Shape and Semantics
for 3D Anatomical Structure Retrieval

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Abstract. In this paper, we propose a framework for the description of anatomical structures based on topological and geometrical features and on semantic annotation. The main goal is to enhance the description of an anatomical structure –understood as a 3D model– with other *non-geometrical* pieces of information relevant to the particular problem-context. Hybrid methods for similarity searches are then introduced and shown to be able to support effective case-based reasoning procedures. The approach is illustrated with examples from several medical application fields in order to discuss its potential impact.

1 Introduction

In the field of medical imaging, the analysis of the shape of anatomical structures may shed new light in understanding their functional properties and may be used to support the decision-making processes in diagnosis and treatment. For example, it has been shown that irregular growth of the hippocampus is strongly correlated to epilepsy [1]. Thus, the development of computerized tools for hippocampus segmentation and reconstruction together with retrieval of similar cases in an annotated database may be used as a clinical decision support in preoperative planning. Further, in the field of neurology, modelling and simulation of intracranial phenomena –such as haemorrhages, neoplasm and hematoma– may be used to analyze the influences they have on neurofunctional structures in the brain [2]. In cardiology, the modelling of the heart may be used at different levels to analyze local and global myocardial performance and define new quantitative parameters for injury evaluation [3].

Imaging modalities are the fundamental source of raw data on which to perform such kind of shape analysis. Nowadays, the more and more increasing number of techniques (e.g. MRI, fMRI, CT, Ultrasound, PET, SPECT, PAM and fPAM, . . .) is able to provide reliable anatomical images together with various and rich functional information, ranging from perfusion to metabolism, from absorption to diffusion. In addition, some of these modalities allow to acquire video sequences of dynamic phenomena, involving for example the deformation of anatomical structures, and, thus, high dimensional data (2 or 3 spatial dimensions plus time).

Further, such diagnostic resources are becoming more and more accessible and common. This results in the production, on a daily basis, of a bunch of heterogeneous

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image data, which undoubtedly represent a great richness for case-based reasoning and data-mining procedures.

However, the organization and exploitation of such data cannot be fully accomplished unless with the help of suitable tools for image analysis, shape representation and annotation.

In the last decade, much effort has been spent in developing methods for the geometric representation of 3D models, especially from a general-purpose perspective (see e.g. [4]). Among other scopes (e.g. classification and categorization), such methods are usually employed to accomplish the retrieval of similar shapes from an annotated database. Given a query shape, the retrieved shapes can then be used for comparison purposes; additional pieces of information available for the retrieved shapes (for example as semantic tags) may also be used as “clues” for analyzing the case at hand.

The impact of such shape description and retrieval techniques has been clearly strong; still, apart from several general-purpose approaches not suited for medical applications, the attempts have been confined to particular and restricted problems without moving towards generic anatomical structures retrieval.

In addition, the association of keywords to 3D models is still a subjective process, often not even based on editable catalogue and, so, exhibiting very limited reusability. Actually, the formalization of the process of geometric and semantic annotation is seen as a necessary condition for enabling cross-modal access to 3D model/image repositories.

This being the general setting, the main aim of this paper is to present a framework for the description of anatomical structures, based both on topological and geometrical features and on semantic annotation. We argue that a 3D model –representing an anatomical structure– may be enhanced with other *non-geometrical* pieces of information relevant to the particular problem-context. Hybrid methods for similarity searches are then introduced and shown to be able to support effective case-based reasoning procedures. This point is illustrated with three examples from various medical application fields, namely neurology, radiotherapy and cardiology.

2 Anatomical Structure Representation

Following the ideas of Grenander and Miller [5], an anatomical structure O embedded in the background space $\Omega \subset \mathbb{R}^d$ $(d = 2,3)$ may be modeled as a collection:

$$O = \{(V^\alpha, P^\alpha)\}_{\alpha=1,2,\dots,k}$$

where each V^α is a smooth manifold (possibly with boundary) embedded in Ω and $P^\alpha : V^\alpha \to \mathbb{R}^{d(\alpha)}$ is a smooth *property function* assuming its values in a suitable properties space. Notice that the collection $\{V^\alpha\}_{\alpha=1,2,\dots,k}$ represents the underlying purely geometrical structure, while the property functions are a structured representation of the local attributes to the geometrical structure.

The smoothness assumption is a quite common hypothesis in computational anatomy and it is satisfied in practice to a large extent; it implies for example that differential geometric properties can be computed everywhere. We use, moreover, collection of manifolds -instead of a single one- to be able to describe structure subparts (possibly

of different dimensionality) by attaching them specific salient attributes via a dedicated property function. For example, in heart left ventricle modeling, the structure of interest is the myocardium, that can be modeled as a 3D manifold, whose boundaries are two surfaces: the epicardium and the endocardium. It is convenient to attach to the boundary surfaces a different (actually richer) set of attributes than those used for internal points. Time-resolved structures $O = (O_t)_{t=0,1,...}$ may be represented as a temporal sequence of structures satisfying some smoothness constraints. Each $O_t = \{(V_t^\alpha, P_t^\alpha)\}_{1 \leq \alpha \leq k}$ should be regarded as the *snapshot* of the deforming structure at time t.
We require that each manifold V_t^α appearing in the snapshot at time t can be smoothly deformed into V_{t+1}^α in the subsequent snapshot. Such modelization is thus adaptable and flexible, permitting to represent geometrically 2D, 3D and time-resolved anatomical structures and their properties in just one framework. Since methods for recovering such representation from raw image data have been extensively described in [6, 7], we focus in the section below on shape characterization for anatomical structures.

3 Shape Characterization

The aim of this section is to provide methods for the representation of a structure which are suitable for similarity searches and data mining procedures. After having reconstructed an anatomical structure as a collection $\{V^\alpha\}_{\alpha=1,2,...,k}$, a first step toward characterization consists in assigning a significant property function $P^\alpha : V^\alpha \to \mathbb{R}^{d(\alpha)}$ to each manifold V^α. Three types of properties may be considered:

- intensity-based properties;
- local shape descriptors;
- local dynamic behavior descriptors (for time-resolved structures only).

Intensity-based properties include gray level value, gradients, textures and the like. Such intensity information may be extracted from the anatomical image leading to structure reconstruction and may correspond to densitometric properties. In addition, data collected from other imaging modalities may be fused (after performing some context-dependent registration procedure) so as to further annotate the structure; for example, in the case of the heart, information regarding perfusion and metabolism, obtained e.g. by means of PET imaging, can be referred to the reconstructed myocardium. Geometric based properties, belonging to the second type, may be extracted directly from the collection of manifolds $\{V^\alpha\}$, and are essential to describe locally the shape of the structure. It is possible to distinguish between context independent features (automatically computable for every manifold of a given dimensionality, such as Gaussian principal curvatures, shape index and curvedness [8] for surfaces) and problem-specific properties.

Notice however that this first characterization (given by collection of manifolds described by functions) is not suited for data mining or similarity searches. The reason is twofold. First, the given description of the whole structures has a dimensionality too high to make the problem computationally feasible. Even worse, a pointwise characterization does not permit, at least in a straightforward manner, the comparison of anatomical structures belonging to different patients, because a point-to-point correspondence

should be first established.
These issues could be addressed in two ways. The first solution is by using a deformable model (given for example by mass-spring models as presented in [2]) and normalizing every instance of anatomical structure to that model: in this way anatomical structures (belonging to the same family) are uniformly described and can be then compared according to the feature-vector paradigm. The second solution, which can be used in tandem with the first, is to use derived global features, not depending of any problem-specific model of the anatomical structure. Generally, the first solution is able to perform a fine discrimination among the dataset; the latter instead may be used to make a first coarse discrimination in order to drastically reduce the search space. We review in the sections below some recent methods for extracting such kind of more intrinsic features using a geometrical approach (Section 3.1) and a topological one (Section 3.2).

3.1 Geometrical Approaches

One of the most simple but flexible geometric approach for the computation of global features not depending on any problem-specific model is given by the so-called *property spectrum* [7]. By definition, the property spectrum is the probability density function (PDF) of a given component of the property function $P^{\alpha}(\cdot)$. The property spectrum captures how the property is globally distributed; thus, comparison of different property spectra is directly feasible; to reduce dimensionality, moreover, it could be effective to compute the momenta of the PDF (mean, variance,. . .). However, property spectrum does not convey any information at all about regional distribution of the property. In clinical applications, this is a drawback which cannot be ignored: actually a small highly anomalous region may not affect appreciably the property spectrum, but its clinical relevance is, usually, not negligible. Hence, spatial distribution of properties has to be analyzed. One approach would be to estimate multidimensional property spectrum. In this way, spatial relationship between different kinds of features could be implicitly encoded. For example, considering the cords going from the center of mass of a structure to its boundary, we may use the cord length and orientation as a property function defined on the structure boundary. See Figure 1.

Then, the associated multidimensional PDF implicitly codifies the elongation axis of the structure. A major issue in dealing with such sort of multidimensional shape distributions is the accurate estimation of the PDF. Some methods, based on the fast Gauss transform, have been reported [9]. Although, this approach may be conceivable for general-purpose 3D structure indexing and retrieval, it has low relevance in medical applications, due to the too implicit encoding and the poor characterization capabilities of local anomalous regions. In the same vein, approaches which do not need a refined model of the structure (e.g., Gaussian image, spherical harmonics, Gabor spherical wavelets and other general purposes shape descriptors used for content-based image retrieval) may be suitable.

However, the introduction of models (or templates) for the anatomical structures under examination should be considered so as to gain more description capability in problem-specific scenarios. Indeed, using matching techniques, the template could be propagated to any particular instance of the anatomical structure to be studied. Then,

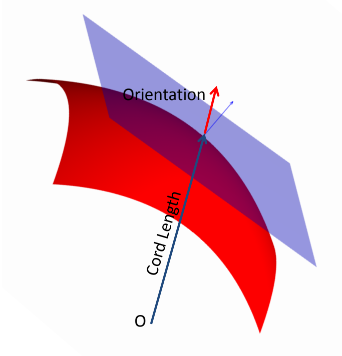


Fig. 1. An example of multivariate property function, encoding important spatial relationship among features. We consider for each point of the structure the cord joining it with the center of mass O of the structure. The length and orientation of such cord define a function in a 3-dimensional property space.

using suitable averaging schemes for the property function on a model primitive (consisting for example in a tetrahedron or in a polygon), a highly discriminative feature vector may be coded.

3.2 Topological Approaches

The most known and well-established topological methods for the description of 3D models include the medial axis transform [10–12], skeletal structures and Reeb graphs [13]. Very often the extraction process is greatly sensitive to small perturbations in the object to be studied. For this reason, in classical approaches, *ad hoc* cleaning of the datasets has been used to achieve stability in the computation of the derived features. Since topological noise is not always easily distinguishable from non-spurious topological features, multi-scale analysis should be generally preferred to ad hoc cleaning. Persistency theory is a quite recent theory (see e.g. [14]) which offers the possibility to build multi-scale hierarchical representations for 3D models, and to analyze and track their topological features. In particular, persistency may describe at which scale a topological feature (e.g. a hole) is created and when it is annihilated (e.g. when the hole has been filled) in a multi-scale representation. Topological features having long lives are more robust and, likely, more salient. The interest in persistency theory has brought several research groups to extend these ideas from the native 3D objects to derived spaces in which geometrical properties are coded in a more explicit way. For example in [15] the original object is replaced by its *tangent complex*, which, informally, may be considered as the original space *extended* with the tangent directions in everyone of its points. A multi-scale representation of the tangent complex is then obtained by considering a filtration based on the curvature. Thus, a blending of geometric information and topology is achievable by persistency analysis. Such synergy between the description power of geometry and the discriminative power of algebraic topology invariants is clearly appealing for shape characterization and retrieval applications. For example, in [16], the use of multidimensional Morse function and persistency is suggested for building multiscale representation of anatomical structures, while in [17], persistency of is applied to the skeletal graph of 3D models. The freedom in the choice of the function driving skeletal extraction coupled with the filtrations arising from a wide-ranging collection of shape descriptors allows the construction of suitable similarity measures for 3D models.

3.3 Extension to Time-resolved Anatomical Structure

In [6] an extension to 3D+1 anatomical structures was proposed, with particular reference to the study of periodically deforming structures (such as the heart and the lungs). Indeed, assuming that the deformations among the different phases of the cycle fit into a smooth family, modal analysis may be used to reduce the problem dimensionality, since the anatomical structure has mainly low frequency excited deformation modes. See [3] for an application to the study of the heart deformation pattern.

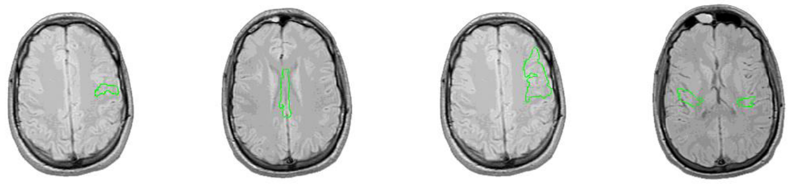
4 Anatomical Structure Semantic Annotation

The shape characterization features introduced so far may be understood as low level features, which do not *explain* the case at hand, but just provide some –more or less transparent– encoding of its appearance. Semantic annotation, on the other side, aims at providing a meaningful, human understandable description of the case under examination. Semantic annotation generally consists in attaching (in a manual or assisted way) textual labels (e.g. keywords) to objects. Such textual labels, however, should have further structure in order to define a more powerful, clear and reusable language. Among other models, ontologies appeared in artificial intelligence as computational artefacts used for building conceptual models of a domain of discourse [18]. They can come in different forms with increasing level of complexity, ranging from simple catalogues of terms to thesauri till complex models with logical constraints that allow automated reasoning. Basically, an ontology contains a *vocabulary of terms* that states what exists in the domain and, then, what can be predicated about.

In this sense, the Foundational Model of Anatomy (FMA, see [19]) defines concepts and relations among anatomical structures; for instance relations such as `has part` are included in FMA (e.g. Heart `has part` Heart Left Ventricle) and may be directly exploited in our framework for cross-modal access (for example a model of the heart clearly represents also the heart left ventricle). Besides the use of a general medical ontology – like UMLS Semantic Network [20] – additional ontologies may be considered to code reference terms for a specific domain, thus resulting in the use of a suite of ontologies to gain modularity, scalability and extensibility.

5 Similarity Searches

The use of both shape and semantic tags for the annotation of anatomical structures results into the possibility to gain cross-modal access to a repository, for example by supporting the following two search strategies:



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

Fig. 2. Sample neurofunctional systems: anterolateral (a), limbic (b), pyramidal (c) and auditorial (d) systems.

- Searches based on similarity metrics for the feature vectors
- Concept-based searches

Well-established techniques are available for tuning similarity metrics for a given dataset of feature vectors (see e.g. [4, 9]). Technologies are also available and mature to perform concept-based searches using terms coded in an ontology and their semantic relations (see e.g. the infrastructure presented in [21]). Our principal interest here is to use these two methods for querying and accessing data and metadata in a hybrid way, for example for supporting *context-sensitive* searches, as we describe next. Suppose indeed that a query anatomical structure consists in a 3D model and that the user has already stated that this model corresponds to a brain butterfly. In a basic way, the two searches strategies above may be both triggered and, then, the two resulting sets of most similar cases are compared to end up with just one set of most similar cases. An improvement to this basic method consists in letting the semantic tag to influence the search based on feature vector similarity. For example, the availability of the `brain butterfly` tag may drive the system to the definition of a particular subset of features to be computed and to the selection of a similarity metric *ad hoc* for the semantic class of brain butterflies. Other type of context-sensitive searches may take into account the *scope* of the query (e.g. corresponding to a particular decisional task such as diagnosis or prognostic stratification) or general information about the patient (e.g. anamnesis). In both cases, similar influences of the semantic tags on the similarity metric may be envisaged.

6 Application Scenarios

The aim of the following sections is to briefly discuss sample scenarios for the application of the ideas of this paper to neurology, radio-therapy and cardiology respectively.

6.1 Neurology

A still interesting problem in neurosurgery is represented by the morphological evaluation of intracranial lesions, especially for what regards the identification of surroundings neurofunctional systems and vascular structures. For these reasons, neurofunctional atlases have been introduced since long time (see e.g. [22]). With this respect, the proposed framework may be used for supporting case-based reasoning in the following way. After having prepared a repository containing 3D models of neurofunctional systems (some samples are shown in Figure 2) and associated metadata (in the form of geometric & topological features and semantic tags), several statistical similarity metrics may be learned, each one specifically designed for some particular sub-populations in the dataset. For example, apart from a general-purpose similarity metric suitable for all the anatomical structures in the repository, a specific similarity metric for the limbic system may be included. This specialized similarity metric should be designed so as to have a better retrieval performance on the subset of anatomical structure corresponding to the limbic system. After this preparation step, the repository may be interrogated at different *context* level; for example for answering a query consisting in just a 3D model with no further information, the general purpose similarity metric should be used; if semantic tags are available, more specialized similarity metrics together with concept-based searches should be triggered instead. Of course, some strategies for on-line updating the learned metrics on the basis of new annotated cases may be conceived.

6.2 Image Guided Radiation Therapy

Image-Guided Radiation Therapy (IGRT; see e.g. [23] for some introductional technical aspects) is a recent technique for the treatment of cancer, involving a workflow even more complex than conventional conformal or intensity-modulated radio-therapy. Indeed, in IGRT, high-resolution imaging modalities (usually CT) are used first for acquiring reliable anatomical images and reconstructing the boundary of the tumor and of the sensible nearby structures (e.g. the spinal cord or genital organs). Then, a radio-therapy plan is made, trying to maximize fraction delivery to tumoral cells and minimizing risk of exposing sensible structures. After the registration of radio-therapy plan to physical world coordinates, the actual treatment delivery starts and is repeated for several days or weeks (without repeating from scratch the radio-therapy planning). During radio-therapy delivery, in addition, images (normally Cone-Beam CT images) of the patient anatomy are acquired on-line and may be used to make more effective and safe the treatment, by checking that sensible structures are not irradiated (e.g. due to registration errors) and tuning the radio-therapy plan according to the actual growth/shrinkage of the tumor during the treatment period. With respect to this scenario, the proposed framework could be used to integrate the several available pieces of information, some of which are depicted in Figure 3.

In particular, we may foreseen the following applications:

- Using as a query the reconstruction of a tumor, the framework may support retrieval of already-available radio-therapy plans. Retrieved plans should be suitable as a starting point for working out a new plan.
- The availability of annotated sensible structures may be used to setting up a decision support system to prevent their exposition to radiation. Such decision support should run in the background and should present its suggestions in the proper context during treatment planning and tuning. Since the latter is made on-line, prevention of trivial mistakes is particularly important.
- Finally, retrieval using as query a temporal sequence of the tumor (for instance depicting the tumor before treatment, after one week of treatment and after two weeks) may be useful to evaluate the success of the therapy.

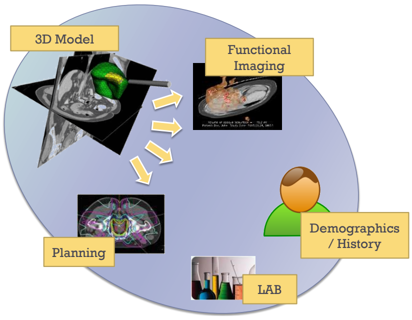


Fig. 3. Integration of shape information in the general process of IGRT.

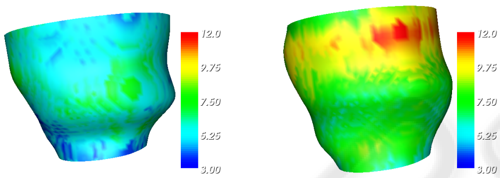


Fig. 4. Wall thickness at end diastole and systole, shown as a property function for the epicardial surface.

Notice that the above applications demand for the management of *scope-sensitive* queries, as defined in Section 5. Of course, if a sufficiently rich dataset is available, such procedures may also take into account patient demographic/anamnesis information, toward a more personalized treatment.

6.3 Cardiology

The analysis of the shape of the heart and of its deformation pattern may be used to support case-based reasoning procedures for diagnosis of several cardiological pathologies and for preoperative planning. For example, we consider here ventricular dyssynchrony. Dyssynchrony is a complex phenomenon whose origins are to be tracked back to electrical conduction disturbances that affect both regional and global function of the heart and which results into incoordinate ventricular wall motion due to activation delay. Despite its relevance, the only dyssynchrony marker that has received some consensus is an ECG-derived parameter, which however is poorly correlated to the outcome of resynchronization therapy, usually consisting in pacing device implantation [24]. Since there is a lack of generally accepted evidence about dyssynchrony therapy, the retrieval of similar cases from a repository may help the physician to make appropriate therapeutic choices. Indeed, after having reconstructed a time-resolved model of the heart of the patient and having computed meaningful features (like activation time, wall motion and thickening; see e.g. Figure 4), the patient anatomy, enriched possibly with demographic and drug assumption information, may be compared with other patients which already underwent resynchronization therapy.

7 Conclusions and Further Work

In this paper, a framework for the description of anatomical structures has been presented. The framework takes into account 1) *topological and geometrical features* and 2) *semantic annotation*. In this way, a 3D model representing an anatomical structure may be extended with non-geometrical pieces of information, ranging from metadata inherent to the instance of the structure (such as textual description of a lesion) to other patient-specific data (regarding age, sex, anamnesis,. . .).
Possible hybrid methods for similarity searches are then envisaged and shown to be useful for refined scope-sensitive retrieval. In this way, enhanced support for case-based reasoning procedures is provided, as illustrated with three sample scenarios extracted from various medical application fields.

In the future, we plan to integrate this work with other already developed infrastructures. Indeed, the presented framework may happily coexist with the system presented in [21], which introduces and uses an ontology for shape descriptors that –after a suitable extension– may be profitable also for the scopes of this paper. Another improvement towards a more ontology-centered framework is seen in the exploitation of the algorithm ontology presented in [25], so as to provide semantic insight also in the feature extraction process.

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