Multi-modality Cardiac Imaging
Multi-modality Cardiac Imaging

Processing and Analysis

Edited by

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Preface

The objective of the present book is to propose a review of processing and analysis methods of images generated by cardiac imaging systems, echocardiography, magnetic resonance imaging and computed tomography, notably.

Part of the work presented in this book has been achieved in the framework of several French collaborative projects, notably:

– two specific actions of the GdR STIC-Santé, GdR CNRS/Inserm 2647, from 2008 to 2011; Multicentric Initiative for an Evaluation Platform in Cardiac Imaging (IMPEIC) and Medical Image segmentation Evaluation (MedIEval); then the research group in cardiac imaging (GRIC);

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Introduction

If there is an application domain of medical image processing which has been and which is still very active, it is certainly the analysis and processing of cardiac images in various modalities. There is not a single conference in the field of medical image processing and analysis that does not involve contributions in cardiac imaging. The first reason for this fact is that dynamic heart and thoracic imaging produces increasingly more images of a diverse nature from which the extraction of useful and quantified information remains difficult. Clinical practice is followed to such an extent today that examinations follow each other in a short period of time and medical reports must be established very early. Another reason for this keen interest is that “the heart organ” presents many different facets – perfusion, tissue properties, mechanical behavior, energy metabolism, electrical propagation, etc. – making it fascinating to most inquisitive minds and an almost inexhaustible source of questions and challenges. Although enormous progress has been made in the understanding of the complex mechanisms involved, there still remain many fundamental questions about the normal functioning of the heart and the alterations generated by pathologies. Whether for a better understanding of the functioning or for a better management of patient care, imaging has become indispensable and with it the needs in terms of quantification increasingly more significant. As an example: how can we extract and evaluate the dynamics of the heart in three dimensions (3D) during the cardiac cycle and present this information in a synthetic manner to the clinician? Software tools must be developed to facilitate interpretation. The concern is about creating support for the extraction, monitoring and characterization of deformable anatomical structures, estimating the motion

Introduction written by Patrick CLARYSSE and Denis FRIBOULET.
of structures, modeling and interpreting motion or contrast enhancement. This book is intended for students, scientists and engineers required to work in this exciting field with the ambition of facilitating the access and the understanding of a rich and multidisciplinary bibliography. It presents a synopsis of image processing and analysis methods dedicated to the heart. We did not try to be exhaustive. Thus, from the point of view of modalities, we have mainly considered ultrasound imaging, magnetic resonance imaging (MRI) and computed tomography. From the point of view of the physical quantities of interest, we have limited ourselves to geometry, kinetics and perfusion. Finally, diagnosis is favored; we will therefore barely speak of interventional cardiology. The methods proposed for the heart are inspired by methodological developments in image processing, sometimes quite sophisticated. This is why we found it useful to organize this book into three parts. Part 1 presents concepts and generic methods of image processing, specifying their adaptation to heart imaging. Thus, Chapters 1–4 focus, respectively, on the extraction of surfaces/contours of the heart, on the quantification and the analysis of motion, on approaches to modeling and for the quantification of the perfusion, and on the decomposition of dynamic image sequences for contrast enhancement and motion analysis. Part 2 presents several examples of applications. In cardiac imaging as in other application contexts of medical image processing, evaluation remains essential but difficult due to the lack of reference. Chapter 5 presents a bibliographical summary of evaluation approaches of segmentation methods of cardiac structures in MRI. Chapter 6 introduces two methods of motion estimation based on spatial phase applied successfully in ultrasound imaging and MRI. The case of MRI with tissue tagging is discussed in Chapter 7 by means of a free software program specifically developed for the quantification of myocardial deformations. A method for the analysis of the cardiac dynamics from matching of surfaces issued from X-ray computed tomography is presented and evaluated in Chapter 8. Finally, the combination of advanced data and image processing methods, and of complex models, makes it possible to prepare a patient-specific cardiology. It is this perspective that Chapter 9 will introduce in the third and final part.
PART 1

Methodological Bases
1.1. Problematics

The analysis of imaged anatomical or biological structures and of their dynamics is an important task in terms of application and therefore of diagnostics. This analysis facilitates the quantification of the shape of these structures and their possible evolution over time, whether this evolution is intrinsic to the functioning of the structure (cardiac motion for example) or indicating a transformation related to a pathology (tumor evolution).

Such an analysis involves in the first place the extraction of these structures from the acquired images according to a given modality, which corresponds, in image processing terminology, to a segmentation phase. This chapter is devoted to this problem: after a very brief overview of the existing techniques, it discusses in detail the methodology of deformable models and more specifically their more flexible form, namely variational active contours. The chapter concludes with specific examples for the application of this type of technique carried out in the field of cardiac ultrasound imaging.

1.2. Overview of segmentation methods

Segmentation is a fundamental operation in imaging and cardiac and thoracic imaging in particular. Its role consists of assigning to the parts of an
image a relevant category (“muscle”, “blood”, “tumor”, etc.) relating to the underlying medical application: detection of the presence/absence of a pathological structure (for example “tumor”, “aneurysm”), evaluation of the area, the extent, the volume of organs or the pathological structures as well as their evolution over time. Due to this central role, image segmentation is a very active area of research. This can be illustrated by observing the result of a search on the Web of Science® (Figure 1.1) and based on the presence of the terms “image segmentation” in the title of articles over 15 years (1994–2009). It can be seen that more than 4,700 articles\(^1\) have been published during this period and that this number is constantly increasing.

\[\text{Total }= 4,790 \text{ articles}\]

**Figure 1.1. Number of articles containing the terms “image segmentation” in the title for the period 1994–2009**

A segmentation method can be schematically characterized by three main elements (see Figure 1.2): (1) the low level properties (or “image information”) used to characterize the objects to detect, (2) \textit{a priori} knowledge introduced to constrain the segmentation and (3) the formalism chosen to integrate these two pieces of information.

\(^1\) It should be noted that these figures likely provide an underestimation of the actual number of articles related to this theme, where research has been restricted to the titles of articles.
If only the “image information” aspect is considered, segmentation can be formally defined as an operation consisting of partitioning the image in related regions verifying a consistency predicate, based for example on statistical properties or on texture. Segmentation can also be carried out according to a dual approach by considering the differences between these regions: two adjacent regions must actually present significant variations of properties along their common border. These variations can be quantified using conventional differential operators (for example, the amplitude of the gray level gradient) or more sophisticated techniques such as the phase-based approach developed by [MUL 00]. Following these definitions, segmentation methods are conventionally qualified as “region-based approaches” or “contour-based approaches”.

Due to imperfections presented by images (i.e. noise, occlusions, lack of contrast, etc.), to perform a segmentation using only the region or contour characteristics previously referred to reveals itself in most cases to be difficult, if not impossible. That is why \textit{a priori} knowledge is usually introduced, relative to the intrinsic properties of the object to be detected, such as its shape, its grayscale distribution or its motion when it comes to image sequence. This knowledge may be purely abstract (for example “the form of the object must be smooth”) or built from the statistical analysis of a training set representative of the images to process. Once established, these \textit{a priori} knowledge...
priori must be formalized and incorporated as constraints in the segmentation process. It is worth noting that the majority of the constraints used refer to the shape of the objects to segment.

These two types of information – image properties and a priori constraints – must then be integrated into a common formalism, itself numerically implemented as an algorithm. The importance of image segmentation research, highlighted above, has led to the development of many approaches, such as active contours, active shape models (ASM), approaches by classification, Markov fields, etc. We will focus in this chapter on one of the most important approaches in cardiac and thoracic imaging, namely deformable models.

1.3. Summary of the different classes of deformable models

Deformable models constitute a dominant approach to segmentation. They were originally introduced by Kass et al. [KAS 88] with the “snakes model” and quickly found applications in medical imaging. This significance relates to the fact that their formulation is very flexible, allowing the integration of many types of image properties and a priori constraints. As such, the literature concerning deformable models is highly significant and in this introductory section, we consider very synthetically two broad classes of approaches:

– energy-based approaches: the energy reflecting the properties of the object to segment (gray levels, shape, etc.) and expressed in terms of the deformable model (position and shape) is built. The segmentation process then corresponds to the minimization of this energy;

– in contrast, “non-energy-based approaches” do not involve energy directly dependent on the model. It should be noted that if some of these methods make use of a criterion minimization stage, it is therefore not expressed directly as a function of the deformable model (thus, for example, “atlas approaches” perform a registration step by minimizing a similarity criterion).

Following this section, we will detail more particularly two deformable model approaches: deformable templates (DTs) in section 1.4 and variational active contours in section 1.5.
1.3.1. Non-energy approaches

1.3.1.1. Active shape models

ASMs were originally described by Cootes in 1995 [COO 95]. This approach can be seen as a method of deformable models incorporating intrinsically an a priori on the shape of the object to segment, this a priori being built using a statistical representation of the space of the eligible shapes.

In practice, this representation is constructed from a training set of images, where contours are manually plotted, aligned and sampled on N points. This step enables the construction of a model of distribution of contour points from which shape statistics are established by using principal component analysis (PCA), which provides the average shape and the K main variation modes of this shape. The object to segment is then detected by iteratively deforming an initial contour: each of the N points of this outline is shifted in order to move it closer to the edge of highest amplitude located in its neighborhood. This set of displacements provides a new set of points that is projected onto the K main variation modes: the new shape obtained is thus forced to belong to the space of eligible shapes defined by these modes. This process is iterated until convergence, namely when the displacements can be considered as negligible.

Active appearance models (AAMs) constitute an extension of the ASMs [COO 01]. In this approach, the constraint concerns not only the shape but also the appearance, defined as the average and the principal variation modes of the normalized gray levels of the region corresponding to the reference contours. An example of the application of this technique in echocardiography can be found in [BOS 02].

1.3.1.2. Atlas-based approaches

The basic principle of atlas-based segmentation is conceptually simple. An atlas corresponds to a pair made of an image of a given modality and its segmentation, represented by a set of labeled regions. This segmentation is most often obtained by performing a manual outline. The segmentation of a new image of the same modality is then performed in two stages. The atlas image and the new image are first mapped using a registration algorithm, which uses the local properties of these images (from gray levels). Thus, this registration phase provides, on output, the transformation that allows us to map the “atlas image” to the new image. This transformation is then applied to the labeled regions of the atlas, thus providing the new image segmentation.

Within this framework, the different approaches of atlas segmentation are distinguished by the type of registration used, namely by the type of
transformation (affine, rigid, nonlinear, etc.) and the similarity measure (absolute differences, mutual information, etc.) implemented in the algorithm. Another important feature lies in the construction and use of the atlas: if the base method considers a single atlas, a number of authors have proposed to improve the method either by using an average atlas, or by selecting the atlas best suited to the new image in a base of atlases. Any reader wishing to deepen their knowledge on the technical aspects of atlas segmentation can usefully consult some general articles such as [ROH 05] and [RAM 10].

1.3.1.3. PDE-based approaches

As a first step, some approaches that make use of deformable models have been developed based solely on the definition of the evolution equation without necessarily going through energy minimization. We will call these methods “PDE-based approaches” because they share the use of a geometric partial differential equation (PDE) to define the evolution of an active contour. These have notably originated conventional approaches such as an “active contour” presented in detail in section 1.5. Thus, Malladi et al. [MAL 95] and Caselles et al. [CAS 93] have introduced as a first step geometric active contours for which the evolution speed of the contour is defined based on intrinsic properties of the image such as the gradient and on geometrical properties of the curve such as curvature. Active contours driven by the balloon force introduced by Cohen et al. [COH 91] also fall within this framework. However, in a seminal work, Ronfard [RON 94] defines an evolution equation based on the characteristics of the internal and external regions of the edge thus resulting in a first PDE based on the characteristics of the regions and not anymore simply on the gradient of the image. We will also quote in this section Gradient Vector Flow-based approaches (GVF-based approaches) by Xu and Prince [XU 98] even if the principle is very different. In this type of approach, a contour displacement field is precomputed and used as additional velocity to the snakes model proposed by Kass et al. [KAS 88].

1.3.2. Energy-based approaches

1.3.2.1. Variational approaches

Deformable models based on the variational approach are most often called “active contours” and constitute the most frequent form of these models. Variational active contours are characterized by an energy functional, whose minimum corresponds to the required segmentation (hence the term variational): thus the object to be detected is segmented by iteratively distorting an initial contour (or a 3D surface), in such a way that this
evolution decreases the energy until it reaches a minimum. In two dimensions, this approach translates into the evolution of an initial curve in an image toward the structure to segment (Figure 1.3).

An important characteristic of this approach lies in the fact that the evolution leading to a minimum can be obtained systematically by standard variational calculation (i.e. Euler-Lagrange equations or Gâteaux derivatives) or by using shape gradients. The implementation of the variational active contours for a given application passes in practice through the following steps and choices:

– choice of the representation of the active contour (see Figure 1.5, sections 1.5.1.2 and 1.5.1.3). This representation may be explicit, or most often parametric or implicit;

– formulation of the energy functional. This step depends on the application, since the functional should be constructed so that a local minimum is associated with the border of the object to be detected;

– obtaining the evolution equation. This step involves the calculation of the variational derivative of the functional (Euler-Lagrange’s equations or Gâteaux derivative) or of the associated shape gradient. This equation consists formally of a PDE.

Figure 1.3. Active contour segmentation principle. The initial contour a) is distorted to detect an object in an image b). For a color version of this figure, see www.iste.co.uk/clarysse/cardiac.zip

The technical aspects of implementing these stages are described in section 1.5. Section 1.6 details the different approaches used to introduce the shape and motion constraints in this formalism and section 1.7 provides examples of the implementation of this approach in the context of 2D and 3D echocardiographic imaging.
1.3.2.2. **Dual approaches**

The use of dual approaches [CHA 99, CHA 04, AUJ 05] and of tools borrowed from convex optimization is one of the current alternatives to conventional minimization methods through the use of a PDE resulting from Euler-Lagrange’s equations. These minimization algorithms thus present the advantage of being generally more effective in terms of calculation costs and above all, they facilitate obtaining the global minimum (or minima). They are based on the duality theory and convex optimization and they therefore require the transformation of the initial optimization problem into a convex research problem of an optimal $u$ function. With regard to the particular case of segmentation, instead of searching for an optimal domain (the search space being non-convex), the approach consists of searching for a functional $u$ belonging to the space of bounded variation functions. The optimal function $u^*$ will then be thresholded in order to split the image into two optimal areas with regard to the considered criterion. In a first approach, Nikolova et al. [NIK 06] have proposed this methodology by providing a first convex resolution of the Chan and Vese’s model [CHA 01]. Then the works of Bresson et al. [BRE 07] helped to highlight the existing relationship between models based on the minimization of the total variation and geodesic active contours. Problematics related to these approaches exist in the choice of the threshold to find the final segmentation and also in the convexification of the initial criterion (it should be noted that a recent solution has been proposed in [BRO 12]). A large number of approaches explore dual methods in applications such as noise removal or restoration. Among the approaches that use dual-based segmentation approaches for medical imaging, [WOJ 10] can be cited, for example, where applications concerning the segmentation of PET-CT multimodal images of the thorax were studied.

1.3.2.3. **Discrete approaches**

We will here mention briefly various segmentation techniques that make use of discrete representations to solve PDEs. Some approaches propose to use properties in graphs after optimization (example [BOY 06]). Other more recent approaches directly reformulate the criterion or the PDEs on discrete structures such as graphs using equivalences between continuous and discrete formulations. These equivalences can be carried out either by combinatorial approaches or by finite difference calculations. Thus, Grady et al. [GRA 08, GRA 09] propose to completely reformulate some segmentation criteria used in the context of deformable models (including that of Chan and Vese [CHA 01]). Their approach is based on the reformulation of the various derivation operators by using combinatorial analogs of differential operators. One of the difficulties of these approaches lies in the discrete mapping of the