do not present pre-disease indicators like brain neurological diseases, muscular diseases, certain forms of cancer, etc.

2.2. Highlights of the year

DROP in RSNA: The deformable image fusion technology of Galen is now an industrial product commercialized from Intrasense that was demonstrated in the Radiological Society of North America (RSNA'09) edition.

CVPR Participation: Galen has participated in the 2009 annual IEEE Conference in Computer Vision and Pattern Recognition (CVPR'09) conference, the leading event in the field of computer vision and medical image analysis with six papers (double blind full submissions, acceptance rate %25) including one oral presentation (out of a 60).

MICCAI/IPMI Participation: Galen has participated in the 2009 annual Medical Image Computing and Computer Assisted Intervention (MICCAI'09) conference and the Information Processing in Medical Imaging (IPMI'09) conference, the leading events in the field of medical image analysis with three and two papers respectively (double blind full submissions, acceptance rate %35). Furthermore, GALEN was the main contributor for one of the tutorials being presented at MICCAI.

ISBI Participation: Galen has participated in the 2009 International Symposium of Biomedical Imaging (ISBI'09) conference, the leading event in the field of medical image analysis with six papers (double blind full submissions, acceptance rate %40) including three oral presentations.

FastPD Release: Galen has released the discrete-optimization library based on efficient linear programming and duality to the research community which currently counts approx 500 institutions/active users.

3. Scientific Foundations

3.1. Discrete Biomedical Image 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 $f_{p_1p_2}(x_{p_1}, x_{p_2})$. 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:

$$\arg\min_{\{x_p\}} \mathcal{P}(g,f) = \sum_{p\in\mathcal{V}} g_p(x_p) + \sum_{(p_1,p_2)\in\mathcal{E}} f_{p_1p_2}(x_{p_1}, x_{p_2}). \tag{1}$$

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 $\{C_i, i \in [1,n] = \{\{p_{i^1}, \cdots, p_{i^{|C_i|}}\}\}$ of order $|C_i|$ that will augment the definition of $\mathcal{V}$ and will introduce hyper-vertices:

$$\arg\min_{\{x_p\}} \mathcal{P}(g,f) = \sum_{p\in\mathcal{V}} g_p(x_p) + \sum_{(p_1,p_2)\in\mathcal{E}} f_{p_1p_2}(x_{p_1}, x_{p_2}) + \sum_{C_i\in\mathcal{E}} f_{p_1\cdots p_n}(x_{p_{i^1}}, \cdots, p_{x_{i^{|C_i|}}}). \tag{2}$$

where $f_{p_1\cdots p_n}$ is the price to pay for associating the labels $(x_{p_{i^1}}, \cdots, p_{x_{i^{|C_i|}}})$ to the nodes $(p_1 \cdots p_{i^{|C_i|}})$. 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; however this is not supported by the existing state-of-the art methods.

3.1.1. Linear Programming, Loose Relaxations & Duality

The binary MRF case, considering the optimization of Eq. 2 for binary variables, has been well studied from the optimization community. The main challenge is to find a computational efficient solution that provides a good compromise between the convergence time and the optimality properties of the solution. To this end, we have introduced a novel method [4], called Fast-PD that outerperforms the state of the art from theoretical point of view (classes of energies which can be considered) as well as from computational perspective (five to ten times faster). This is an optimization technique, which builds upon principles drawn from the duality theory of linear programming in order to efficiently derive almost optimal solutions for a very wide class of NP-hard MRFs. Here, we will just provide a brief, high level description of the basic driving force behind that algorithm. This driving force will consist of the *primal-dual schema*, which is a well-known technique in the Linear Programming literature. Let $\mathbf{x}$, $\mathbf{y}$ represent the vectors of primal and dual variables respectively. We seek an optimal solution to the primal program, but with the extra constraint of $\mathbf{x}$ being integral. Due to this integrality requirement, this problem is in general NP-hard and so we need to settle with estimating approximate solutions. In [4] we have adopted a primal-dual f-approximation algorithm that is using the following iterative schema, which can derive an f-approximate solution:

Primal-Dual Schema 1 Keep generating pairs of integral-primal, dual solutions $\{(\mathbf{x}^k, \mathbf{y}^k)\}_{k=1}^{t}$, until the elements $\mathbf{x}^t$, $\mathbf{y}^t$ of the last pair are both feasible and have a primal-dual gap which is less than f.

In order to apply the above schema to MRF optimization, it suffices to cast the MRF optimization problem as an equivalent integer program.

3.1.2. Tight Relaxations, Cycle Repairing & Duality

Despite their success, LP-based methods are doomed to fail if relaxation does not approximate well the actual problem MRF (*i.e*, it is not tight), which is exactly what happens when one has to deal with very hard MRF problems. We believe this is an issue that has to be addressed, if a further advance is to be made in MRF optimization.

In [3] we have attempted to go beyond most existing MRF techniques, by deriving algorithms that are based on much tighter LP relaxations. Towards this goal, we try to strengthen relaxation $\mathcal{P}(\bar{\mathbf{g}}, \bar{\mathbf{f}})$. However, instead of doing that in the primal domain, which is inefficient, our strategy consists in applying this procedure in the dual domain. As a result, we create an hierarchy of increasingly tighter dual relaxations, going all the way up to a dual relaxation that actually coincides with the original problem MRF. This is a novel LP-based algorithm for MRF optimization, which, contrary to most state-of-the-art techniques, no longer relies on a weak LP-relaxation. To this end, we have shown shown how one can take advantage of a very tight class of relaxations from our increasingly tighter hierarchy, named cycle-relaxations. This is done through an operation called cycled repairing, where inconsistent cycles get repaired during optimization, instead of simply being ignored as was the case up to now.

The outcome is an algorithm that can handle difficult MRF problems with arbitrary pairwise potentials. The impact of our work can be both practical and theoretical. On the one hand, the proposed method makes one more step towards the design of optimization algorithms that can effectively handle very general MRFs, thus allowing users to freely exploit such MRFs for a better modeling of future vision problems. On the other hand, for a further advance to be made in MRF optimization, the use of tighter relaxations is a direction that, we believe, has to be followed. To this end, the idea of cycle-repairing, as well as that of a dynamic hierarchy of dual relaxations (of which only the cycle-relaxations have been explored here), provide an extremely flexible and general framework that can be useful in opening new research avenues in this regard.

3.1.3. Master-Slave Decompositions, Message Passing and Higher-Order MRFs

MRF inference is extremely popular in medical imaging and related fields. However, with a few exceptions only, its use was mainly confined to the case of pairwise MRFs up to now. One reason is because optimization of higher order MRFs can be extremely difficult (*i.e*, algorithms that yield almost optimal solutions are hard to get in this case) and, furthermore, these algorithms often have a very high computational cost that is prohibitive in practice. Yet, many medical imaging problems could greatly benefit from the use of higher order models as this would allow far more expressive priors to be encoded, and also multiple interactions to be captured. This would, in turn, lead to a far better and more accurate modelling, which is clearly needed by many vision tasks (*e.g*, notice that in many cases there is a large disagreement between the global optimum, that can often be computed for pairwise MRFs, and the ground truth). Towards dealing with the above issues, we proposed in [30] a powerful framework for high-order MRF optimization. It uses a *master-slave* based scheme [10], which relies on the core idea that even a hard high-order MRF problem (with, *e.g*, large cliques or complicated structure) can often be decomposed into high-order MRF subproblems that are very easy or even trivial to solve. This leads to a very general and flexible framework. Hence, on the one hand, we use it to derive a generic optimizer, which is applicable to almost any high-order MRF, and which provably computes the global optimum to a strong dual LP-relaxation of the MRF problem. On the other hand, due to its flexibility, the proposed framework can also be easily adapted to lead to even more powerful algorithms when it comes to dealing with specific classes of high-order MRFs.

3.2. Galen Research Axes

The aim of GALEN research activities is to develop a novel, generic mathematical framework and its computational solution for computer aided diagnosis. In particular, we would like to address the mail challenges of the entire biomedical image chain, in particular (i) Automatic extraction of meaningful anatomical and pathological indices, (ii) Automatic interpretation of these biomarkers towards computer aided diagnosis, with emphasis on pre-screening as well as therapy evaluation treatment and (iii) Longitudinal modeling of these indices towards understanding their correlations and providing novel means of diseases assessment. To be more specific, our research axes are the following:

- Introduce a novel, modular (in terms of clinical applications, mathematical perception models and bio-imaging signals), and computational efficient inference framework for biomedical imaging perception to address the most fundamental problems of medical imaging. Such an approach will facilitate the development of computer-aided diagnosis for every-day clinical use (opposite to clinical research purposes that is mostly the case nowadays). Such an effort will require the development of novel, efficient, discrete modeling, optimization and inference techniques that could impact a number of domains.
- Exploit recent advances and introduce novel machine learning techniques for computer-aided diagnosis. In particular, we will focus on novel efficient means for modular unsupervised clustering (in terms of clinical applications, mathematical perception models and bio-imaging signals) towards capturing the most prominent biomedical signals of various diseases. Furthermore, we will look on efficient dimensionality redaction methods that will allow the classification process to learn from small training sets, one of the most important constraints of data mining.
- Propose organ evolution models that account for aging through inference from multi-dimensional bio-imaging signals. To this end, we imagine a set of subjects being imaged with a certain frequency non-invasively. Longitudinal modeling aims at automatic interpretation using non-linear time series models that couple anatomical and pathological indices. Such an approach will provide: (i) a better understanding of the aging process, (ii) means of recovering risk factors for certain diseases at very early stage, (iii) means of diagnosis for long-term pathologies without pre-clinical symptoms. This will be of particular challenge when focusing either on children (where one observes rapid, and unknown to a certain extent evolution in number of organs), or adults being affected with diseases of unknown temporal signature.

4. Software

4.1. Deformable Registration Software

Participants: Nikos Paragios [Correspondant], Ben Glocker, Pascale Beliveau, Fabrice Michel, 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 1,500 users worldwide.

4.2. 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.

5. New Results

5.1. Reconstruction & Classification of Scalar and Vectorial Signals

Participants: Noura Azzabou, Ahmed Besbes, Radhouene Neji, Nikos Komodakis, Nikos Paragios.

- In [7] we introduced a reconstruction framework that explicitly accounts for image geometry when defining the spatial interaction between pixels in the filtering process. To this end, image structure is captured using local co-occurrence statistics and is incorporated in the enhancement algorithm in a sequential fashion using the particle filtering technique. In this context, the reconstruction process is modeled using a dynamical system with multiple states and its evolution is guided by the prior density describing the image structure. To optimally explore the image geometry, an evaluation process of the state of the system is performed at each iteration. The resulting framework explores optimally spatial dependencies between image content towards variable bandwidth image reconstruction.
- The case of structured vectorial data was considered in [34] where a kernel-based approach to the clustering of diffusion tensors and fiber tracts. We proposed to use a Mercer kernel that implicitly models the connectivity along fiber tracts. Tensor segmentation is performed using kernel-PCA compounded with a landmark-Isomap embedding and k-means clustering. The method was extended to the fully unsupervised case in [32] where a linear programming formulation of prototype based clustering was proposed that circumvents the necessity to embed the data in low dimensional spaces and determines automatically the number of clusters. Furthermore, we proposed the use of angular Hilbertian metrics between multivariate normal distributions to define a family of distances between tensors that we generalize to fibers. These metrics are used to approximate the geodesic distances over the fiber manifold. Last, but not least the use of diffusion maps to fiber tract clustering in the human skeletal muscle was considered in [33] where a metric is defined between fiber tracts that encompasses both diffusion and localization information.

5.2. Model-free & Model-based Segmentation

Participants: Ahmed Besbes, Salma Essafi, Ben Glocker, Laura Gui, Nicolas Honnorat, Iasonas Kokkinos, Nikos Komodakis, Nikos Paragios, Mickael Savinaud, Aristeidis Sotiras.

- In [24] we propose a novel approach for the segmentation of curvilinear structures in medical images. Our approach combines machine learning techniques, unsupervised clustering and linear programming. In particular, numerous invariant to position/rotation classifiers are combined to detect candidate pixels of curvilinear structures. These candidates are grouped into consistent geometric segments through the use of a state of-the art unsupervised clustering algorithm. The complete curvilinear structure is obtained through a linking of these segments using the elastica model in a linear programming framework. The same problem was addressed in the temporal domain through an MRF-based tracking approach [23] using efficient linear programming.
- In [27] we introduce an hierarchical framework to match deformable models to images. A coarse-to-fine method was considered that resulted in a multifold speed improvement: we first fit a model by requiring a coarse match of its parts and subparts, and then use this match to guide fine-level matching. In [28] we learn such models without manually annotated data. For this we use (i) automated AAM learning to find the model contours, (ii) Affinity Propagation to find its parts, and (iii) Multiple Instance Learning (MIL) to learn the cost function that drives the matching. The learned model accounts for the principal contours of the deformable object, while MIL results in accurate matches and improved detection performance.
- In [15], [16] we have introduced a new deformable shape model for knoweldge-based segmentation. The representation is similarity-invariant and consists of an incomplete graph with its

structure/topology being learned using unsupervised clustering. This clustering refers to the co-dependencies between the control points. Efficient linear programming-based optimization and manifold learning techniques were combined in [15] with a Voronoi diagram representation of the data term in a segmentation framework, and results of the segmentation of the hand in 2D images were shown. This method was extended in 3D in [16] to the particular application of the segmentation of the left ventricle. More globally, this work is in line of the use of the Markov Random Fields (MRFs) representations in biomedical image analysis, as detailed in the invited paper [29].

- In [17] we have proposed a novel hierarchical decomposition of prior knowledge using diffusion wavelets. Such a representation can reflect arbitrary continuous interdependencies in shape data. The main contribution of the method refers to the optimization of the coefficients, the number and the position of landmarks, and the object topology - the domain on which the wavelets are defined - during the model learning phase, in a coarse-to-fine manner. Furthermore, we have considered a novel criterion towards compact representation of the manifold being described from the diffusion coefficients. The theoretical framework was considered to address two challenging medical imaging applications, the case of the left ventricle in CT images [18] and the case of magnetic resonance images of the human skeletal muscle [19].
- In [8] we introduced a general framework for fusing bottom-up segmentation with top-down object behavior inference over an image sequence using a variational formulaton [5]. This approach is beneficial for both tasks, since it enables them to cooperate so that knowledge relevant to each can aid in the resolution of the other, thus enhancing the final result. In particular, the behavior inference process offers dynamic probabilistic priors to guide segmentation. At the same time, segmentation supplies its results to the inference process, ensuring that they are consistent both with prior knowledge and with new image information. The prior models are learned from training data and they adapt dynamically, based on newly analyzed images.
- The case of multi-view stereo reconstruction for post-arthroplasty examination with the aim to create a 3-D shape model of the bone as well as the prosthesis using a set of 2-D X-rays from various viewpoints was considered in [14]. The most important challenge to be addressed is the lack of texture, the most common feature to recover shape from multiple views. In order to overcome this limitation, we reformulate the problem using a novel multi-view segmentation approach where we use 3-D surface evolution implemented with level-set methods to recover the shape of bones and prostheses in post-operative joints.
- in [40] we introduced the notion of mutual population segmentation using discrete optimization were results from a given example influence results for the rest of the examples to improve the overall segmentation performance. The aim was to combine prior knowledge along with consistency through the simultaneous segmentation of the whole population. This was achieved through their mutual deformation towards the atlas, while being constrained through a simultaneous all-to-all deformable diffeomorphic registration. Promising results using low signal to noise ratio radiographic images demonstrated the potentials of the method.

5.3. Shape, Landmark & Image-based Deformable Registration

Participants: Ahmed Besbes, Michael Bronstein, Christos Davatzikos, Ben Glocker, Nikos Komodakis, Nikos Paragios, Mickael Savinaud, Aristeidis Sotiras.

- In [44] we introduce scale-invariant descriptors of 3d shapes that are represented as triangulated meshes. Starting from a scale-covariant descriptor, we take the magnitude of its Fourier Transform. This results in local descriptors that are invariant to the global and, to a large extent, the local scalings of the 3D shape and therefore can be a valuable element for 3D landmark-based registration and matching.
- In [35] we present a framework for extracting mutually salient landmark pairs for registration. Our method detects landmarks pair-by-pair across images, and those pairs are required to be mutually-salient, i.e., uniquely corresponding to each other. The second merit of our framework is that, instead

of finding individually optimal correspondence, which is a local approach and could cause self-intersection of the resultant deformation, our framework adopts a Markov-random-field (MRF)-based spatial arrangement to select the globally optimal landmark pairs. In this way, the geometric consistency of the correspondences is maintained and the resultant deformations are relatively smooth and topology-preserving.

- In [6], we advanced the state of the art by considering an efficient registration method that aims to recover a one-to-one correspondence between shapes as well as measures of uncertainties driven from the data and explain the local support of the recovered transformations. To this end, a free form deformation is used to describe the deformation model that is combined with an objective function defined in the space of implicit functions used to represent shapes in 2D and 3D. The outcome of this procedure associates local deformation vectors with uncertainties that do vary spatially and are determined according to the image-based confidence of the registration process.
- In [20] we developed a novel task-driven prior constraint in deformable registration [2] using learned deformations through a MRF-based paradigm. Such an approach consists in learning the manifold deformation co-dependencies and translating them into pair-wise constraints within an appropriate discrete formulation that combines terms accounting for optimal data-matching, smooth deformation field and the best possible projection to the learned manifold. In [21] we have introduced a novel regularization term into the pairwise MRF formulation, through a penalty term that is invariant to linear transformations. Last, in [22] we developed a flexible MRF model which can sufficiently represent any kind of linear transformation by simple changes on the graph.
- In [37] we have proposed motion based enhancement of optical imaging through a combination of landmark, shape and image-based terms while imposing smoothness on the deformations. The aim of this approach was to improve localization of the luminescent data for a freely moving animal using motion information obtained with an additional camera. The same problem, was addressed in a more elegant manner through a group-wise fusion method which reformulates the registration problem where the two signals are registered in the same deformation field [38]. Last, we have introduced/fused measurements through multi-view devices towards increasing the quality and the appropriateness of the obtained signal [36].
- In [25] we have proposed a multi-modal fusion of the spinal column. We developed a method inferring biplanar reconstructed 3D spine models to intraoperative CT data acquired for corrective spinal surgery. The intervertebral articulations of the model were optimized using an integrated and interconnected Markov Random Field (MRF) graph that involves singleton potentials (data support) and pairwise costs (constraints between two vertebrae). Successful image registration results were obtained from simulated and real data experiments. Increased landmark localization was then achieved by incorporating higher order energy functions which have the ability to encode global structural dependencies [26].
- In [39] we proposed a novel framework on a graphical model formulation to unite a population of n-examples to the same pose through their mutual deformation. The registration criterion comprises three terms, one that aims to impose local smoothness on each deformation field, a second that aims to minimize the individual distances between all possible pairs of images, while the last accounts for global statistical measurements based on "compactness" criteria. The problem is reformulated using a discrete MRF, where the above constraints are encoded in singleton (entropic) and pair-wise potentials (smoothness (intra-layer costs) and pair-alignments (interlayer costs)). The resulting paradigm is optimized using efficient linear programming.
- In [31] we have introduced a novel approach for metric learning in image fusion. The central idea is to learn transport functions which will allow transforming the source feature space towards the target. This was achieved through a combination of a mixture of experts model accounting for the statistical behavior of the transport functions and a discrete MRF-formulation imposing smoothness properties on the reconstructed image. Such a direct transformation method may fail when dealing with highly heterogeneous data. In order to cope with such a case in [43] we have used a boosting-driven framework that aims to project both feature spaces into a common binary one such that their

Hamming distance is minimal. Promising results in computer vision and medical imaging problems demonstrated the extreme potential of this method.

5.4. Discrete Optimization, Duality & Linear Programming

Participants: Nikos Komodakis, Nikos Paragios.

In [30] we have introduced a novel optimization approach to address MRFs of higher order with arbitrary dependencies between the model variables. The method can be applied to almost any higher-order MRF and optimizes a dual relaxation related to the input MRF problem. Such a generic approach is extremely flexible and thus can be easily adapted to yield far more power algorithms when dealing with subclasses of high-order MRFs. We introduce a new powerful class of high-order potentials, which are shown to offer enough expressive power and to be useful for many vision tasks. In order to address them, we derive a novel and extremely efficient message-passing algorithm, which goes beyond the aforementioned generic optimizer and is able to deliver almost optimal solutions of very high quality.

5.5. Clinical Applications

Participants: Jean-Francois Deux, Alain Rahmouni, Hicham Kobeiter, Pierre Carlier, Phillipe Grenier, Phillipe Trosini-Desert, Thomas Similowski.

- **Diffusion Tensor Imaging and the Human Skeletal Muscle** [CHU Henri Mondor & APHP Pitie SalPetriere]: Myopathies encompass various inherited or acquired disorders of the skeletal muscle tissue affecting both children and adults. The reduction of functional muscle cells (myofibers) results in skeletal muscle weakness and atrophy. Clinical follow-up as well as therapeutic trial evaluation are mainly based on functional tests and physiological measurement of muscle strength that are limited by the lack of sensitivity or poor reliability. Muscle tissue biopsy allows a direct microscopic myofiber count but it is an invasive method only suitable for diagnostic purpose. Diffusion Tensor Magnetic Resonance Imaging (DTI) is a technique that allows measuring the random motion of water molecules in biological tissues in vivo such as the white mater of the brain where it has been shown to allow non-invasive mapping of the connectivity. Myofibers refer to anatomical structures where the propagation/diffusion of water could lead to a complete understanding of the muscle structure. Such local and global structure is altered when muscular diseases are present. To this end, one first has to account for the highly sparse data of such a modality (capturing diffusion in a limited number of directions), the presence of strong noise at the acquisition model, the extraction of the muscle fibers from isolated measures, and the understanding of the global muscle structure through the statistical characterization of these fibers. Furthermore, we would like to correlate DTI results with morphometric data resulting from myofiber examination by microscopic histological study of the same muscle. The objective of this project is the development of a novel quantitative method for in vivo muscle imaging (DTI-muscle) leading to near "virtual muscle histology". DTI-muscle may offer a new reliable non-invasive approach allowing quantification of myofibers in the setting of pharmaceutical drug evaluation as well as for gene and cell therapy clinical trials.
- **Machine Learning, Deformable Registration and Virtual Bronchoscope**: [APHP Pitie SalPetriere]: The technological advance introduced by the flexible bronchoscope dates back to the 1960s. Easier to use and more comfortable for the patient, flexible bronchoscopy rapidly became a recognized diagnostic method and one of the standard diagnostic techniques in chest medicine. It is used for diagnostic procedures as well as therapeutic ones. The idea behind such a project is to be able to perform real-time multi-modal alignment between preoperative annotated data (CT) and interventional data bronchoscope images. Such a process will lead to an automatic navigation tool on the 3D bronchial topography model obtained through preoperative procedures. Therefore it will allow physicians to perform better diagnosis as well as better treatment of diseases. Such a process is challenging due to the following reasons: (i) pre-operative data is three dimensional while the bronchoscope images correspond to 2D depth views, therefore we are looking into a

2D-to-3D registration problem, (ii) these modalities have nothing in common and conventional registration criteria will fail to provide any meaningful correspondences, (iii) the process has to be almost real-time as the navigation takes the place of the flexible bronchoscope. This is a novel concept of computer-aided guided bronchoscopy through biomedical image fusion that has never been investigated before.

6. Other Grants and Activities

6.1. National Actions

Participant: Nikos Paragios.

- Galen participates in the AFM Grant DTI-Muscle (2007-2010) with aim to study the use of diffusion tensor imaging towards computer aided diagnosis for muscular diseases in collaboration with Siemens and CHU-Henri Mondor University Hospital.
- Galen participates in the Medicen Competitively Cluster Grant stereos+ (2008-2010) with aim to develop novel medical imaging-based diagnostic tools for osteopathy in collaboration with BiospaceMed.

6.2. European & International Actions

Participant: Nikos Paragios.

- Galen has worked with the CS Department of the Technical University of Munich and the CS Department of the University of Crete studying the use of discrete optimization methods in the field of deformable pair-wise and population registration.
- Galen has worked with the CS Department of the University of Crete aiming the development of efficient discrete optimization methods and their applications to the medical image analysis field.
- Galen has worked with the Department of Radiology, of the University of Pennsylvania aiming the development of joint landmark and iconic based registration tools using discrete modeling and their applications in medical image analysis.

6.3. Industrial Collaborations & Grants

Participant: Nikos Paragios.

- Galen has worked with Siemens towards the development of automatic segmentation tools for the human skeletal muscle.
- Galen has worked with Intrasense towards the development of automatic segmentation tools for liver images as well as automatic tumor cancer detection.
- Galen has worked with BiospaceLab towards the development of automatic registration and fusion between fluoroscopic and video images towards signal enhancement.
- Galen has worked with GE-HealthCare towards development of automatic segmentation and tracking methods for assisting surgeons using interventional imaging.

7. Dissemination

7.1. Scientific Community animation

7.1.1. Journal & Conference Editorial Activities

Participants: Nikos Paragios, Iasonas Kokkinos, Nikos Komodakis, Georg Langs.

- **Editorial Boards**: N. Paragios is member of the editorial boards of the (i) Medical Image Analysis Journal (MedIA), (ii) IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI), (iii) International Journal of Computer Vision (IJCV), (v) Computer Vision and Image Understanding Journal (CVIU), (iv) Journal of Mathematical Imaging and Vision (JMIV), (v) Image and Vision Computing Journal. N. Paragios was guest editor for the International Journal in Computer Vision of the special issue in Scale Space and Variational Methods.
- **Conference Boards**: N. Paragios was an area chair for the Computer Vision and Pattern Recognition Conferense (CVPR'09).
- **Conference Committees & Journal Reviewing Activities**:
  - I. Kokkinos was reviewer for the IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI), the IEEE Transactions on Image Processing (T-IP), and the Computer Vision and Image Understanding Journal (CVIU).

    I. Kokkinos was member of the conference committee for the IEEE International Conference in Computer Vision (ICCV'09), the IEEE Computer Vision and Pattern Recognition Conference (CVPR'09), the International Symposium on Visual Computing (ISVC'09), the Energy Minimization Methods in Computer Vision and Pattern Recognition Conference (EMCVPR'09), the Asian Conference on Computer Vision (ACCV'09), the IEEE Stochastic Image Grammars Workshop (SGW'09) and the IEEE Workshop on Multimedia Signal Processing (MMSP'09).
  - N. Paragios was member of the conference committee for the Medical Image Computing and Computer Assisted Intervention (MICCAI'09), the IEEE International Conference in Computer Vision (ICCV'09), the Mathematical Methods in Biomedical Image Analysis (MMBIA), the IARP International Conference in Pattern Recognition (ICPR'09), the Asian Conference on Computer Vision (ACCV'09), the Canadian Conference in Computer Vision (CRV'09), the International Symposium on Visual Computing (ISVC'09), the Advanced Concepts for Intelligent Vision Systems Conference (ACIVS'09), the IEEE Non-Rigid Shape Analysis and Deformable Image Alignment (NORDIA'09), the MICCAI Probabilistic Models in Medical Imaging Workshop (PMMIA'09), the IEEE Workshop on eHeritage and Digital Art Preservation (EHW'09), the International Workshop on Image Analysis for Multimedia Interactive Services (WIAMIS'09)

    N. Paragios was reviewer for the Austrian Science Foundation, the European Union Commission (FP7), and the Agence National de la Recherche (ANR), the Austrian Science Foundation and the Swiss Research Council.

7.1.2. Thesis & Doctoral Committees Participation

Participant: Nikos Paragios.

- **Reviewer of PhD Thesis Committees**: N. Paragios was reviewer for: (1) Elias Grinias - University of Crete, (2) Nicolas Thorstensen - Ecole de Ponts.
- **Membder of PhD Thesis Committees**: N. Paragios was member for: (1) Martin de la Gorce - Ecole Centrale, (2) Xavier Hubert - Ecole Centrale, (3) Cedric Allene - Universite de Paris-Est, (4) Francois Lecellier - ENSICAEN.

7.1.3. Invited Lectures & Honors, Distinctions

Participants: Samuel Kadoury, Iasonas Kokkinos, Nikos Paragios.

- **Distinctions/Honors**:
  - S. Kadoury Kadoury received an excellence award for his Ph.D. thesis in biomedical engineering. The selection of the best doctoral thesis was made by a committee of experts from the 67 dissertations submitted at École Polytechnique de Montréal during the 2008-09 academic year and will represent the university in the national contest in the field of science.
  - I. Kokkinos received the best reviewer award for his contributions at the IEEE International Conference in Computer Vision (ICCV'09). ICCV is the most prestigious conference in the field of computer vision.
- **Tutorials**:

  N. Paragios presented a tutorial in Discrete Optimization at the Medical Image Computing and Computer Assisted Intervetion (MICCAI'09).
- **Invited Presentations**:
  - I. Kokkinos gave invited presentations at: National Technical University of Athens, IEEE Student Branch.
  - N. Paragios gave invited presentations at: University of Houston, IEEE Engineering in Medicine and Biology Society, Technical University of Munich, Second International Workshop on Shape Perception in Human and Computer Vision, WSEAS International Conference on Computers, Applied Mathematics in Medicine and Biology, BIOTRIBOLOGY: Basics and Trends in Medicine, Engineering and its Societal Impacts, Telecom-Paris, University of Paris 6, Imperial College.

7.2. Teaching

Participants: Nikos Paragios, Iasonas Kokkinos.

- **In Charge**: 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. program of the ENS-Cachan in Applied Mathematics, Machine Learning and Computer Vision.
- **Instructor**:
  - I. Kokkinos was the instructor or has participated in:
    - Signal Processing Class (second year) at the Ecole Centrale de Paris (36 hours),
    - Introduction to Pattern Recognition (M.Sc. level) at the Ecole Centrale de Paris (24 hours),
    - Introduction to Computer Vision (second year) at the Ecole Centrale de Paris (36 hours).
  - N. Paragios was the instructor or has participated in:
    - Signal Processing Class (second year) at the Ecole Centrale de Paris (36 hours),
    - Algorithmic Computer Vision Class (M.Sc. level) at the Ecole Normale Superieur (12 hours),
    - Advanced Methematical Methods in Computer Vision (M.Sc. level) at the Ecole Normale Superieur/Ecole Centrale de Paris (24hours).

8. Bibliography

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