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Short Papers

A Unified Representation for the Model-based Visualization of Heterogeneous Anatomy Data

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Abstract

In the course of anatomical research, anatomists acquire and attempt to organize a great deal of heterogeneous data from different sources, such as MRI and CT data, cryosections, immunohistochemistry, manual and automatic segmentations of various structures, related literature, the relations between all of these items, and so forth. Currently, there is no way of storing, accessing and visualizing these heterogeneous datasets in an integrated fashion. Such capabilities would have great potential to empower anatomy research. In this work, we present methods for the integration of heterogeneous spatial and non-spatial data from different sources, as well as the complex relations between them, into a single model with standardized anatomical coordinates. All captured data can then be interactively visualized in various ways, depending on the anatomical question. Furthermore, our model enables data to be queried both structurally, i.e., relative to existing anatomical structures, and spatially, i.e., with anatomical coordinates. When new patient-specific medical scans are added to the model, all available model information can be mapped to them. Using this mapping, model information can be transferred back to the new scans, thus enabling the creation of visualizations enriched with information not available in the scans themselves.

Categories and Subject Descriptors (according to ACM CCS): I.3.m [Computer Graphics]: Miscellaneous—Miscellaneous

1. Introduction

Anatomical knowledge is not only an important part of medical education, but also of great relevance in daily practice. In surgery, for instance, knowing the exact location of nerves and arteries can be of paramount importance in improving surgical outcome. Anatomists currently have no comprehensive and intuitive way of storing and sharing the knowledge, both spatial and non-spatial, they possess with medical professionals. Examples of spatial volumetric data they work with are cryosectional slices, CT scans, MRI scans and histological slices. This however can be enriched by data that is inherently non-spatial, such as the related literature, knowledge about anatomical topologies, anatomical systems and the relationships between structures. There is clearly a need for a system that can integrate all of these different heterogeneous data types. If model information can then also be mapped to patient-specific scans, all available knowledge could be visualized in the anatomical context of a specific patient. Such a model could be of great value for anatomy education and surgical planning.

With this work, we present a model-based representation for the storage, flexible querying and visualization of heterogeneous anatomical data. Our approach is based on a standardized coordinate system of the human body to which arbitrary anatomical datasets, both spatial and non-spatial, can be associated. One of the unique aspects of our method, is that we perform lazy normalization. In other words, datasets are stored in their raw form, enriched with a locator and a number of mappings. The locator enables us to perform spatial indexing, whilst each mapping describes a different task-specific transformation from the raw dataset space to the standardized anatomical space. In addition, our approach enables an arbitrary number of overlapping, differently sampled, multi-modal datasets. Besides storage, querying and visualization, our pipeline enables the task-specific mapping of model-based information onto new patient-specific datasets, also creating possibilities for surgical planning and guidance.

For the system we envision, the technical requirements are the following: 1) The system needs to be able to **store** arbitrary types of heterogeneous anatomical information and should be able to handle spatial data in arbitrary resolutions and spacings. 2) The system needs to allow the user to **query** stored information per topic of interest and all information in the system should be queryable spatially in a shared coordinate system. 3) The system needs to be able to **visualize** all available information relevant to the users interest in anatomical spatial context and the relation to the other available representations should be clearly defined.

The system that we designed provides a way of integrating all anatomical knowledge in one unified model. With this, our scientific contributions are the following: We present a generic and unified representation to store all anatomical information (both spatial and non-spatial). The use of standardized anatomical coordinates enables domain-specific queries with spatial/visual querying due to the use of a schema-less database and kd-tree. Furthermore we describe freeform relations that can be defined to represent any type of relationship between model objects, capturing not only the data itself, but also the connectivity of the data.

2. Related Work

The VOXEL-MAN project, started in 1985 in Germany by the research group led by Professor Karl Heinz Höhne, has made great progress in combining spatial models with symbolic descriptions. Using the Visible Human dataset combined with segmentation and visualization techniques, the group created an anatomical atlas, combining anatomy, function and radiological appearance. In 1993 Tiede et al. created a 3D anatomical atlas of the human skull and brain [TBH*93]. In the next year Pommert et al. defined several concepts for structuring anatomical information in a semantic network model [PSR*94]. By assigning an anatomical structure to every voxel in a 3D volume and connecting the anatomical knowledge base, the group created a medical education tool [PRS*94]. In 1995, the group presented the intelligent volume approach [HPP*95]. They also did some work on high quality rendering techniques for attributed volume data at subvoxel precision [TSH98]. In 2001, they created a high-resolution spatial/symbolic model of the inner organs and presented a segmentation tool in colorspace [Pom01, HPP*01]. Furthermore, an interactive atlas of the hand was presented [GHL*06]and use of the VOXELMAN model for simulation of surgical procedures [PHB*06]. The VOXEL-MAN model represents a single general anatomy, while our model is enriched by the anatomical information from multiple datasets. For this reason, the VOXEL-MAN group had no way to describe interindividual variatons, age variations or “fuzzy” anatomical object boundaries [HPP*95].

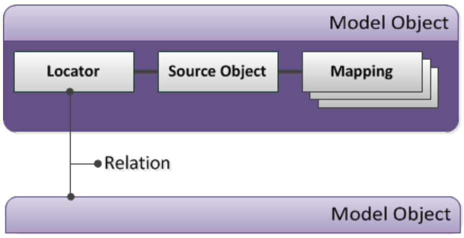


Figure 1: *A raw dataset (a source object) can be added to the anatomical model by enriching it with a locator, used in spatial indexing, and any number of mappings to the standardized coordinate system. Arbitrary relations between datasets can be described as well.*

In the BrainGazer project by Bruckner et al., visual queries for neurobiological research are introduced [BvG*09]. The BrainGazer system uses large databases of transgenic specimens and the acquisition of confocal microscope images of fruit fly brains in which distinct neuronal types are highlighted together with annotated anatomical structures to enable neurobiologists to query this data both visually and through the database interface. Furthermore, in the biology domain, the Allen Brain Atlas and related software Brain Explorer visualize gene expression in a 3D anatomical context [LNT*08]. The research presented in this paper differs from that of the BrainGazer research, in that our model needs to support a number of different modalities with significantly differing sampling resolutions and strategies, and that it also needs to cope with the storage of pristine data sources, each packaged with a number of different task-specific spatial transformations. This last characteristic is in fact one of the main factors differentiating our work from similar research.

An extended version of this work was presented at CASA 2012 in the 3D Physiological Human workshop detailing the medical context of this approach [SKD*12].

3. Method

The method we propose is a model-based representation for storage, querying and visualization of heterogeneous anatomy data. Using an anatomical standardized coordinate system, this system enables users to integrate arbitrary anatomical data into a single unified model. Figure 1 shows the primary concepts used our system. The model is designed in such a way that it forms a solid foundation for further development of anatomical and surgical applications.

Source objects represent original unprocessed information that the user would like to add to the model. Relevant anatomical knowledge can occur in various forms, such as cryosectional slices, CT scans, MRI scans, histological slices, anatomical structure names and related scientific literature. All these different types of knowledge can be divided in two categories. The first category of source objects are those that have an inherent geometry. The spatial data types include acquisitions from medical imaging devices that can be acquired in vivo, such as MRI-scans, CT-scans and PET-scans. Other examples of spatial data include cryosectional slices and histological images. The second category of source objects is those that do not have an inherent geometry. Examples of this include anatomical terms, literature that is deemed relevant to a certain anatomical structure, statistics, and bio-mechanical tissue characteristics. A special feature of these types of data is that even though they do not have an inherent spatial component themselves, they can be spatially embedded in model space through their relations with other model objects.

Source objects are added to the model by augmenting them with a locator and one or more task-specific mappings to model space. The combination of the source object, its locator and its mappings is then called a **model object**. Once a dataset becomes a model object, it becomes a part of the standardized anatomical coordinate system. This means that it can be queried and visualized in the same space as all other model objects. Once a source object becomes part of model space, when queries are executed at a certain point or even a region, this added source object will show up in the query results. This is possible because the locator describes the spatial extent of a model object. Using one of the mappings that was added, the source object can be transformed to model space and visualized together with other model objects of interest in the standardized coordinate system. The standardized coordinate system has its origin in the sacral promontory. This is a bony anatomical landmark that can easily be found in any patient scan that includes the pelvis. Another benefit of choosing this point is that it is independent of patient pose and central in the human body. The axis are defined in standard anatomical pose. The z-axis points in the cranial or superior direction, the x-axis points to the left hand side of the patient and the z-axis points forward to the anterior or front of the body. Using the sacral promontory as the origin, any point in the human body, arranged in a standard pose, can be intuitively defined with respect to this point.

In order to be able to represent source objects added to the model, **mappings** need to be added. These mappings consist of the transformations that map a source object to model space. The transformations required to do this are acquired during a registration process and can be rigid, affine, deformable or hybrid, for example articulated registration [BMD*10]. Because of the different modalities available, registration of the different source objects is no easy task. Furthermore, inter-patient variability further complicates the process. Up to now, we have been using a mix of tools such as MITK, elastix and 3DSlicer, to create gold standard mappings interactively.

The **locators** are used to define where in model space the model objects are defined. Depending on the data type, the locator can be defined in several forms. Specifically, the locator can represent a point set, a volume or a non-geometric model object. In the case of a volume locator, the origin, extent and spacing are stored in order to be able to check if a volume is available at any given point in model space. The pointsets are used as a spatial index for fast spatial querying, by storing them as kd-trees for instance. For non-geometric model objects, the locators do not store any extra information, but are used in defining relations between model objects.

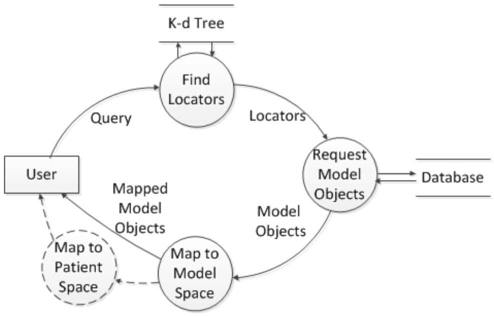


Figure 2: *The high-level data flow diagram for querying in our system.*

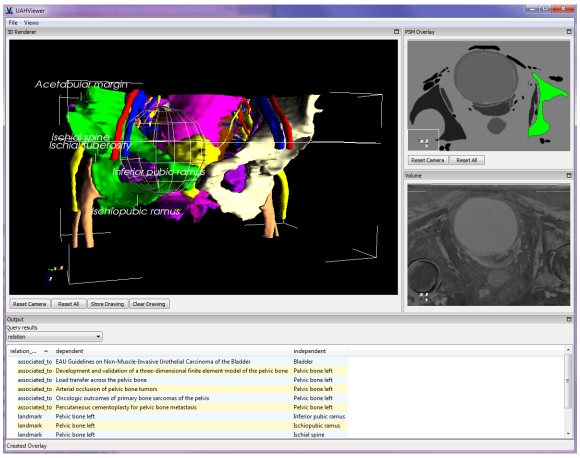
Relations are always defined between locators. They link the model objects together through their locators. The relationships are free-form, which means they can be one-to-many, many-to-many or one-to-one and have any meaning required. A relation then consists of a type, one or more independent variables and one or more dependent variables. Also an extra parameter can be defined. Examples of relation types are associated_to, lookupvalue, defined_by, landmark or subdivision. An associated_to relation can for instance define the link between an anatomical structure and the paper that is relevant to that specific anatomical structure.

4. Results

To evaluate the practical applicability of the system, a prototype application was implemented. This prototype application to store, explore and query model information is implemented in Python as a DeVIDE module [BP08], employing the Visualization Tookit (VTK) for its visualization functionality. The current standardized anatomical space is based on a semi-automatic segmentation in Amira [SWcH05] of cryosectional images of a Dutch female pelvis. An important component of our implemented system is the underlying database, which was implemented using MongoDB, a *schema-less* document-oriented database technology that is designed to be agile and scalable. It is easy to extend this database when new types of data are provided as there is no fixed schema required. The concepts described in the Method section are implemented directly as collections and

System	Modalities	Resolution	Variations	Relations
VOXEL-MAN	multiple	single	single general anatomy	structural, functional, abstraction
Braingazer	single	single	multiple specimens	semantic, spatial
Our system	multiple	multiple	multiple specimens	free-form

Table 1: *Comparison between VOXELMAN, Braingazer and our system.*



relation_...	dependent	independent
associated_to	EAU Guidelines on Non-Muscle-Invasive Urothelial Carcinoma of the Bladder	Bladder
associated_to	Development and validation of a three-dimensional finite element model of the pelvic bone	Pelvic bone left
associated_to	Load transfer across the pelvic bone	Pelvic bone left
associated_to	Arterial occlusion of pelvic bone tumors	Pelvic bone left
associated_to	Oncologic outcomes of primary bone sarcomas of the pelvis	Pelvic bone left
associated_to	Percutaneous cementoplasty for pelvic bone metastasis	Pelvic bone left
landmark	Pelvic bone left	Inferior pubic ramus
landmark	Pelvic bone left	Ischiopubic ramus
landmark	Pelvic bone left	Ischial spine

Created Overlay

Figure 3: *Spatial querying through sphere selection. A distance query reveals the literature and anatomical landmarks associated to the structures within the selection sphere.*

embedded documents in the database. GridFS is used for the efficient storage and retrieval of large volume data.

A high-level data flow diagram overview for system queries (such as selected structures, distance, text or relations) can be seen in figure 2. The data can be queried directly by selecting an anatomical structure of interest or spatially, by using a selection sphere to find all model objects within a certain area of interest. In figure 3, such a spatial query is demonstrated. The query results contain all structures within the sphere of interest along with their relations to other model objects. In this case, the user has added related literature to several structures and annotated anatomical landmarks on the structure in 3D. By following the relations that model objects have, it is also possible to query the related model objects and to chain these related query results up to arbitrary distances in the connectivity graph.

Table 1 shows a comparison between our proposed system and existing systems such as VOXEL-MAN and Braingazer. While there are many similarities, our proposed system excels in allowing multi-modal, multi-resolution datasets to be stored, queried and visualized. Considering the ability to handle variations, we observe that the VOXELMAN-project represents only a single general anatomy, while our system allows the user to store and visualize datasets with age, interindividual and anatomical variations. When we examine the relational capabilities, we see that in the VOXELMAN-project, relations are used to describe anatomical links that are structural, functional or represent abstraction in a semantic network [HPP*95]. For the Braingazer project, semantic and spatial relations can be defined. Our relations can be used to define all of these links, but extend this idea by allowing relations to be defined between locators of arbitrary types of model objects.

5. Conclusions and Future Work

We have presented a novel method to integrate heterogeneous spatial and non-spatial data from different sources, as well as the complex relations between them, into a single model. Using a standardized coordinate system, all available anatomical knowledge can be queried interactively in the prototype application, both topically and spatially. The model data can be visualized as is, compared in linked views, or be used to enrich patient-specific scans with additional information from the model. Due to the flexibility of the model, anatomists will be able to store arbitrary heterogeneous data in the model in a generic way. As such the system forms a excellent foundation for future pre-operative surgical planning and intra-operative guidance applications.

At this moment, we are busy filling the model with more data. So far we have performed a manual segmentation of the cryosectional slices of a Dutch female pelvis, a significant part of the segmentation of the high resolution Visible Korean female, a number of CT and MRI sets, as well as test data in the form of scientific papers and anatomical relations extracted from the literature. During the coming years, we will populate the model with more highly detailed anatomical data.

Future work includes enhancing the registration process. Since the registration process is such a crucial step in the practical applicability of our model in patient-specific applications, a software application that enables the user to semi-automatically and interactively create a task-specific and even structure-specific registration that is the best fit for the anatomical structure of interest. Currently only the mapping transformation itself is saved in the model, but we plan to store the residual local registration error in the near future. We can use this error to provide uncertainty feedback to the user. This is of paramount importance in pre-operative planning, where any uncertainty regarding the exact location of an anatomical structure must be made immediately apparent to the user.

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