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 BIO

Activity Report

2008

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1. Team

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2. Overall Objectives

2.1. Galen@Ecole-Centrale

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

Recent developments on the hardware side have led to a new generation of scanners as well as image modalities where the in vivo visualization of anatomical structures of biological systems is possible in a non invasive fashion. The exploitation of such an information space is a great challenge of our days and consists of understanding the anatomical structure of biological systems and in particular the effect of pathologies on their complex mechanisms of operation.

One can consider such a task from a mathematical perspective. In such a case, for a given modeling task the first objective consists of parameterizing the problem or associating the understanding of a complex mechanism through a mathematical model that describes a generic behavior and depends on a number of parameters. Given such a model, the next step aims to establish a relation between the theoretical model and the available observations in a linear or non-linear manner. In simple words, we should be able to understand the impact of model parameters to the data. Last, but not least, inference of the model parameters given the data is to be performed, or recover the set of values that once applied to the model will optimally explain the data. There are several challenges in such a process. The first is the curse of dimensionality. Biological behaviors are rather complex procedures and their parameterization requires substantial number of parameters. In simple words, complex models are needed to reasonably simulate complex behaviors. The second is the curst of non-linearity due to the fact that is almost impossible to explicitly associate the model parameters with the available observations. Last, but not least one should address the problem of ill-posedeness, since recovering the set of optimal parameters given the data/model associations are in most of the cases NP-hard/complete problems. To this end, for the past decade I have developed a number of scientific tools to address these demands. The most common clinical scenario involves the extraction of a structure of interest from images, the mathematical modeling of the normal case which consists of recovering a probabilistic representation of the healthy and in some cases the non-healthy subjects.

In the above mentioned scenario, one can point out two important limitations. The first is due the interdependencies between the three tasks of the processing chain, in particular as it concerns the data-association and inference steps where the models are hard-encoded in the process, decreasing the modularity of the proposed methods to specific clinical problems and even more specific class of models. The second limitation relates to the fact that despite enormous progress made on computer-aided diagnosis, the existing tools exploit organ aging information in a very limited fashion. Understanding the evolution of organs either due to aging or because of major health events is an area that has gained very little attention. 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.

The main challenge being undertaken from the group consists of addressing the above mentioned limitations of computational medical imaging. We would like to develop modular methods [7] where the (i) model definition, (ii) data association and (iii) parameters inference are decoupled and the overall approach offers great flexibility on modeling a variety of medical imaging problems [8]. Furthermore, we are willing to develop organ evolution models due aging from images with aim (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.

2.2. Highlights of the year

CVPR Participation: Galen has participated to the 2008 edition of the annual IEEE Conference in Computer Vision and Pattern Recognition (CVPR'08) conference, the leading events in the field of computer vision and medical image analysis with five papers (double blind full submissions, acceptance rate %25) including two oral presentations (out of a 60).

MICCAI Participation: Galen has participated to the 2008 edition of the annual Medical Image Computing and Computer Assisted Intervention (MICCAI'08) conference, the leading events in the field of medical image analysis with four papers (double blind full submissions, acceptance rate %35) [23], [30], [35], [40]. Furthermore, GALEN was the main contributors for one of the tutorials being presented at MICCAI.

ISBI Participation: Galen has participated to the 2008 edition of the International Symposium of Biomedical Imaging (ISBI'08) conference, the leading event in the field of medical image analysis with five papers (double blind full submissions, acceptance rate %40) [28], [29], [36], [37], [38].

DROP Release: Galen ha released the discrete-optimization deformable registration tool to the research community which currently counts approx 1,000 institutions/active users. Furthermore, an agreement was signed towards commercialization of this technology while 2 United States patents have been submitted. Last, but not least the associated publication at the Medical Imaging Analysis journal [1] is one of the most downloaded articles within 2008.

3. Scientific Foundations

3.1. Computational Organ Modeling

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 the above mentioned objectives, feature extraction, structuring, characterization and modeling are to be inferred from medical images. The notion of feature can refer either to simple primitives (image characteristics like interest points, etc.), or more complex structure (like for example organ segmentation). Once features have been determined, the next step consists of recovering the most appropriate measurements for the considered mathematical model and then infers the model from these images. To this end, at the lower end of the approach is to address: (i) the problem of corrupted or incomplete measurements through novel reconstruction models, (ii) the problem of redundancy through non-linear dimensionality reduction of the observation space towards the most discriminative and meaningful features, and (iii) propose linear and non-linear prediction models towards longitudinal modeling of the evolution of these features, a valuable indicator for diagnosis.

Despite enormous efforts in the field of medical imaging for the past two decades, still most of the above mentioned problems are still open:

- Feature extraction and dimensionality reduction have gained almost no attention in the field, and given the explosion both in terms of signals as well as in terms of resolution; one has to seriously consider structuring the data,
- Knowledge-based segmentation - even if numerous organ-specific solutions exist - is still an open. Questions related with the optimal shape representation, connection between the model parameters and the available images as well as parameters inference are still to be addressed,
- Deformable image fusion is one of the main limitations in the field both in terms of performance and computational requirements despite being one of the most valuable tools required to advance clinical research.
- Despite enormous efforts to study spatial and inter-population statistical variations of organ representations, no attention has been paid to the temporal evolution of these models, a critical component towards computer aided diagnosis.

It is reasonable to claim, that most of the existing solutions are organ-specific suffering both in terms of scalability as well as in terms of modularity. In simple words, while progress was made on a number of problems, it is hard to imagine how one can combine tools coming from different clinical contexts towards a unifying framework that can be easily amended to deal with a similar problem in a new anatomical setting.

3.2. Galen Research Axes

In order to address these questions, GALEN currently develops a unified framework to address biomedical image analysis that consists of three components:

1. **Data Representation** tries to determine automatically the most valuable information for a context-specific application towards computer aided diagnosis. Techniques coming for unsupervised, semi-supervised and supervised learning are considered in this context driven from the clinical application under investigation.
2. **Model Definition** aims to recover a compact parametric representation of the problem, where interactions between variables are minimal while at the same time offers scalability (2D/3D/4D/5D) and portability from one clinical setting to another. To this end, statistical models of variations representing the global manifold through accumulation of constraints over reduced rank manifolds accounting for the limited interaction between variables are considered.
3. **Inference** involves two components, one that associates the model with the considered data representation and a second that aims to recover the optimal set of parameters towards explaining these features. In order to introduce "‘modularity"’ with respect to the choice of image metric, as well as obtain guarantees on the performance of the method, we study the use of discrete optimization in the medical imaging field. Such an approach can be an excellent compromise between performance (in terms of converging to a good solution) and computational complexity.

Towards addressing the above mentioned tasks, we have investigated the use of variational methods and discrete MRFs. The use of variational continuous formulations allows an explicit modeling of the problem and offers substantial freedom in terms of interactions between the model variables. On the other hand, such an approach leads to sub-optimal results. Discrete methods are constrained to local interactions between the model variables but offer more efficient means of recovering a good sub-optimal solutions within reasonable computational requirements while being modular both in terms of the model representation, as well as in terms of the data association procedure.

A wide variety of tasks in medical 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 to an object p, we are forced to pay a price according to the so called *singleton* potential function $V_p(x_p)$, while each time we choose to assign a pair of labels, say, x_p and x_q to two interrelated variables p and q (two objects that are connected to each other 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 $V_{pq}(x_p, x_q)$ (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:

$$\arg\min_{\{x_p\}} \sum_{p \in \mathcal{V}} V_p(x_p) + \sum_{(p,q) \in \mathcal{E}} V_{pq}(x_p, x_q). \tag{1}$$

The use of such a model can describe a number of challenging problems in medical image analysis.

4. Software

4.1. Deformable Registration Software

Keywords: *deformable image and volume registration*.

Participants: Nikos Paragios [Correspondant], Ben Glocker, Pascale Beliveau, Aris Sotiras, Nikos Komodakis.

DROP is a deformable registration platform in C++ for the medical imaging community (publicly available at http://campar.in.tum.de/Main/Drop) 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 approx 1,000 users worldwide.

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

Keywords: *discrete optmization*, *duality*, *graph cuts*, *markov random field*.

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. Data Representation, Dimensionality Reduction & Clustering

Participants: Nikos Paragios, Iasonas Kokkinos, Georg Langs, Nikos Komodakis, Radhouene Neji, Daniel Pescia.

Towards structuring the data:

- We have introduced the use of advanced non-linear machine learning approach [37] based on adaboost for tumor detection and differentiation in CT liver images. The focus of the method was optimal feature selection towards tumor/healthy tissues separation through the optimization of a class-specific filter band.
- In [16] we proposed the use of modulation models to describe the orientation, scale and contrast of oscillatory patterns. We demonstrate their usefulness as low-dimensional texture features and develop model selection tools to adaptively determine the influence of the texture, edge and intensity cues during image segmentation. In [31] we introduced a scale- and rotation- invariant appearance descriptor that does not require estimating the local image scale or orientation. As such our descriptor is applicable to a broad range of image structures, such as edges, where scale estimation is unreliable.
- We proposed a shape population metric that reflects the interdependencies between points observed in a set of examples [34]. It provides a notion of topology for shape and appearance models that represents the behavior of individual observations in a metric space, in which distances between points correspond to their joint modeling properties. With this metric functional clustering, deformation- or motion segmentation, sparse sampling and the treatment of outliers can be dealt with in a unified and transparent manner. The method was extended to arbitrary models, resulting in model maps and was applied to understand task-specific dependences of the brain in [35].
- In [4] we introduced a novel center-based clustering algorithm that first formulated clustering as an NP-hard linear integer program and we then use linear programming and the duality theory to derive the solution of this optimization problem. This led to an efficient and very general algorithm, which works in the dual domain, and can cluster data based on an arbitrary set of distances. The resulting method is independent of initialization, has guaranteed convergence, and can also provide online optimality bounds about the quality of the estimated clustering solutions.
- We introduced a kernel-based approach to perform clustering of semi definite positive matrices [44]. We proposed to use a Mercer kernel over these manifold defined at medical image volumes where both spatial and diffusion information are taken into account. This kernel highlights implicitly the connectivity along measurements. Based on a soft fiber representation, we extended the kernel to deal with succession of measurements using the multi-instance kernel. This concept was applied towards supervised and unsupervised clustering of diffusion imaging tensors of the human skeletal muscle.

5.2. Model-free and Model-based Segmentation, Tracking

Participants: Nikos Paragios, Georg Langs, Nikos Komodakis, Ahmed Besbes, Salma Essafi, Iasonas Kokkinos, Mickael Savinaud.

- In [11] we have proposed a variation approach 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. 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 an active contours 3-D surface evolution with level-set implementation is used to recover the shape of bones and prostheses in post-operative joints. The recovered shape may then be used to track 3-D motions in dynamic X-ray sequences to obtain kinematic information. The outcome of this method was to study the effect of arthroplasty, the implantation of prostheses into joints.

- In [2] and [9] we proposed a level set method for shape-driven object extraction. We introduced a voxel-wise probabilistic level set formulation to account for prior knowledge. To this end, objects were represented in an implicit form. Constraints on the segmentation process were imposed by seeking a projection to the image plane of the prior model modulo a similarity transformation. The optimization of a statistical metric between the evolving contour and the model has led to motion equations that evolve the contour toward the desired image properties while recovering the pose of the object in the new image. Upon convergence, a solution that was similarity invariant with respect to the model and the corresponding transformation were recovered. Promising experimental results demonstrated the potential of such an approach medical imaging or computer vision problems.
- In [24], we proposed a novel approach to model shape variations. It encoded sparsity, exploited geometric redundancy, and accounted for the different degrees of local variation and image support. In this context we have considered a control-point based shape representation. Their sparse distribution is derived based on a shape model metric learned from the training data, and the ambiguity of local appearance with regard to segmentation changes. The resulting sparse model of the object improved reconstruction and search behavior, in particular for data that exhibit a heterogeneous distribution of image information and shape complexity. Furthermore, it went beyond conventional image-based segmentation approaches since it is able to identify reliable image structures which are then encoded within the model and used to determine the optimal segmentation map. We report promising experimental results comparing our approach with standard models in various clinical settings.
- In [42] we introduce a new approach to knowledge-based segmentation. Our method consists of a novel representation to model shape variations as well as an efficient inference procedure to fit the model to new data. The considered shape model is similarity-invariant and refers to an incomplete graph that consists of intra and intercluster connections representing the inter-dependecies of control points. The clusters are determined according to the co-dependencies of the deformations of the control points within the training set. The connections between the components of a cluster represent the local structure while the connections between the clusters centers account for the global structure. The distributions of the normalized distances between these connections encode the prior model. During search, this model is used together with a discrete markov random field (MRF) based segmentation, where the unknown variables are the positions of the control points in the image domain. To encode the image support, a Voronoi decomposition of the domain is considered and regional based statistics are used. The resulting model is computationally efficient, can encode complex statistical models of shape variations and benefits from the image support of the entire spatial domain.
- In [3] we introduced an Expectation-Maximization (EM) Algorithm is used to jointly segment and recognize deformable objects: our approach consisted in iteratively registering an object with the image, using Active Appearance Model fitting, and then segmenting the object domain using Curve Evolution. Using the variational interpretation of EM both tasks are phrased as optimizing a lower bound on the likelihood of the image, yielding a concise framework for the combination of the two tasks.
- In [15], [27], we proposed a general framework for fusing bottom-up segmentation with top-down object behavior inference over an image/volume sequence. This approach was 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.

5.3. Shape, Landmark & Image-based Deformable Registration

Participants: Nikos Paragios, Georg Langs, Nikos Komodakis, Ari Sotiras, Ben Glocker, Mickael Savinaud.

- Registration of shapes is an important problem in computer vision and medical imaging. Despite enormous progress made over the past decade, still this problem is open. In [10], 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. Such a technique introduces the ability to account for potential registration errors in the model.
- In [6] we have proposed a landmark-point point registration method for highly deformable shapes. This method was used to assess the motion after thoracic endovascular repair. The method has used shape maps [34] to determine the most appropriate correspondences and thin plate splines towards estimating the deformation between the two shapes for the case of highly deformable structures [28]. In [39] we have extended this method towards incorporating shape information (silhouette-driven matching), as well as intensity correspondences (optical flow constraint) within a variational framework. The resulting was used for temporal filtering of measurements on optical images of small animals through motion compensation.
- In [1] we introduced a novel and efficient approach to dense image registration, which does not require a derivative of the employed cost function. In such a context the registration problem is formulated using a discrete Markov Random Field objective function. First, towards dimensionality reduction on the variables we assume that the dense deformation field can be expressed using a small number of control points (registration grid) and an interpolation strategy. Then, the registration cost is expressed using a discrete sum over image costs (using an arbitrary similarity measure) projected on the control points, and a smoothness term that penalizes local deviations on the deformation field according to a neighborhood system on the grid. Towards a discrete approach the search space is quantized resulting in a fully discrete model. In order to account for large deformations and produce results on a high resolution level a multi-scale incremental approach is considered where the optimal solution is iteratively updated. This is done through successive morphing of the source towards the target image. Efficient linear programming using the primal dual principles is considered to recover the lowest potential of the cost function. Towards addressing the main limitation of the discrete optimization methods that is the quatization of the search space, in [26] we have proposed the use of uncertainties to locally determine the range of the search space.
- In [45] we proposed a novel framework 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 is a 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.

5.4. Discrete Optimization, Duality & Linear Programming

Participants: Nikos Komodakis, Nikos Paragios, George Tziritas.

Parameters inference is the most critical aspect in computational medicine and efficient optimization algorithms are to be considered both in terms of computational complexity as well as of inference performance. Discrete MRFs are a very promising framework that assumes local/limited interactions between the model variables. Such a paradigm can be used to efficiently model a number of problems in medical imaging, like denoising, enhancement, feature extraction, segmentation, shape alignment, registration, etc. However, most of the existing methods were constrained from the type of interactions that one can introduce between the model variables. The use of relaxation techniques, linear programming and duality are a prominent direction to deal with the minimization of generic MRFs.

- In [5] we introduced a novel method to address minimization of static and dynamic MRFs. Our approach is based on principles from linear programming and, in particular, on primal dual strategies. It generalizes prior state-of-the-art methods such as α-expansion, while it can also be used for efficiently minimizing NP-hard problems with complex pair-wise potential functions. Furthermore, it offers a substantial speedup - of a magnitude ten - over existing techniques, due to the fact that it exploits information coming not only from the original MRF problem, but also from a dual one. The proposed technique consists of recovering pair of solutions for the primal and the dual such that the gap between them is minimized. Therefore, it can also boost performance of dynamic MRFs, where one should expect that the new new pair of primal-dual solutions is closed to the previous one.
- In [32] we have focused our attention on MRFs problems where the relaxation is known to be loose, or the solution of the relaxed problem is not optimal for the original one. We have introduced a novel generic solver that it does so by relying on a much tighter class of LP-relaxations, called cycle-relaxations. With the help of this class of relaxations, our algorithm tries to deal with a difficulty lying at the heart of MRF optimization: the existence of inconsistent cycles. To this end, it uses an operation called cycle-repairing. The goal of that operation is to fix any inconsistent cycles that may appear during optimization, instead of simply ignoring them as usually done up to now. The more the repaired cycles, the tighter the underlying LP relaxation becomes. As a result of this procedure, our algorithm is capable of providing almost optimal solutions even for very general MRFs with arbitrary potentials.
- In [43] towards addressing MRFs of higher order with arbitrary dependencies between the model variables we have introduced a novel optimization approach to derive an optimizer. . 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: Nikos Paragios, Jean-Francois Deux, Alain Rahmouni, Hicham Kobeiter, Pierre Carlier, Phillipe Grenier, Phillipe Trosini-Desert, Thomas Similowski, Jerome Garrot.

- **Risk Assessment of Abdominal Aorta Prosthetic Surgery after aortic aneurysm** [CHU Henri Mondor]: The purpose of this study is to evaluate the magnitude of local stress in patients that have undergone aortic surgery. To this end, we assume that multiple cardiac phases have been acquired after surgery and we aim to determine the local risk of failure of the prosthetic segment due to important motion within the cardiac cycle. Such study aims to demonstrate that the risk is varying spatially and aims to improve performance of the procedure through reinforcement in areas sustaining important deformations within the cardiac cycle. To this end, within the scope of this research initiative four aspects are to be addressed, (i) registration between multiple cardiac phases, (ii) estimation of the local displacement of the abdominal aorta within the cardiac cycle, (iii) separation/decomposition of this motion into two components; one due to the motion of the abdominal aorta due the heart beating and the second due to the local motion, (iiii) statistical characterization of the local motion and estimation of risk factor through a global analysis on the observed motion vectors.

- **Diffusion Tensor Imaging and the Human Skeletal Muscle** [12] [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 on 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.
- **Mathematical Modeling of the Remodeling Process of the Left Ventricle after Myocardial Infarction**: [CHU Henri Mondor]: Cardiovascular diseases are the leading cause of deaths in the developed countries. Among them, myocardial infarction is a predominant disease that affects the capacity of the ventricle of pumping oxygenated blood to the entire body. Such a disease affects an important percentage of the population, and is often quite threatening with the survival rate being very low. Diagnosis on the vitality of the subject is often related with the ability of the ventricle to remodel towards accounting for the presence of dead tissues. Such diagnosis is often based in subjective criteria related with the physiological conditions of the subject (age, physical conditions, medical history, etc.) prior to infarction. To accelerate the remodeling process, cell therapy may be considered through ejection in infracted areas. In the context of this project we aim to study the remodeling process after infarction and build mathematical models capable of predicting the state of the ventricle in the future from past states. Such an ambitious objective will be the first attempt to propose a patient objective-driven quantification of the remodeling process that could be used to adjust treatment strategies.
- **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 to the physicians 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 navigation take places of 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 has participated to the ANR-Blanc Grant SURF (2005-2008) with aim to bridge the gap between continuous and discrete optimization in collaboration with the Ecole de Ponts, ESIEE, and Paris-Dauphine.
- Galen has participated to 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 has participated to the Region-IDF Grant TER-Motion (2007-2008) with aim to study the impact of thoracic endo-vascular repair through the analysis of spatio-temporal computed tomography images in collaboration with the CHU-Henri Mondor University Hospital.
- Galen has participated to 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 Univerity 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 ECE Department of the Ecole Federale Polytechnique de Laussane aiming the development of joint segmentation/classification tools and their applications in computer vision and medical image analysis.

6.3. Industrial Collaborations & Grants

Participant: Nikos Paragios.

- Galen has worked with Siemens towards development of automatic segmentation tools for the human skeletal muscle.
- Galen has worked with Intrasense towards development of automatic segmentation tools for liver images as well as automatic tumor cancer detection.
- Galen has worked with BiospaceLab towards development of automatic registration and fusion between fluroscopic and video images towards signal enhancement.
- Galen has signed an agreement with Intrasense towards non-exclusive commercialization of the deformable registration technology developed within the group.

7. Dissemination

7.1. Scientific Community animation

7.1.1. Journal & Conference Editorial Activities

Participants: Nikos Paragios, Iasonas Kokkinos, Nikos Komodakis, Nikos 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). N. Paragios was guest editor for the Computer Vision and Image Understanding Journal of the special issue in Discrete Optimization in Computer Vision.
- **Conference Boards**: N. Paragios was an area chair for the Medical Imaging and Computing Computer Assisted Intervention Conference (MICCAI'08), and the IEEE International Conference on Bioinformatics and Bioengineering (BIBE'08). N. Paragios was tutorial chair for the European Conference in Computer Vision Conference (ECCV'08) and the IEEE European Signal Processing Conference (EUSIPCO'08).
- **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), the IEEE Transactions on Information Forensics and Security (T-IFS) and the Computer Vision and Image Understanding Journal (CVIU).
  - N. Komodakis was member of the conference committee for the IEEE Computer Vision and Pattern Recognition Conference (CVPR'08), the European Conference in Computer Vision Conference (ECCV'08), the IARP International Conference on Pattern Recognition (ICPR'08), the International Symposium on Visual Computing (ISVC'08), the IEEE European Signal Processing Conference (EUSIPCO'08) and the Advanced Concepts for Intelligent Vision Systems Conference (ACIVS'08).

    N. Komodakis was reviewer for the IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI), the IEEE Transactions on Image Processing (T-IP)the Journal of Machine Learning Research (JMLR), the Computer Vision and Image Understanding Journal (CVIU) and the International Journal of Computer Vision (IJCV.
  - G. Langs was member of the conference committee for the IEEE Computer Vision and Pattern Recognition Conference (CVPR'08), the European Conference in Computer Vision Conference (ECCV'08), the Medical Imaging and Computing Computer Assisted Intervention Conference (MICCAI'08), the Advanced Concepts for Intelligent Vision Systems Conference (ACIVS'08) and the IEEE International Conference on Bioinformatics and Bioengineering (BIBE'08).

    G. Langs was reviewer for the IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI), the IEEE Transactions on Medical Imaging (IEEE-TMI), the IEEE Transactions on Image Processing (IEEE-IP) and the Elsevier Computers in Biology and Medicine Journal.
  - N. Paragios was member of the conference committee for the IEEE Computer Vision and Pattern Recognition Conference (CVPR'08), the European Conference in Computer Vision Conference (ECCV'08), the IARP International Conference in Pattern Recognition (ICPR'08), the IEEE International Conference in Image Processing (ICIP'08), the Canadian Conference in Computer Vision (CRV'08), the International Symposium on Visual Computing (ISVC'08), the Advanced Concepts for Intelligent Vision Systems Conference (ACIVS'08) and the IEEE European Signal Processing Conference (EUSIPCO'08).

N. Paragios was reviewer for the IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI),IEEE Transactions on Medical Imaging (T-TMI), the IEEE Transactions on Image Processing (T-IP) and the NeuroImage Journal (Neuro).

N. Paragios was reviewer for the Swiss Research Council, the Austrian Science Foundation, the Israeli Science Foundation, the Belgium Science Foundation, the Canadian Science Foundation and the European Union Commission (FP).

7.1.2. Thesis & Doctoral Committees Participation

Participant: Nikos Paragios.

- **Reviewer for Doctoral Science Dissertations**: N. Paragios was reviewer for: (1) Dr. Adrien Bartoli, University of Clermont-Ferrand.
- **Reviewer of PhD Thesis Committees**: N. Paragios was reviewer for: (1) Laura Gui - Ecole Federale Polytechnique de Lausanne, (2) Effrosyni Kokiopoulou - Ecole Federale Polytechnique de Lausanne, (3) Pierre Maurel - Ecole Normale Superieure, (4) Ting Peng - Chinese Academy of Sciences, (5) Sylvain Boltz - University of Nice-Sophia Antipolis, (6) Hanna Martinsson - University of Clermont-Ferrand, (7) Kinda Saddi - Ecole Polutechnique de Montreal.
- **Membder of PhD Thesis Committees**: N. Paragios was member for: (1) Noura Azzabou - Ecole de Ponts, (2) Camille Izard - University of Lille.

7.1.3. Invited Lectures & Honors, Distinctions

Participants: Nikos Paragios, Nikos Komodakis, Nikos Langs.

- **Distinctions/Honors**: N. Paragios was the recipient of the Bodosakis Foundation Prize, the highest distinction for young (under the age of 40) Greek academic scholar and scientists (origin or descent) in the field of applied sciences.
- **Tutorials**:
  - N. Komodakis presented a tutorial in Discrete Optimization at the IEEE European Signal Processing Conference (EUSIPCO'08).
  - G. Langs presented a tutorial on Autonomous Model Bulding at the Medical Imaging and Computing Computer Assisted Intervention Conference (MICCAI'08).
- **Invited Presentations**:
  - N. Komodakis gave invited presentations to the: Microsoft Research - Cambridge, Institut of Pure and Applied Mathematics - UCLA and NIPS Workshop on Approximate Inference in Graphical Models.
  - G. Langs gave invited presentations to the: State University of New York at Stony Brook and National Bookheaven Laboratory.
  - N. Paragios gave invited presentations to the: Pattern Recognition Laboratory of the Chinese National Academy of Science, Ecole Polytechnique, and Medical Image Understanding and Analysis Conference (MIUA'08).

7.2. Teaching

Participants: Nikos Paragios, Iasonas Kokkinos, Georg Langs, Olivier Juan.

- **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 of the pattern recognition class (M.Sc. level) at the Ecole Centrale de Paris (24 hours),
- G. Langs was the instructor of the medical imaging class (second year) at the Ecole Centrale de Paris (21 hours, 15 students),
- O. Juan was the instructor of the computer vision class (second year) at the Ecole Centrale de Paris (21 hours, 35 students),
- N. Paragios was the instructor or has participated to:
  * 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

Major publications by the team in recent years

[1] B. GLOCKER, N. KOMODAKIS, G. TZIRITAS, N. NAVAB, N. PARAGIOS. *Dense Image Registration through MRFs and Efficient Linear Programming*, in "Medical Image Analysis Journal", 2008, (in press).

[2] L. GUI, J.-P. THIRAN, N. PARAGIOS. *Cooperative Object Segmentation and Behavior Inference in Image Sequences*, in "International Journal of Computer Vision", vol. 76, n^{o} 3, 2008, p. 231-243.

[3] I. KOKKINOS, P. MARAGOS. *Synergy Between Image Segmentation and Object Recognition Using the Expectation Maximization Algorithm*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", 2009, in press.

[4] N. KOMODAKIS, N. PARAGIOS, G. TZIRITAS. *Clustering via LP-based Stabilities*, in "Neural Information Processing Systems (NIPS'08)", 2008, (in press).

[5] N. KOMODAKIS, G. TZIRITAS, N. PARAGIOS. *Performance vs Computational Efficiency for Optimizing Single and Dynamic MRFs: Setting the State of the Art with Primal Dual Strategies*, in "Computer Vision and Image Understanding Journal", 2008, (in press).

[6] G. LANGS, P. PELOSCHEK, H. BISCHOF, F. KAINBERGER. *Automatic Quantification of Joint Space Narrowing and Erosions in Rheumatoid Arthritis*, in "IEEE Transactions on Medical Imaging", 2008, (in press).

[7] N. PARAGIOS, Y. CHEN, O. FAUGERAS. *Handbook of Mathematical Models in Computer Vision*, Springer, 2009.

[8] N. PARAGIOS, J. DUNCAN, N. AYACHE. *Medical Image Analysis: Methodologies and Applications*, Springer, 2009.

[9] M. ROUSSON, N. PARAGIOS. *Prior Knowledge, Level Set Representations and Visual Grouping*, in "International Journal of Computer Vision", 2008.

[10] M. TARON, N. PARAGIOS, M.-P. JOLLY. *Registration with Uncertainties and Statistical Modeling of Shapes with Variable Metric Kernels*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", 2009, (in press).

[11] K. VARSHNEY, N. PARAGIOS, J.-F. DEUX, A. KULSKI, R. RAYMOND, P. HERNIGOU, A. RAHMOUNI. *Post-Arthroplasty Examination Using X-Ray Images*, in "IEEE Transactions on Medical Imaging", 2009, (in press).

Year Publications

Articles in International Peer-Reviewed Journal

[12] J.-F. DEUX, P. MALZY, N. PARAGIOS, G. BASSEZ, A. LUCIANI, P. ZERBIBA, A. VIGNAUD, A. RAHMOUNI. *Assessment of calf muscles contraction by Diffusion Tensor Imaging*, in "European Radiology", 2008, p. 2303-2010.

[13] B. GLOCKER, N. KOMODAKIS, G. TZIRITAS, N. NAVAB, N. PARAGIOS. *Dense Image Registration through MRFs and Efficient Linear Programming*, in "Medical Image Analysis Journal", to appear, 2008.

[14] L. GUI, J.-P. THIRAN, N. PARAGIOS. *Cooperative Object Segmentation and Behavior Inference in Image Sequences*, in "International Journal of Computer Vision", vol. 76, n^{o} 3, 2008, p. 231-243.

[15] L. GUI, J.-P. THIRAN, N. PARAGIOS. *Cooperative Object Segmentation and Behavior Inference in Image Sequences*, in "International Journal of Computer Vision", to appear, 2008.

[16] I. KOKKINOS, G. EVANGELOPOULOS, P. MARAGOS. *Texture Analysis and Segmentation Using Modulation Features, Generative Models and Weighted Curve Evolution*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", 2009, p. 142-157.

[17] I. KOKKINOS, P. MARAGOS. *Synergy Between Image Segmentation and Object Recognition Using the Expectation Maximization Algorithm*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", in press, 2009.

[18] N. KOMODAKIS, G. TZIRITAS, N. PARAGIOS. *Performance vs Computational Efficiency for Optimizing Single and Dynamic MRFs: Setting the State of the Art with Primal Dual Strategies*, in "Computer Vision and Image Understanding Journal", to appear, 2008.

[19] G. LANGS, P. PELOSCHEK, H. BISCHOF, F. KAINBERGER. *Automatic Quantification of Joint Space Narrowing and Erosions in Rheumatoid Arthritis*, in "IEEE Transactions on Medical Imaging", to appear, 2008.

[20] M. ROUSSON, N. PARAGIOS. *Prior Knowledge, Level Set Representations and Visual Grouping*, in "International Journal of Computer Vision", 2008.

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[22] K. VARSHNEY, N. PARAGIOS, J.-F. DEUX, A. KULSKI, R. RAYMOND, P. HERNIGOU, A. RAHMOUNI. *Post-Arthroplasty Examination Using X-Ray Images*, in "IEEE Transactions on Medical Imaging", to appear, 2009.

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[23] N. AZZABOU, N. PARAGIOS. *Spatio-Temporal Speckle Reduction In Ultrasound Sequences*, in "International Conference on Medical image computing and computer assisted intervention (MICCAI'08)", to appear, 2008.

[24] S. ESSAFI, G. LANGS, N. PARAGIOS. *Sparsity, Redundancy andOptimal Image Support towards Knowledge-based Segmentation*, in "IEEE Conference in Computer Vision and Pattern Recognition (CVPR'08)", to appear, 2008.

[25] B. GLOCKER, N. PARAGIOS, N. KOMODAKIS, G. TZIRITAS, N. NAVAB. *Optical Flow Estimation with Uncertainties through Dynamic MRFs*, in "IEEE Conference in Computer Vision and Pattern Recognition (CVPR'08)", to appear, 2008.

[26] B. GLOCKER, N. PARAGIOS, N. KOMODAKIS, G. TZIRITAS, N. NAVAB. *Optical Flow Estimation with Uncertainties through Dynamic MRFs*, in "IEEE Conference in Computer Vision and Pattern Recognition (CVPR'08)", to appear, 2008.

[27] L. GUI, J.-P. THIRAN, N. PARAGIOS. *Finger-spelling Recognition within a Collaborative Segmentation/Behavior Inference Framework*, in "IEEE European Signal Processing Conference (EUSIPCO-08)", to appear, 2008.

[28] Y. HAN, G. LANGS, N. PARAGIOS. *Group-wise MDL based registration of small animals in video sequences*, in "International Symposium on Biomedical Imaging (ISBI'08)", to appear, 2008.

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[31] I. KOKKINOS, A. YUILLE. *Scale Invariance without Scale Selection*, in "IEEE Conference in Computer Vision and Pattern Recognition (CVPR'08)", to appear, 2008.

[32] N. KOMODAKIS, N. PARAGIOS. *Beyond Loose LP-relaxations: Optimizing MRFs by Repairing Cycles*, in "European Conference in Computer Vision (ECCV'08)", 2008.

[33] N. KOMODAKIS, N. PARAGIOS, G. TZIRITAS. *Clustering via LP-based Stabilities*, in "Neural Information Processing Systems (NIPS'08)", to appear, 2008.

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[37] D. PESCIA, N. PARAGIOS, S. CHEMOUNY. *Automatic Detection of Liver Tumors*, in "International Symposium on Biomedical Imaging (ISBI'08)", to appear, 2008.

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[40] C. WACHINGER, B. GLOCKER, N. ZELTNER, N. PARAGIOS, N. KOMODAKIS, M. HANSEN, N. NAVAB. *Deformable Mosaicing for Whole-body MRI*, in "International Conference on Medical image computing and computer assisted intervention (MICCAI'08)", to appear, 2008.

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[41] N. PARAGIOS, J. DUNCAN, N. AYACHE. *Medical Image Analysis: Methodologies and Applications*, Springer, 2009.

Research Reports

[42] A. BESBES, N. PARAGIOS, N. KOMODAKIS. *Cue Integration and Discrete MRFs towards Knowledge-based Segmentation*, to appear, Technical report, INRIA, 2009.

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