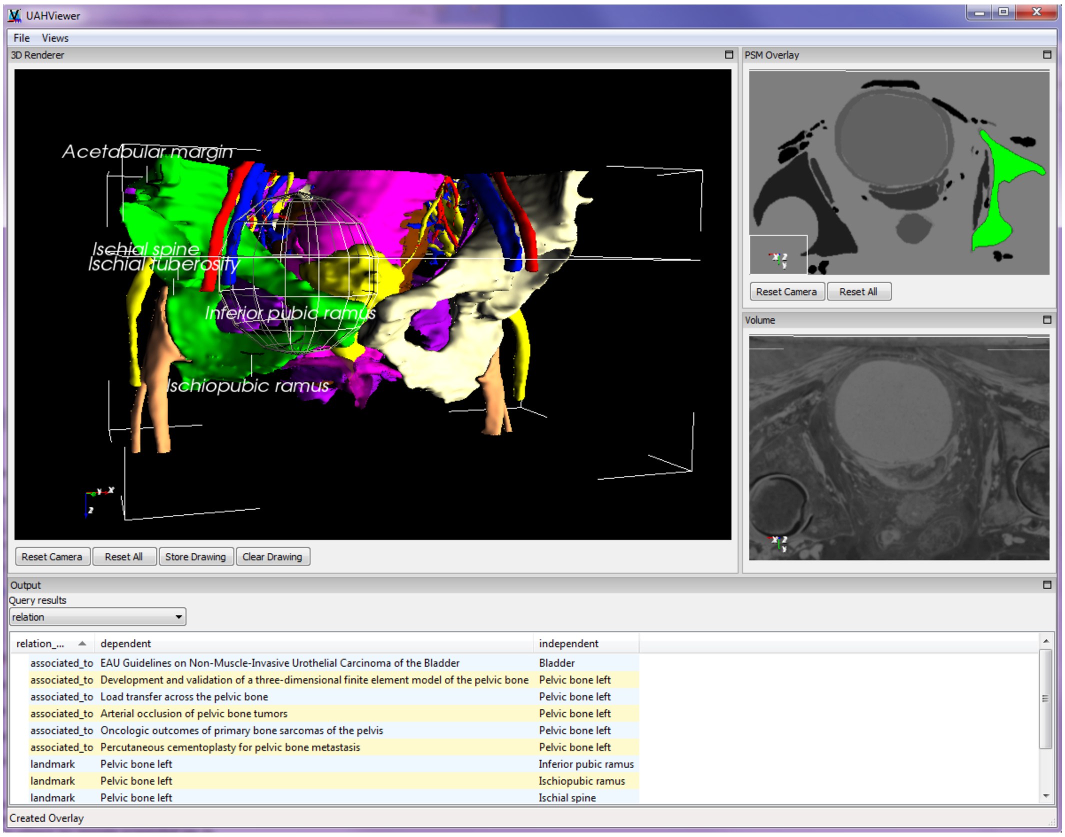
The Unified Anatomical Human: Model-based Visualization of Heterogeneous Anatomy Data

Master's Thesis



Query results

relation

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

Noeska Smit

The Unified Anatomical Human: Model-based Visualization of Heterogeneous Anatomy Data

THESIS

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The Unified Anatomical Human: 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. Anatomical variation between subjects further complicates this organization. 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 these, into a single model with standardized anatomical coordinates: The Unified Anatomical Human. 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.

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Preface

The research presented in this Master's thesis report represents the final chapter in obtaining my Master of Science in Computer Science: Media and Knowledge Engineering at the Delft University of Technology. This work is the result of a nine month project that has been carried out in collaboration with the Leiden University Medical Center (LUMC). The Leiden anatomists have beautiful datasets representing complex human anatomy and huge amounts of anatomical knowledge, but unfortunately no way of unifying all these concepts into a single model. I was happy to collaborate with these researchers to shape the foundations for such a model.

This however, would not have been possible without the help of some amazing people. First of all, I would like to thank my boyfriend, Gerrit Rijken. If he hadn't encouraged and motivated me to take the leap to university, I wouldn't even be here in Computer Science right now and would still be working in the hospital as a radiographer. Secondly, I'd like to thank my friends and family for their support, on both the academic and personal level. I would also like to extend my gratitude to the Computer Graphics and Visualization group as a whole. The students, researchers and staff make it a great place to work and going to work something to look forward to. On that note, my office roomies Peter Kok, Francois Malan and Thomas Kroes also deserve special mention. I really believe we have the best office in the building and it's not only the plants, comfy couch and colourful decorations, but especially the pleasant company that puts a smile on my face every single day. But let's not forget to thank the neighbors for the countless coffee/tea breaks and afternoon sugar fixes. I'd really like to thank my supervisor Charl Botha, for initiating aforementioned sugar fixes, DeVIDE, his insight, excellent advice and enthousiasm. Finally, I'd like to thank the Leiden team: Marco de Ruijter, Annelot Kraima and Daniël Jansma for the great collaboration and meetings, which always gave me inspiration and energy.

In conclusion, I'd like to add that I really look forward to continuing our work on this project as a PhD candidate.

Noeska Smit
Delft, the Netherlands
February 25, 2012

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Chapter 1

Introduction

In this chapter we introduce the motivation for this research, including some background information on the problem domain. This is followed by the primary research questions and research approach. After this we elaborate on the technical requirements for our solution and the contributions of our work.

1.1 Motivation

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. An example of this can be found in the treatment of colorectal cancer. Since 1982, when Heald first described this procedure, total mesorectal excision (TME) has been the gold standard for treatment [17]. The procedure, however, is not free from complications. Post-operative urinary incontinence occurs in 34 percent of the cases and fecal incontence in 39 percent [41]. There is also a 56 to 79 percent risk of sexual disfunction after the procedure [22]. The reason for all of these complications is damage to the autonomic nerves [24]. This damage is difficult to prevent, because the exact location of the autonomic nerves and their relation to the fascial structures (layers of connective tissue) surrounding the rectum is debatable [21]. If the understanding of the complex pelvic anatomy could be improved, surgical outcome could also be significantly improved.

The TME procedure is just one example among many other surgical procedures in the pelvic area. Other examples include gynecological procedures and orthopaedic surgery. A lot of work has been done towards surgical planning applications for orthopaedic implant placement, for instance the TraumaCad system for total hip replacement planning [35], and intra-operative guidance of these procedures, such as the hipnav hip prosthesis placement navigator [12]. A recent survey on computer-assisted tumor resection has shown that the whole field is still limited to the skeletal structures of the pelvis [13]. Pre-operative planning and intra-operative guidance systems are currently not available for soft tissue surgical procedures such as TME.

Ideally, pre-operative planning and intra-operative guidance applications would not require new anatomical models for every type of surgical procedure. The long-term goal for this project is to eventually build a Virtual Surgical Pelvis (VSP), a highly detailed anatomically and biomechanically correct model of the pelvis, based on three-dimensional segmentations. If this VSP would indeed include all surgically relevant details of the complex pelvic anatomy, all this information can be used in applications for arbitrary pelvic surgery procedures.

Furthermore, anatomists currrently have no comprehensive and intuitive way of storing and sharing the knowledge they possess with medical professionals. Anatomists have many different types of data at their disposal, both spatial and non-spatial. 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 this model information can then also be mapped to patient-specific scans, all available model knowledge could be visualized in the anatomical context of a specific patient. Such a model is of great value for anatomy education and surgical planning. Furthermore, this model can be used as the basis for many surgical applications, such as the VSP. By selecting the information contained in the model that is surgically relevant, applications can be made that enrich surgical education and pre-operative planning. With the work described in this thesis, we lay the foundations for exactly such a model, called the Unified Anatomical Human (UAH).

1.2 Research Questions

Our main research questions are the following:

- How can we develop a model that can store and integrate arbitrary heterogeneous anatomical data and relations between these?
- How can we allow the users to query and visualize model data in a prototype application and how can we enrich patient-specific scans with model data?

As described in the motivation, anatomists collect and store huge amounts of spatial and non-spatial anatomical information, but currently have no way of storing all this data in a unified way. It is currently not possible to organize and integrate their heterogeneous data sources. The first challenge is to design a model that can store and integrate heterogeneous anatomical data.

After this model is created, the second important research question arises. Given the developed model, how can the users query and visualize anatomical information relevant to their interests in an intuitive way? This question can be answered by developing a prototype application that enables anatomists to query structures or regions of interest structurally or spatially. Pre-operative planning can benefit from the model by mapping anatomical knowledge from the model to patient-specific scans.

1.3 Research Approach

With this work, we present a model-based approach for the storage, flexible querying and visualization of heterogeneous anatomical data. This model is called The Unified Anatomical Human. 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.

Furthermore, we present the UAHViewer, a prototype application that enables the user to visualize data stored in The Unified Anatomical Human database. Besides three-dimensional and slices-based views on the volumetric spatial data, queries can also be executed topically as well as spatially to examine the non-spatial data stored in the model. Anatomical landmarks that are hard to define in a two-dimensional context can be drawn directly onto three-dimensional structures and stored from the prototype application.

1.4 Technical Requirements

The technical requirements specify the essential features that are compulsory for a successful solution. For the system we envision, the requirements are the following:

- Storage requirements:
  - The system needs to be able to store arbitrary types of heterogeneous anatomical information.
  - The system should be able to handle spatial data in arbitrary resolutions and spacings.
- Query requirements:
  - The system needs to allow the user to query stored information per topic of interest.
  - All information in the system should be queryable spatially in a shared coordinate system.
- Visualization requirements:
  - The system needs to be able to visualize all available information relevant to the users interest in anatomical spatial context.

  - All stored volume data should be visualized in such a way that the relation to the other available representations is clearly defined
  - When a patient-specific scan is added, the user should be able to view all available stored information in the context of this patient-specific scan.

1.5 Contributions

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 novel generic model 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.
- We offer a generic approach to mapping of information to patient-specific scans, enabling a richer visualization than the scans alone could provide.

Several challenges arise in the design of the Unified Anatomical Human-system. First of all, the model needs to be generic and flexible enough to allow any type of anatomical knowledge to be added to the system in an incremental fashion. The model needs to be ready to deal with all possible types of data that the anatomists deem relevant, even if they had not foreseen this type of data to be necessary in the initial system requirements elicitation. A second major challenge is creating a correct mapping from model space to patient space and vice versa. In order for this to be successful, the registration needs to be done in such a way that the error introduced by it is measurable and can be visualized to show uncertainty in the mapping results.

1.6 Organization

The rest of this thesis report is organized as follows: in Chapter 2, related work is discussed. In Chapter 3 an overview of our proposed method: the Unified Anatomical Human is given. Chapter 4 describes the implementation of our prototype. This is followed by the results in Chapter 5.1. Finally, conclusions and future work are presented in Chapter 6.

Chapter 2

Related Work

In this chapter the scientific work related to our research is examined. We start off by briefly describing related surgical planning work, this is followed by an overview of existing high-resolution anatomical datasets and reconstructions thereof. We conclude the chapter with a description of two anatomical models, namely the successful VOXEL-MAN project and the Braingazer project.

2.1 Surgical Planning

In this section we briefly examine the available surgical planning applications for pelvic surgery. When we look at the work done in this field, we notice that a lot of work has been done towards surgical planning and guidance applications for orthopaedic implant placement. such as the TraumaCad system for hip replacement planning [35] and the hipnav hip prosthesis placement navigator for intra-operative surgical guidance [12]. Another software system for virtual operation planning is VIRTOPS, which can be used to plan surgical reconstruction procedures for the treatment of bone tumors based on multi-modal image information [16]. A great overview of Computer Assisted Orthopaedic Surgery (CAOS) in general is given in the book 'Computer and Robotic Assisted Knee and Hip Surgery' [11].

When it comes to surgical planning and guidance of non-orthopaedic pelvic surgery, a recent survey on computer-assisted tumor resection has shown that the whole field is still limited to the skeletal structures of the pelvis [13]. This means that pre-operative planning and intra-operative guidance systems are currently not available yet for soft tissue surgical procedures.

2.2 High-resolution Anatomical Datasets

Four major groups have worked towards creating high-resolution anatomical datasets by taking photographs of the entire human body slice by slice. Using a cryomacrotome or milling machine, a frozen cadaver is fully sectioned and a high-resolution photo is taken of every slice. The first among these projects was the Visible Human Project (VHP) dataset [33]. In 1994, the Visible Human Male was sectioned. This complete dataset is 15 Gigabytes

Figure 2.1: An example of a single cryosectional slice from the Visible Korean Female [26].

(GB) in size and consists of radiographs, MRI images, CT images and cryosectional images. These 1871 cryosectional images were sliced at 1 mm intervals and have a resolution of 2048 by 1216 pixels. A 39 GB complete female dataset is also available, this dataset has 5189 axial anatomical cryosectional images obtained at 0.33 mm intervals [1].

In 2003 the Chinese Visible Human (CVH) dataset was created [42]. A male and female free of organic laesions (unlike the cadavers used in the VHP) were sectioned and MRI and CT scans were made. The total male dataset was 90 GB and the female dataset consists 131 GB of images. The resolution of cryosectional images was 3072 x 2048 pixels and the slice thickness varied between 0.1 and 1 mm depending on the anatomical region.

The Visible Korean Human (VKH) dataset was created to compensate the shortcomings of the previous two projects [26]. According to the authors, the VHP data was based on elderly people with pathological findings, there are slices missing (between the four blocks that the cryosection was performed in) and anatomical structures smaller than 0.2 mm can not be seen because the size of the interval and pixel size used. The CVH project failed to keep the colors lifelike, because a red gelatin solution was perfused and only small slices of the head and neck were made. Both projects did not publish segmented images. The VKH datasets consists of a male and female specimen and are a total of around 300 GB. The cryosectional slices for the male have a resolution of 3040 by 2008 pixels and were sliced at 0.2 mm intervals. For the female cadaver, a resolution of 5616 by 3744 pixels and a 0.2 mm interval was chosen. A cryosectional slice of the Visible Korean Female is shown in figure 2.1.

The final dataset, the Virtual Chinese Human (VCH) consists of four datasets of two male and two female cadavers [36]. These datasets have intervals ranging from 0.1 mm to 0.2 mm and a resolution of 3024 by 2016 up to 5440 by 4080 pixels. This forms the biggest dataset so far, with a grand total of about 1.6 Terabytes of data.

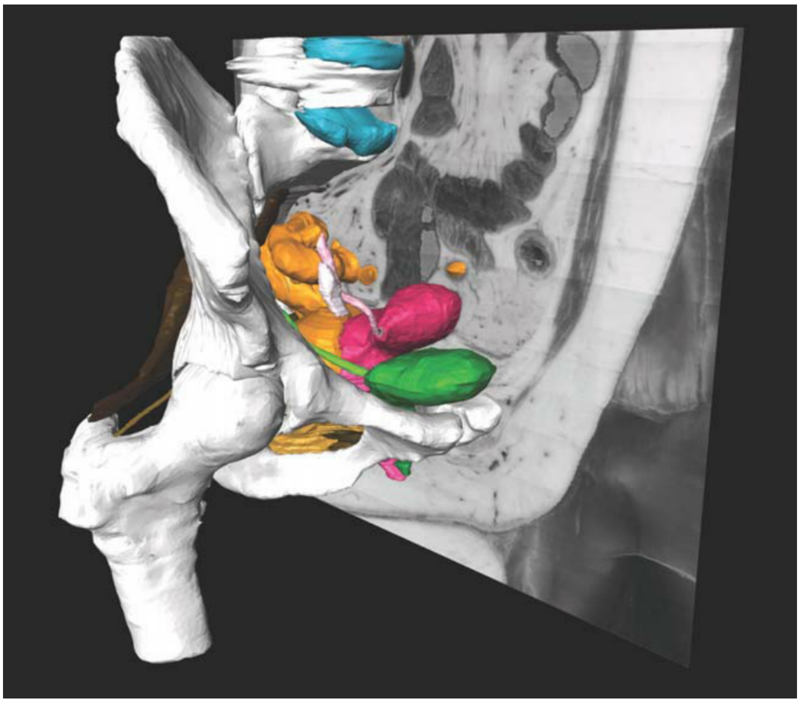


Figure 2.2: A surface reconstruction shown together with a saggital slice of the Visible Human Female [32].

2.3 Reconstructions

Several reconstructions based mostly on Visible Human-type datasets have been made to model pelvic anatomy. These models were mainly constructed for medical education and surgical training purposes. In 1998 Brooks et al. constructed an anatomical model of the male pelvis based on the Visible Human dataset [7]. By manually drawing Bezier curves onto the cryosectional slices, 18 structures were segmented to improve understanding of male pelvic anatomy for urological surgery. Pearl et al. reconstructed the pelvic floor anatomy based on a physical model that was CT scanned in 1999 [27]. The male and female pelvic floor was reconstructed for education through teleconferencing and telepresence. In 2001, Beyersdorff et al. also reconstructed the pelvic floor, but used CT scans, MR scans and sheet plastination as a basis [5]. This reconstruction was made for anatomical and radiological education. Bajka et al. made a segmentation of the Visible Human Female pelvis using self-written segmentation software in 2004 [3]. The three-dimensional reconstruction and visualization methods used were not specified. In that same year, Venuti et al. reconstructed a male pelvic model for anatomical teaching based on the Visible Human Project male [40]. Their aim was to create a realistic three-dimensional model, but nerves and vessels were left out. Parikh et al. reconstructed the female pelvic floor based on an MRI in order to establish methods for development of a three-dimensional model [25]. They found that such models lead to improved performance and test scores and reduce teaching

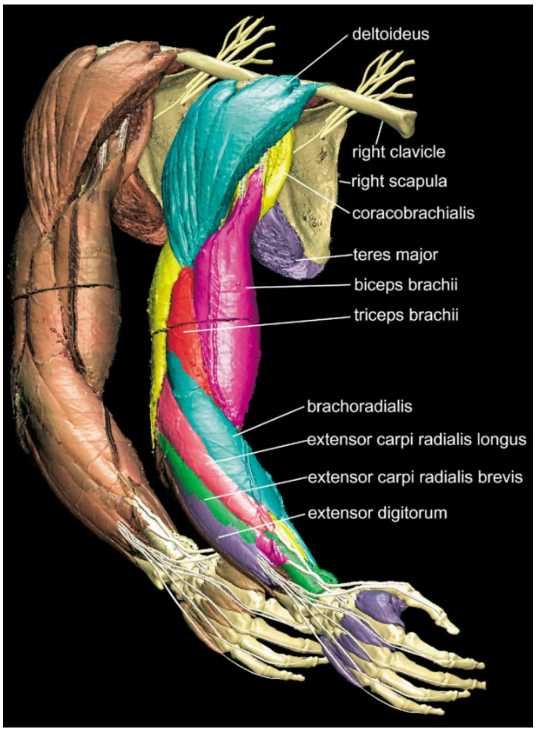


Figure 2.3: VOXEL-MAN anatomical model of the arm based on the Visible Human.[30]

time. The fourth pelvic reconstruction made in 2004 was made by Heinrichs et al. [18]. This model, named LUCY, was created for laparoscopic surgical training. Two more pelvic reconstructions were made in 2010. Chung et al. made a three-dimensional model based on segmentations of the Visible Korean Human female pelvis [10]. The model created was focussed on the female urogenital tract and adjacent structures. Sergovich et al. reconstructed a stereoscopic three-dimensional model based on the Visible Human Project Female for virtual dissection in education [32]. They mention that the added value to education is under debate, because it might handicap students with poor spatial ability. An example of their work is shown in figure 2.2.

2.4 Anatomical Models

When we look at the research done in the field of anatomical models, the VOXEL-MAN and Braingrazer project come to mind. We first discuss the body of work produced by the VOXEL-MAN project over the past decades. The VOXEL-MAN research focused on the storage, querying and visualization of anatomical data and has made a significant impact on the field. We also compactly discuss the BrainGazer project, as it also shows a number of similarities with the research presented in this paper.

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 [37]. In the next year Pommert et al. defined several concepts for structuring anatomical information in a semantic network model [29]. 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 [31]. In 1995, the group presented the intelligent volume approach, by combining attribute volumes as big as the image volume, for instance one for blood supply, one for function volume, and one for morphology volume [19]. In the same paper, they also demonstrated that it was possible to derive X-ray projections from available CT-data.

The group also did some work on high quality rendering techniques for attributed volume data at subvoxel precision [38]. The group created a high-resolution spatial/symbolic model of the inner organs based on the Visible Human Project and presented a segmentation tool in color space [28, 20]. Furthermore, an interactive atlas of the hand was presented were the group came across a number of limitations of the Visible Human dataset: cryosection cutting artifacts, poor CT quality and lack of visibility of small vessels and nerves [14]. In 2006 Pommert et al. presented their work on using the VOXEL-MAN model for simulation of surgical procedures [30].

Our approach extends the work done by the VOXEL-MAN Group in the following ways. First of all, our model allows for multiple anatomical structures to be defined at any point in model space using information from various different data sources. Secondly, 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[19].

In the BrainGazer project by Brucker et al., visual queries for neurobiological research are introduced [8]. 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. 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.

Chapter 3

The Unified Anatomical Human

The method we propose as an answer to our research questions is The Unified Anatomical Human (UAH), a model-based solution for storage, querying and visualization of heterogeneous anatomy data. Using an anatomical standardized coordinate system, this model enables users to integrate arbitrary anatomical data into a single unified model. As mentioned in the introduction chapter, the long-term goal of this project is to build the Virtual Surgical Pelvis, a highly detailed anatomical model of the pelvis that encompasses segmentations of all anatomical structures in the pelvis. This VSP can then be used to provide correct anatomical data for pre-operative planning and intra-operative guidance applications for arbitrary pelvic surgery procedures. The UAH model is designed in such a way that it forms a solid foundation that the VSP can be built on.

In this chapter, the model is described in a brief overview, followed by some examples of model uses. A detailed description of each of the concepts in the method folllows and the sections is concluded by a short summary.

3.1 Data Representation

3.1.1 Overview

Figure 3.1 shows the primary concepts used in The Unified Anatomical Human. In our approach, raw unedited anatomical data are referred to as source objects. Each of these source objects can be added to anatomical space and placed in the anatomical standardized coordinate space by adding a locator and one or more mappings. The locator describes the spatial embedding of the object and is used for spatial indexing. Each of the mappings represent a different transformation from the raw dataset space to the standardized anatomical space. Any number of relations, each of an arbitrary type, can be defined, and make use of the model object locators as operands.

3.1.2 Examples

In this section two examples are given of using our approach. These serve as introductory illustrations of our work, but more detailed examples are presented in chapter 5.1. The first

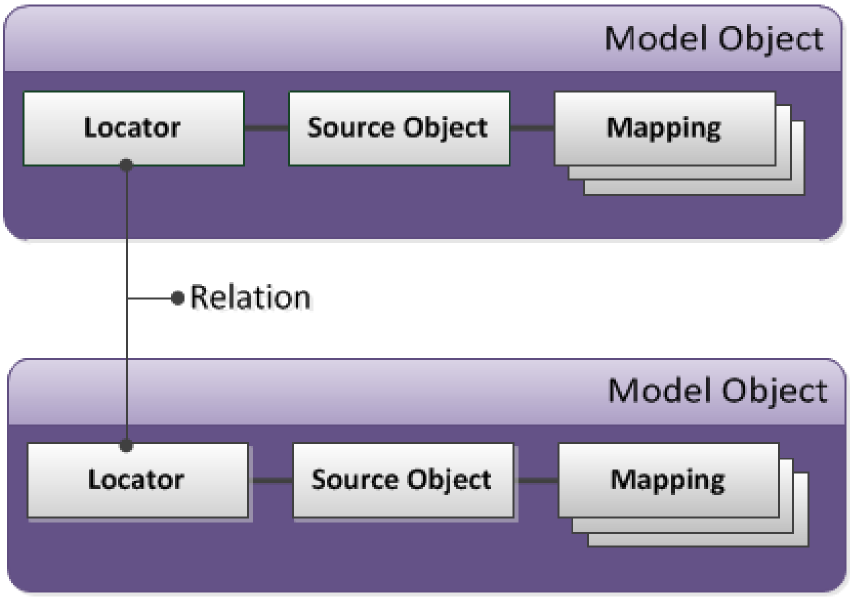


Figure 3.1: A raw dataset, referred to as a source object, can be added to the anatomical model by enriching it with a locator, used in spatial indexing, and any number of mappings, each describing a task-specific transformation from source object space to the standardized anatomical coordinate system. Any number of arbitrary relations between datasets can be described as well.

example is the process of adding a segmentation of an anatomical structure to the model. The second example describes adding a patient-specific CT-scan to the model.

Based on cryosectional images, a user has semi-automatically segmented the iliac bones and wants to add this anatomical structure to the model. A schematic overview of this process can be seen in figure 3.2. The label volume describing the segmentation is now a source object, a pristine unprocessed data acquisition. To get the scan into model-space, two elements need to be added. The first is a locator, which describes the spatial extent in model space. Secondly, a mapping needs to be added that transforms the source object to model space. The locator describes the spatial embedding of the anatomical structure and is used for spatial indexing. The locator in this case is formed by a sparse point sampling of the surface of the anatomical structure. In this example, since the segmentation is based on the cryosectional images that form the basis for our anatomical model, no mapping is required. A relation that can be defined in this instance can connect a related scientific research paper to the iliac bones. This related paper is also considered a source object and can also be stored without a mapping. Since the locator is non-geometric, it is placed in model space through a relation with the iliac bones.

In our second example, a user wants to add a CT-scan of the pelvis to the model. This CT-scan is then considered a source object. As in the previous example, a locator and one or more mappings need to be added to make it a model object. A schematic representation of the CT scan as a model object can be seen in figure 3.3 In this instance the locator of

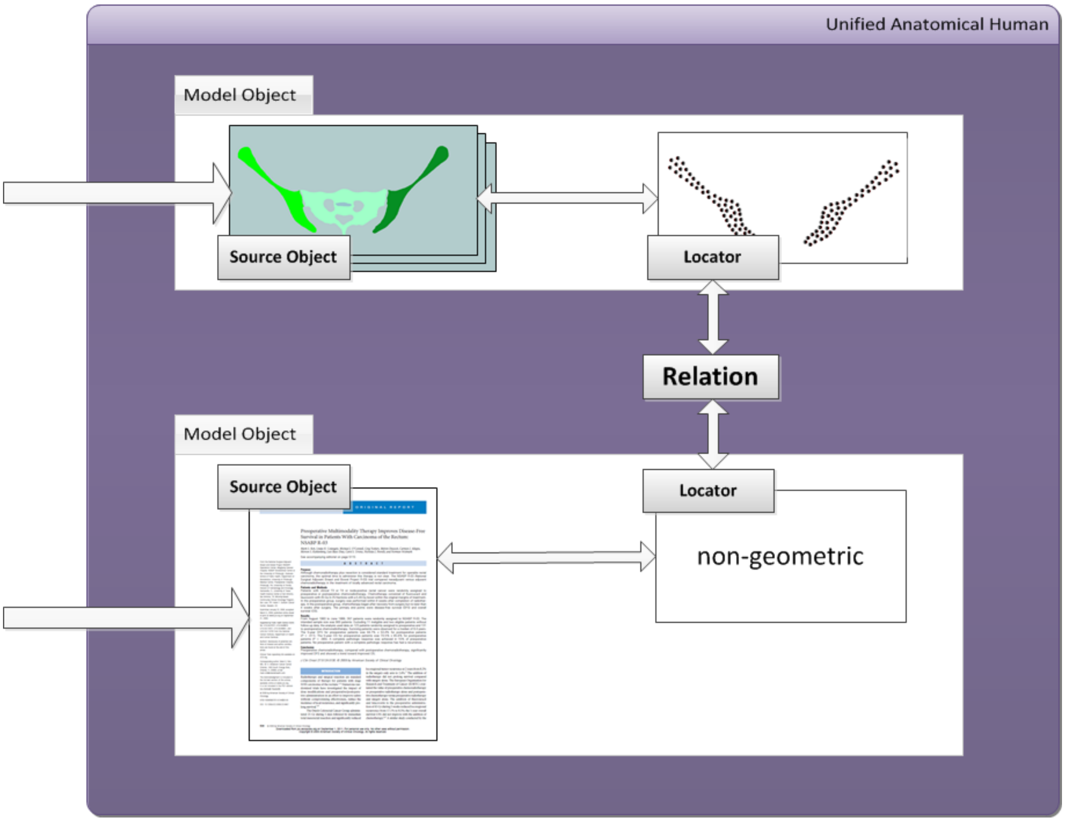


Figure 3.2: This figure demonstrates the process of adding an anatomical structure to the Unified Anatomical Human model and adding a scientific paper that is related to this structure.

this volume is defined by storing the origin, extent and spacing of the volume. The primary mapping is a rigid transformation matrix. Relations can now be defined that relate this CT-scan to other model objects. For instance, a relation might connect a Young's modulus lookup table to the CT-volume, enabling the user to associate material elasticity to objects in the model.

After these steps, the CT-scan will be available for querying in model space. An added benefit is that knowledge from other model objects can also be mapped back to the patient scan. This means that the original scan can be enriched with knowledge that was not available from the original CT modality alone. For instance, the location of the autonomous nerves mentioned in the introduction can be projected to the original scan for pre-operative planning.

3.1.3 Concepts

This section describes the concepts mentioned in the overview and examples in more detail.

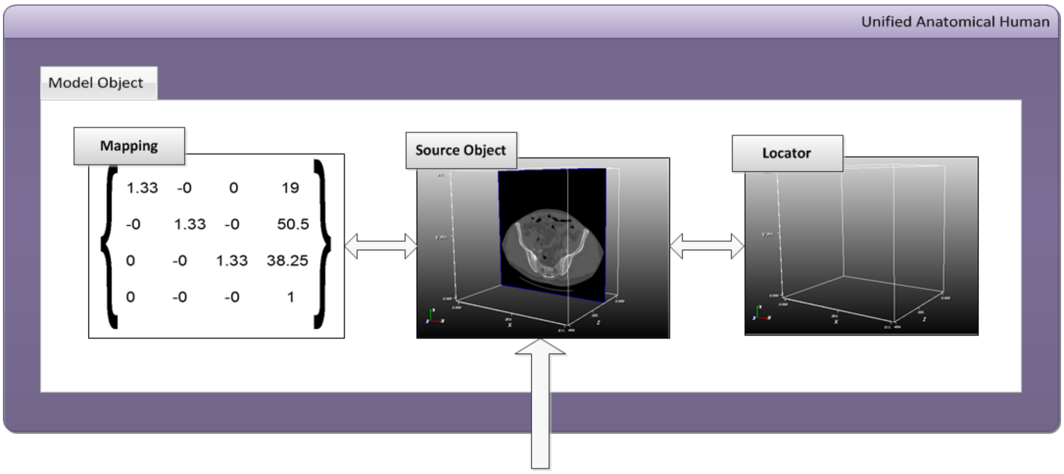


Figure 3.3: This figure demonstrates the process of adding a patient-specific CT scan to the Unified Anatomical Human model.

Source Objects

Source objects in the model 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 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.

It is important to store these source objects in their original state in the model, so that at any point, the user can retrieve the objects exactly as they were stored. This is especially true for patient-specific data. When for instance a CT-scan is mapped to model space, it can be deformed to fit the model, but by storing the scan ‘unmapped’ a user can also view see the original scan at any time.

Model Objects

Source objects are added to the UAH 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

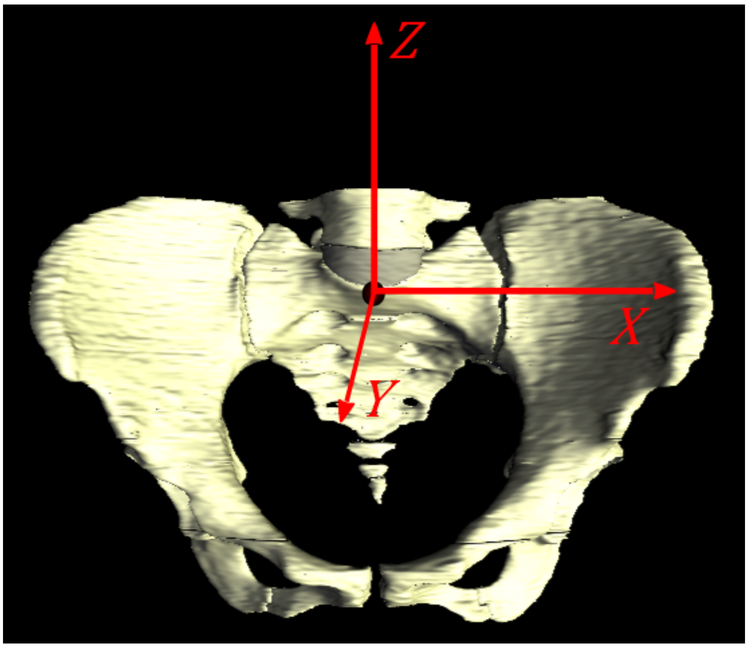


Figure 3.4: This figure shows the standardized coordinate system. The origin lies in the sacral promontory.

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. As can be seen in figure 3.4, 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.

Mappings

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 using registration and can be

Mapping	Category	Type
rigid	linear	translation and rotation
affine	linear	translation, rotation, shearing, scaling
nonrigid	non-linear	deformable
hybrid	non-linear	combination of the above

Table 3.1: Currently defined mapping types.

Locator	Category	Information
points	spatial	set of points
volume	spatial	origin, extent, spacing
nongeometric	non-spatial	-

Table 3.2: Supported locator types

rigid, affine, deformable or hybrid, for example articulated registration [2] (see table 3.1). Because of the different modalities available, registration of the different source objects is no easy task. Furthermore, inter-patient variability further complicates the process.

The exact type of registration chosen for the source object, greatly depends on the clinical or research question. It can for instance depend on what the surgical structure of interest is. If a surgeon is interested in the nerves around the rectum, the registration needs to be near-perfect around the rectum and the correctness of the bone-to-bone mapping is of less importance. Therefore, the model allows multiple task-specific mappings to be stored. The mapping most suitable for the clinical or research question at hand can be freely chosen at all times. Since the source objects are stored ‘unmapped’, at any point in time the user can also view the original data objects.

Along with the mappings themselves, the errors made in the registration process need to be stored in order to use them to visualize uncertainty in the final representation. By storing the local error metric along with the mapping, an indication of location reliability can be given. When multiple mappings are used in succession, the successive errors made need to be combined. Any uncertainty in the exact locations of the nerves for instance, can have devastating consequences for the surgical outcome and therefore need to be made apparent to the users.

Locators

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 (see table 3.2). 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. This can be seen in figure 3.5. For non-geometric model

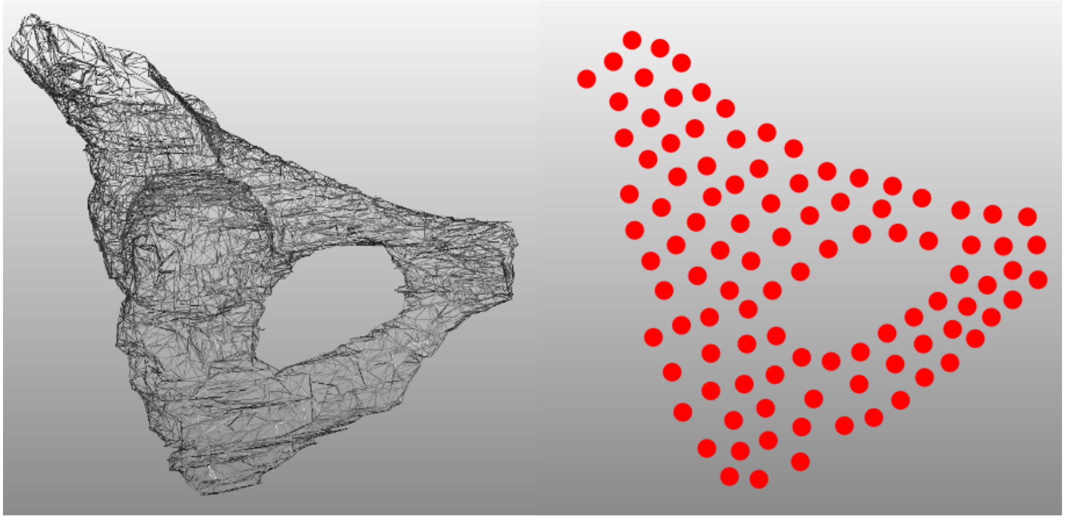


Figure 3.5: A points locator. On the left: a surface wireframe for the iliac bone with a total of 67746 points. On the right: an illustration of the sparse point sampling of this surface that forms the locator for this structure.

Relation	Dependent	Independent	Parameter
associated_to	literature	structure	-
lookupvalue	value	volume	-
defined_by	structure	structure	operation
landmark	structure	points	type
subdivision	structure	structure	planes

Table 3.3: Types of relations that are currently supported by our system. This can easily be extended with new types at any time.

objects, the locators do not store any extra information, but are used in defining relations between model objects.

Since there can be several model objects that have the same spatial properties, the locators are used, so that when the spatial properties of several model objects sharing the same locator change, no changes need to be made to all of these model objects themselves. An example of this is when several differently weighted MRI scans of the same series are available. The spatial extent for all of these volumes is the same, but if a mistake was made in for instance the x-axis extent, it can be fixed by simply adjusting one locator value.

Relations

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

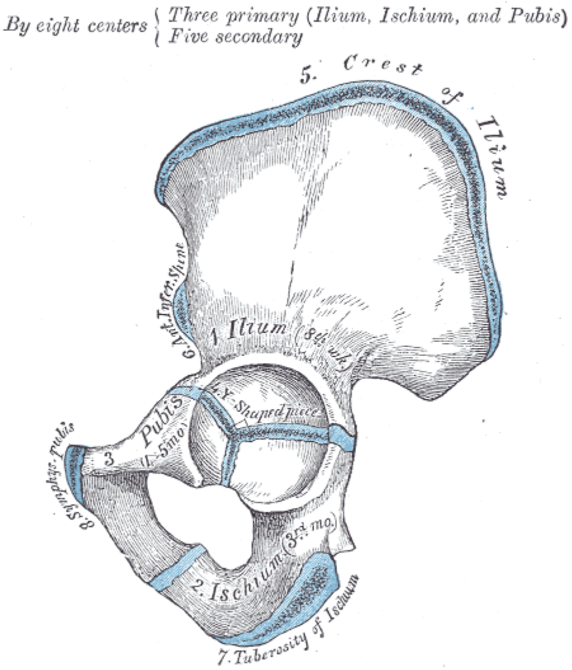


Figure 3.6: The figure above demonstrates the ossification plan of the hip bone. Its three main components: the ilium, ischium and pubis, start uniting after puberty. The superior part of the ilium show the location of the iliac crest [15].

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 (see table 3.3). 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.

In the VOXELMAN-project, relations are used to describe anatomical links that are structural, functional or represent abstraction in a semantic network [19]. 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. For instance, the hip bone consists of three main components: the ilium, ischium and ilium, that are not connected at birth, but are fused together in adulthood [15]. This subdivision can be seen in figure 3.6. Using our relations, the ilium can be defined geometrically as a subdivision where the ilium is a part of the hip bone and two splitting planes (one separating the ilium from the pubis and one separating the ilium from the ischium) define exactly how this part is defined geometrically. In this case, the dependent variable is the ileum, the independent variable is the hip bone and the parameters describe the splitting planes.

Another example of a free-form relation is defining the location of the iliac crest (see figure 3.6). It would be tedious to denote the exact location of this crest during the semi-automatic segmentation stage, as there is no clearly defined boundary between the ilium and the iliac crest. Therefore, it is preferable to define the iliac crest at a later stage based on a 3D surface model of the original segmentation using a landmark relation. The dependent variable will be the ilium, the independent variable a points locator describing the extent of the iliac crest and the parameter will describe the landmark type (a crest in this case). This landmark relation can be used to define many anatomical landmarks that can not easily be delineated in the segmentation phase. Other examples of landmark types are holes, spinas (a sharp thornlike anatomical process) and lines.

3.2 Processing

In this section we elaborate on the processing required to add anatomical data to the model described in the previous section and more specifically the mapping that is needed to convert this data to model space. The transformation or mapping is the result of a registration process. This registration, as mentioned earlier, can be done in multiple ways: rigid, affine, nonrigid or a hybrid. But this is not the full story, there will be cases in which a mapping is required to be perfect around, for instance, the rectum, but can be estimated everywhere else. In other cases, the mapping needs to be affine in order not to completely warp away anatomical variations that are fundamentally different than the registration target. This is why the model allows for multiple different mappings to be stored with every model object, so that the user can decide at any moment what mapping is most suitable for the current situation.

In the first case, what is really required is a structure-specific mapping, that lets the registration of the structure of interest be as close to perfection as possible. This can for instance be achieved by segmenting the structure of interest of the patient-specific source scan, calculating a distance field and registering that to the distance field of the same anatomical structure in the target model space. When registering the data in this way, the mapping will be as correct as possible for the rectum, and structures around the rectum will be left untouched. Constraints can be added to the registration process that make sure that the registration result always has structures that are anatomically correct (shape or positional constraints for instance). In a way, these structure-specific mappings are a more generalized case of articulated registration.

3.3 Summary

In this chapter we presented The Unified Anatomical Human. In this model-based approach, arbitrary heterogeneous anatomical data can be stored, queried and visualized. There are several concepts that, when combined, form the basis of The Unified Anatomical Human:

- **Source Objects:** original unprocessed anatomical data
- **Model Objects:** source objects augmented with a locator and mapping(s)
- **Mappings:** transformations from source object to model space
- **Locators:** descriptions of model space extent of source objects

- **Relations:** links between model objects

The anatomical information stored in the model has great added value in itself, for instance in anatomical and surgical education. But by using the ability to store mappings with model objects, model information can be transformed to fit patient-specific scans, thus being an invaluable asset to surgical planning and intra-operative guidance applications.

Chapter 4

Implementation

This chapter describes the implementation of the prototype UAHViewer application, a module that allows the user to visualize and query information from the Unified Anatomical Human-database and to store new information in the database. The first section describes the software technologies that were used to implement the UAHViewer. The second section describes the design decisions made for the implementation of this prototype.

4.1 Software

The prototype application to store, explore and query model information is implemented in Python as a DeVIDE module[6], employing the Visualization Tookit (VTK) for its visualization functionality. DeVIDE, or the Delft Visualisation and Image processing Development Environment, is a cross-platform software framework for the rapid prototyping, testing and deployment of visualisation and image processing algorithms.

An important component of our system is the underlying database, which was implemented using MongoDB. MongoDB is a *schema-less* document-oriented database technology that is designed to be agile and scalable. Since there is no fixed schema design required in the initial stages of the project, a benefit of using this technology is that it is easy to further extend our model as new information is provided to us by the anatomists, without any changes required to the existing database. Furthermore, MongoDB's GridFS enables us to store large volume data and rapidly retrieve it from the database.

The current model is based on a semi-automatic segmentation in Amira[34] of cryosectional images of a dutch female pelvis. Based on this segmentation, an iso-surface was rendered using the Marching Cubes algorithm[23]. The registration of an MRI of the same patient and a CT-scan of a male patient to the cryosectional images was done using the 3DSlicer software package.

4.2 Design Decisions

This section describes several design decisions in the implementation of our prototype application, namely spatial indexing and the database design.

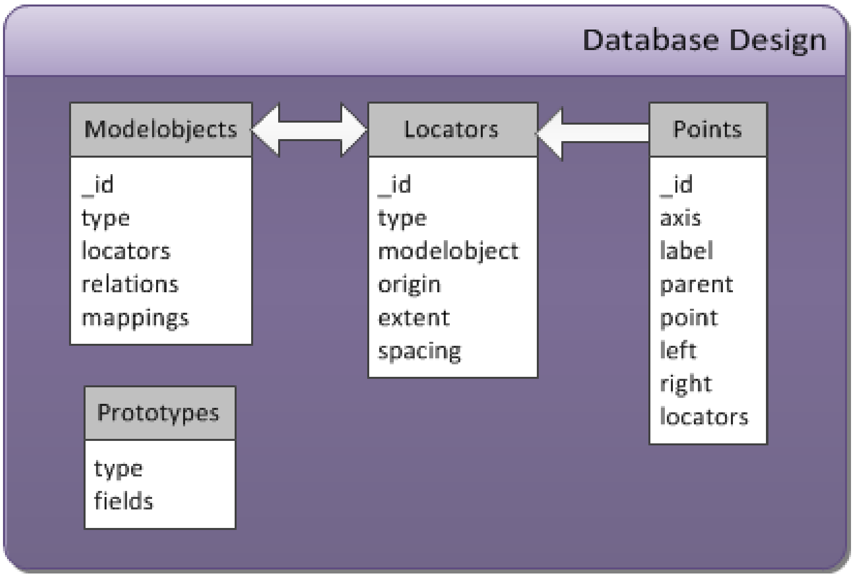


Figure 4.1: The database design for the Unified Anatomical Human. Model objects store a reference to the locator and locators store a reference to the model object that it is related to. Points used in k-d tree construction are stored in a separate collection and have a reference to the locator.

4.2.1 Spatial Indexing

MongoDB supports two-dimensional geo-spatial indexing, which is useful for queries such as ’find me the closest N items to a certain locations’. Since the anatomical structures we want to store and query are inherently three-dimensional, however, a different approach had to be implemented. To be able to locate three-dimensional structures through their locators, points on the surface structure are selected via sparse point sampling. The spatial indexing of the sparse point sampled objects is then done by building a k-d tree and storing it in our database[4].

A k-d tree is a well-known multidimensional binary search tree. It partitions the k-dimensional space to organize points into a tree structure. For the three-dimensional space in our application, the algorithm works as follows. In the first step of the algorithm, the median of all points is found in the x-axis direction, this point defines the first hyperplane that splits the space in two. All the points to the left of this plane are considered for the left subtree and all points to the right for the right subtree. In the second step, the median in the y-axis is found for both point subsets. These medians form the left and right child nodes and define a hyperplane in the y-direction. In the third step the z-axis is considered and the whole procedure repeats itself until all points become a node in the tree. This algorithm is easy to implement and very suitable for nearest neighbor and spatial region queries.

4.2.2 Database Design

A schema-less database differs from a traditional relational database in that there is no predefined data model or schema. Instead of tables and rows it has collections and documents. The documents store BSON (binary-serialized JSON-like data) fields as key-value pairs and can embed other documents. The key-value pairs consist of a name as the key and the value can contain any basic type (such as a string, integer, timestamp, binary, etc.), document or array of values. In a document-oriented database technology such as MongoDB, there are no joins, but the ability to embed documents reduces the need for join-operations. The effect of these design decisions is that a high performance can be attained making read and write operations fast.

The collections that form the database are consistent with the method described in the previous chapter. An overview of the database collections can be seen in figure 4.1. There is a collection for the model objects and locators. The source objects are stored embedded in the Modelobjects collection (keep in mind that source objects become model objects when a locator and mappings(s) are added). The mapping(s) associated with a volume are also stored as embedded documents within the Modelobjects collection. Relations are stored in the database in the Modelobjects collection of the relation type. The parameter, dependent and independent components are then stored as fields of the relation type model object.

Additionally, there are two collections in the database design not described in the previous chapter. The k-d tree, as described in the previous subsection, is stored in the points collection. The second extra collection is the prototypes collection. This stores the prototype description of current types of modelobjects available in the modelobjects collection. The fields of those model object types that are compulsory for that type are stored as a prototype. The prototypes collection can then be used for instance to format query output per type.

Chapter 5

Results

To evaluate the practical applicability of the Unified Anatomical Human model, a prototype application was built: the UAHViewer. This prototype application offers several visualization functionalities and demonstrates the usefulness of our model. The user interface consists of three render windows that represent the surface model along with two linked slice viewers, that can display arbitrary volume data. The user is not only able to query anatomical structures topically (by subject), by selecting an anatomical term from a drop-down list or clicking on a structure in any view, but can also query the model spatially.

The dataset used as an example in this chapter is based on a course semi-automatic segmentation of a dutch female pelvis. This segmentation was drawn on cryosectional slices using Amira [34]. A total of 34 anatomical structures were segmented, but the dataset lacks a detailed segmentation of surgically relevant structures, such as the autonomic nerves. A MRI scan of the same specimen is also available.

In this section we demonstrate the utility of our model-based anatomy visualization prototype using three examples. These examples our followed by an evaluation of how the technical requirements are met. The chapter is concluded by a short summary.

5.1 Generic Multi-modal Data Querying

By mapping volumes to anatomical model coordinates, it becomes possible to simultaneously slice through volumes of different modalities and different subjects. The linked volume representations enable the user to compare arbitrary multi-modal volumes side-by-side in an interactive and intuitive way.

It is also possible to query a specific voxel value in all available volumes at a selected point. This type of spatial querying is done by either clicking on a structure in the surface rendering or in one of the slice viewers. A high-level data flow diagram of this process is shown in figure 5.1. When the user selects ’value’ from the query results, the coordinates of the point last clicked by the user are acquired. These coordinates are then used to find all available volumes in that point using the volumes’ locators. Since the locators for volumes store the spatial extent, spacing and origin for every volume, it is straight forward to check if a coordinate in standardized anatomical space is available in that specific volume. When

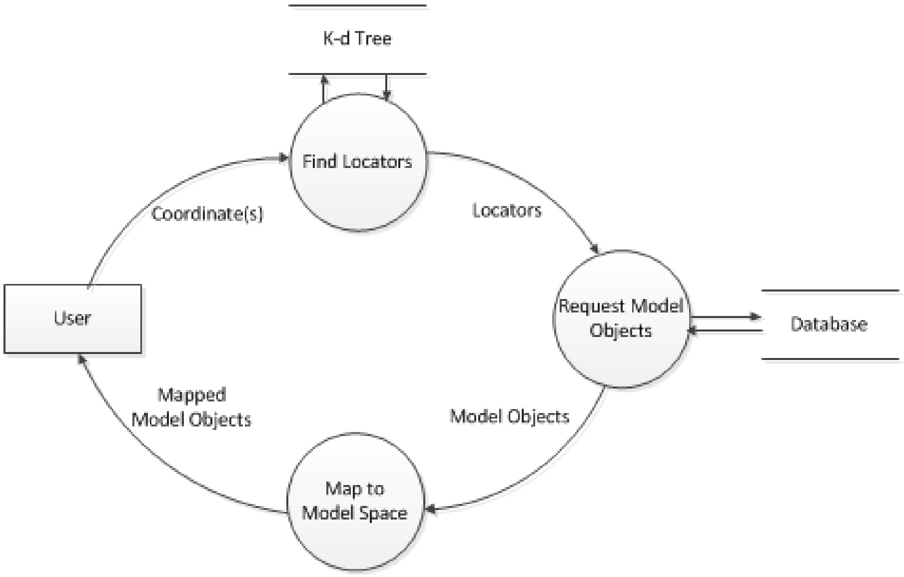


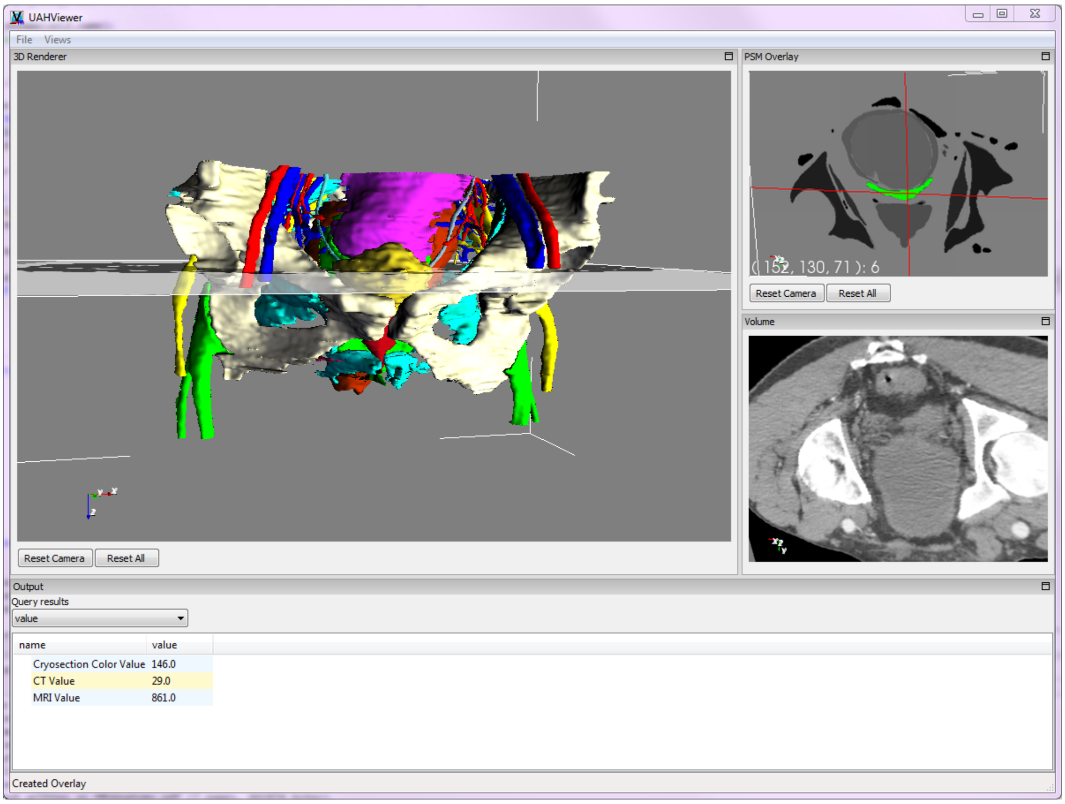
Figure 5.1: The high-level data flow diagram for querying in the Unified Anatomical Human.

the available volumes are returned from the database, the value at the query-coordinate can be acquired and returned to the user. For example, in figure 5.2 a point is queried in the segmentation label volume. This query returns the voxel values for all volumes available in that point. The linked representations make it easy to locate points of interest in any view prefered by the user. The CT Hounsfield value can then be used for instance to calculate the Young's modulus (compressive stiffness) of bone [39].

Another way of querying model information is to select an anatomical structure of interest topically, i.e. by selecting the structure of interest from a drop-down menu or by clicking on the structure directly in an arbitrary view. Figure 5.3 demonstrates this functionality. After selecting the structure of interest, the structure is highlighted and the query results for that structure are returned. In this case, the user has drawn anatomical landmarks on the bone in the three-dimensional surface reconstruction and stored these in the database. Also the user has associated relevant literature to this structure. Since the literature and landmarks are stored as relations in the database, the related model objects are easily found and added to the query results. The query results therefore consists of all available information for this structure itself, for instance the name and segmentation value, as well as the literature and anatomical landmarks related to this structure.

5.2 Distance Querying

Besides topical queries, spatial queries are also possible. The user can query a specific volume of the model space by using a selection query sphere. In this way, users can select an area of interest and perform a distance query in this area. The application then returns the



(152, 130, 71): 6

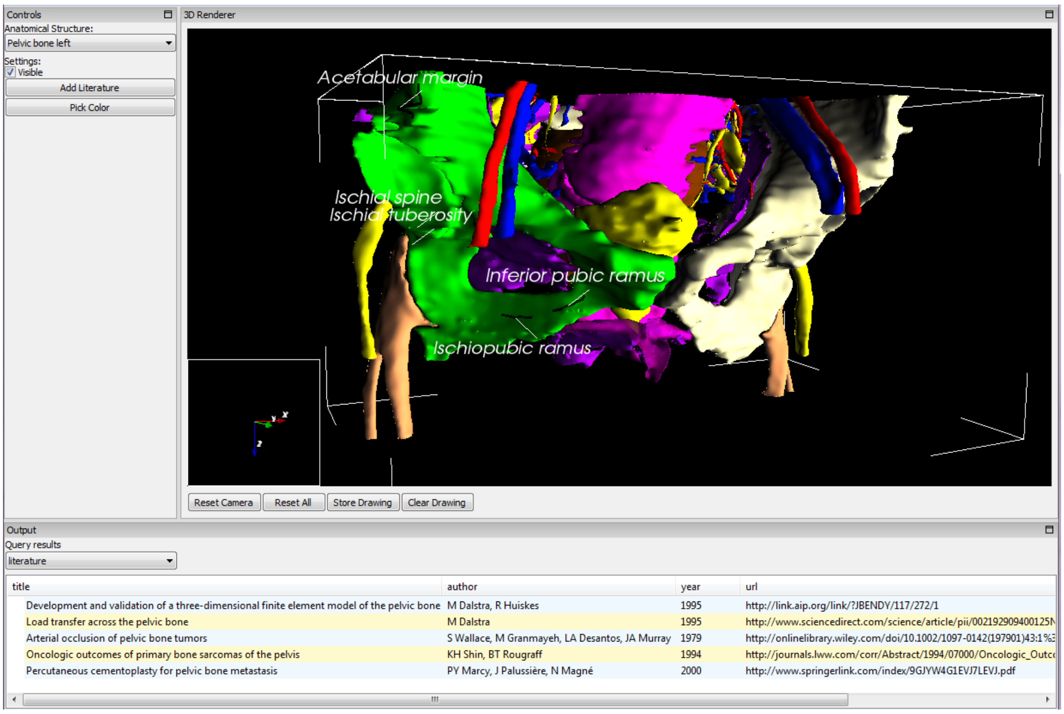
name	value
Cryosection Color Value	146.0
CT Value	29.0
MRI Value	861.0

Created Overlay

Figure 5.2: Value querying in arbitrary views presents query results for all available volumes in that point. The surface render shows an MRI slice while the top right render window displays the linked segmentation label volume slice and the lower right render window displays the mapped CT slice

query results of the point that was selected as well as all locators in the region encompassed in the selection sphere. The query process is similar to the one shown in figure 5.1, but the locators are found by specifying a coordinate and range of interest. As an example, when a user is interested in all information on anatomical structures within a region of interest surrounding the bladder, a query sphere can be placed to define that region. Figure 5.4 shows how the sphere selection returns query results based on the locators found inside the sphere. In this figure, the anatomical structures found in the sphere are shown, but it is also possible to show only the literature relevant to structures inside the sphere by their relations. In figure 5.5 a distance query presents the relations of all structures found inside the selection sphere and literature associations within the sphere are revealed.

As mentioned in the implementation chapter, the segmentation of anatomical structures is stored by building a k-d tree from a sparse point sampling of each structure. The locator for an anatomical structure thus consists of a set of points that represent the spacial extent in model space. When a query is sent to the database, specifying a coordinate and the range, the k-d tree is rapidly traversed to find all points within the area of interest. Having



Anatomical Structure: Pelvic bone left

Settings: ☑ Visible

Query results: literature

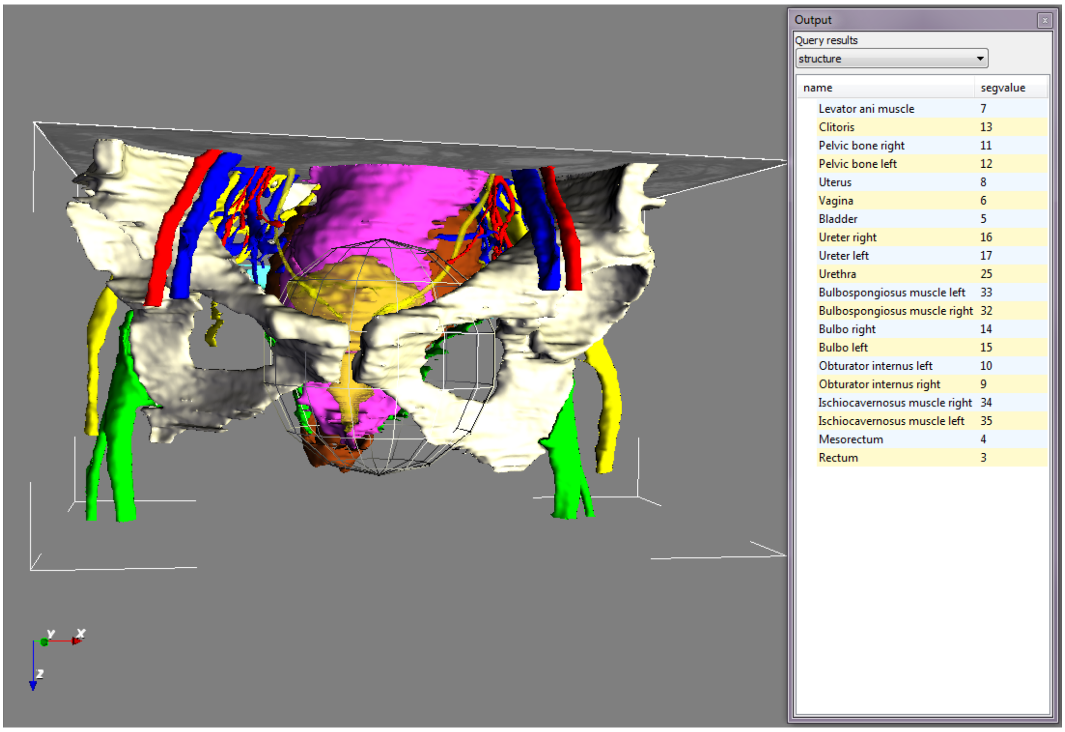
title	author	year	url
Development and validation of a three-dimensional finite element model of the pelvic bone	M Dalstra, R Huiskes	1995	http://link.aip.org/link/?JBENDY/117/272/1
Load transfer across the pelvic bone	M Dalstra	1995	http://www.sciencedirect.com/science/article/pii/002192909400125N
Arterial occlusion of pelvic bone tumors	S Wallace, M Granmayeh, LA Desantos, JA Murray	1979	http://onlinelibrary.wiley.com/doi/10.1002/1097-0142(197901)43:1%3
Oncologic outcomes of primary bone sarcomas of the pelvis	KH Shin, BT Rougraff	1994	http://journals.lww.com/corr/Abstract/1994/07000/Oncologic_Outc
Percutaneous cementoplasty for pelvic bone metastasis	PY Marcy, J Palussière, N Magné	2000	http://www.springerlink.com/index/9GJYW4G1EVJ7LEVJ.pdf

Figure 5.3: Topical querying can be done by selecting an anatomical structure of interest from the dropdown list in the top left of the screen or clicking on that structure in an arbitrary view. The structure of interest is highlighted and the query results return all related information from the model. Shown here are anatomical landmarks drawn on the structure in 3D and related literature results.

found the locators representing these points, the associated model objects can be found by querying the model objects collection for objects that use these locators. Using the database implementation of a k-d tree as a spatial index of the point sets, spatial query results can be updated dynamically in real time. This means that when the sphere is moved in the three-dimensional view, the query results update in real time to reflect the model objects that are at that time present in the sphere of interest. This provides the users with the ability to rapidly explore all model objects within a region of interest in an intuitive way.

5.3 Mapping Model Information to Patient Data

A third example of a prototype functionality is enriching unseen patient scan data with the information provided by model objects. By registering a patient-specific scan from an arbitrary modality and providing a mapping to model space, it becomes possible to reveal structures that can not be denoted in that modality by default. For instance, because there is not enough contrast between nerves and surrounding soft tissues in CT-scans, the location of nerves is not visible in a CT-scan. In histological and cryosectional images, however,



name	segvalue
Levator ani muscle	7
Clitoris	13
Pelvic bone right	11
Pelvic bone left	12
Uterus	8
Vagina	6
Bladder	5
Ureter right	16
Ureter left	17
Urethra	25
Bulbospongiosus muscle left	33
Bulbospongiosus muscle right	32
Bulbo right	14
Bulbo left	15
Obturator internus left	10
Obturator internus right	9
Ischiocavernosus muscle right	34
Ischiocavernosus muscle left	35
Mesorectum	4
Rectum	3

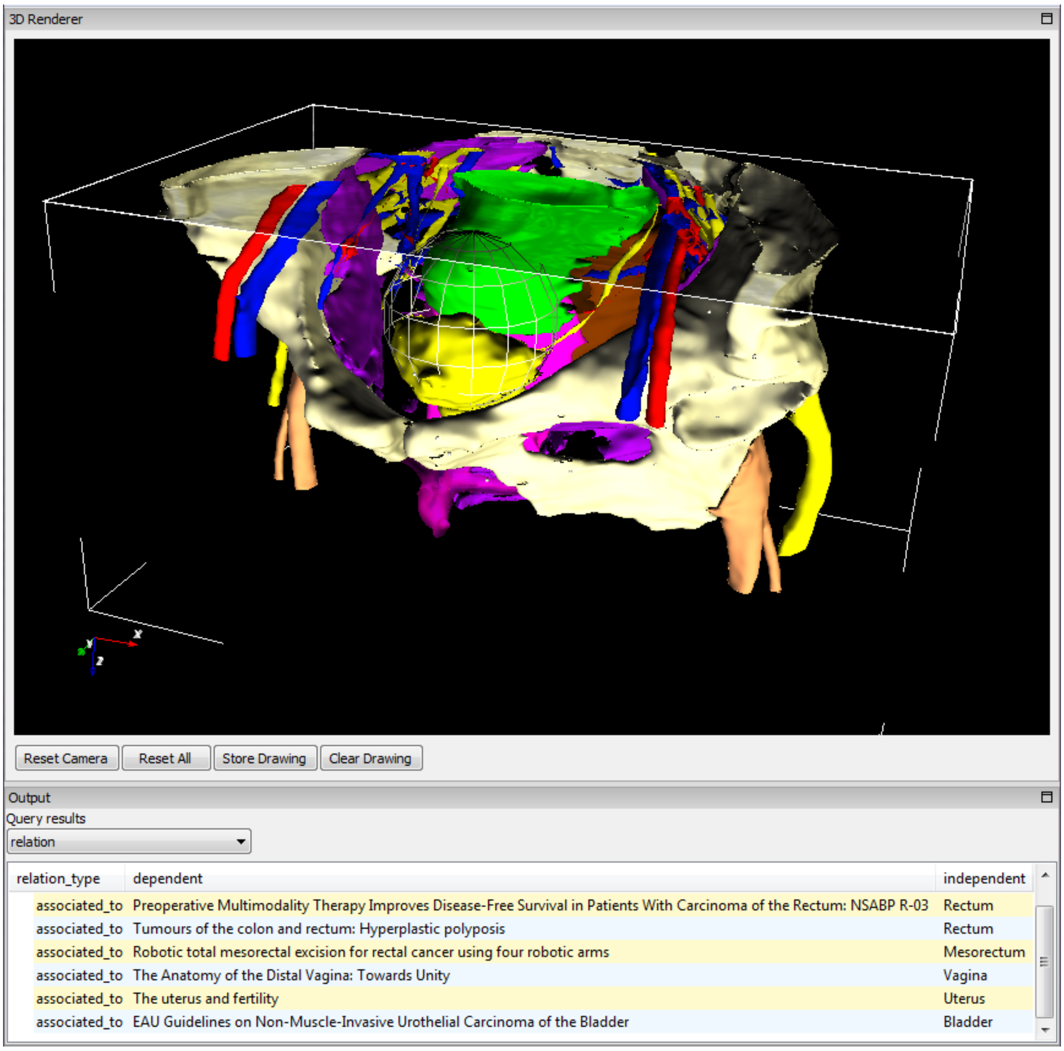
Figure 5.4: Spatial querying through sphere selection. The central render window shows the 3D surface model and selection sphere. On the right, the query results are presented, in this case we show all the anatomical structures that are available inside the selection sphere.

the nerves can be seen and segmented. In figure 5.6, a CT-scan added to model space is enriched with an isosurface render of the nerves segmented based on cryosectional images.

In general, figure 5.7 shows the process of making arbitrary structures stored in the UAH patient-specific. By selecting a structure of interest and an arbitrary modality mapped to model space, the stored mapping is used to map the structure of interest to patient space. This process can be used to map the cryosectional volume that forms the basis of the model space and standardized coordinate system back to a patient-specific scan. This does of course require the transformation stored in the mapping to be invertible. By selecting the mapping that is most appropriate for the task at hand, for instance a mapping based on a structure-specific registration process, it becomes possible to map structures of interest to patient-specific scans in the most optimal way given the structure of interest.

Using this same mapping principle, it is also possible to map the entire segmentation label volume to patient-specific data. If the registration is done correctly, this creates an automatic segmentation of the unseen patient-specific scan. This mapped segmentation can be used to make a three-dimensional patient model by rendering the isosurfaces.

At this time, this example is a demonstration of the available data structures in the model and their flexibility. For the future work on this project, structure- and task-specific mappings are planned. More about this is described in chapter 6.



relation_type	dependent	independent
associated_to	Preoperative Multimodality Therapy Improves Disease-Free Survival in Patients With Carcinoma of the Rectum: NSABP R-03	Rectum
associated_to	Tumours of the colon and rectum: Hyperplastic polyposis	Rectum
associated_to	Robotic total mesorectal excision for rectal cancer using four robotic arms	Mesorectum
associated_to	The Anatomy of the Distal Vagina: Towards Unity	Vagina
associated_to	The uterus and fertility	Uterus
associated_to	EAU Guidelines on Non-Muscle-Invasive Urothelial Carcinoma of the Bladder	Bladder

Figure 5.5: A distance query reveals the literature associated to the structures within the selection sphere.

5.4 Reflection on Requirements

When we consider the technical requirements posed in the introduction, we see that the proposed model and prototype application based on the model fulfill the demands. In the storage requirements we stated that the system should be able to store arbitrary types of heterogeneous anatomical data of different resolutions and spacings. The first of the three examples in this chapter demonstrate that spatial data such as cryosectional data and segmentation data as well as metadata (such as segmentation values per structure) can be stored in a single system. In the third example we see that even CT-data of another patient, resolution and spacing can be stored in the model along with a proper mapping.

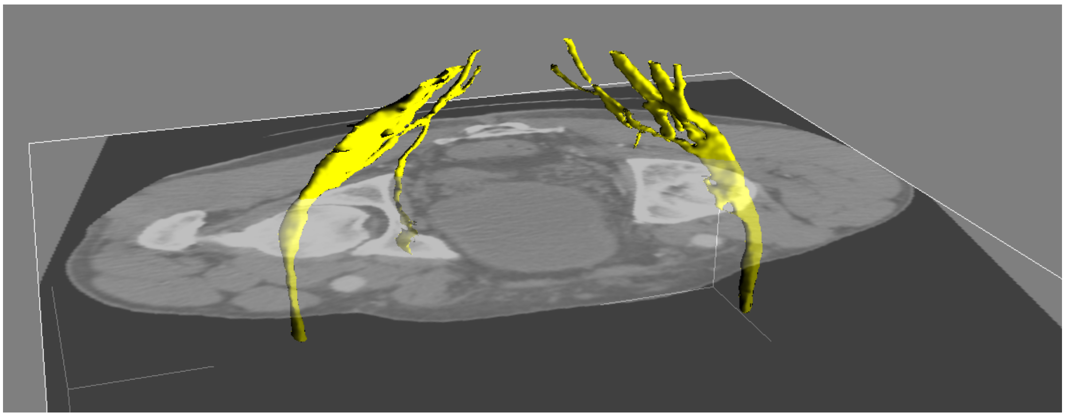


Figure 5.6: Using our approach, the nerves that were segmented in the cryosectional images can be mapped to unseen patient specific CT-scan data. The location of these nerves is not visible in the original CT-scan.

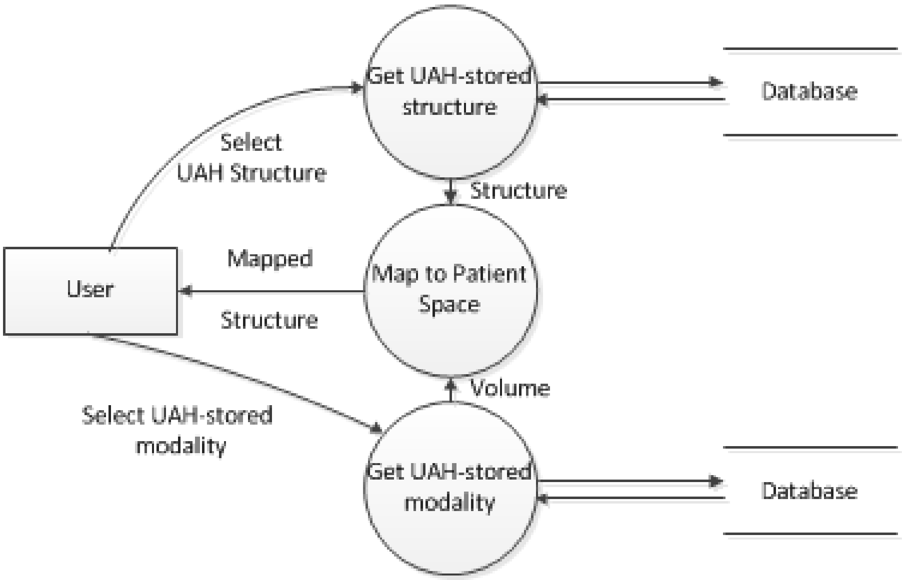


Figure 5.7: The high-level data flow diagram for mapping structures stored in the UAH to a UAH-stored modality such as a patient-specific-scan.

The second requirement was that topical and spatial queries should be executable in a shared coordinate system. Our model demonstrates the fulfillment of this requirement in the first and second example. The first example demonstrates how a user can query a structure of interest topically, by selecting it from a dropdown list. The second example shows spatial querying by presenting the user to query all information available in a sphere of interest that can be placed in model space interactively. The implied necessary shared coordinate system requirement is fulfilled by storing a mapping to model space for every stored volume that is not in the same space as the original cryosectional data that the model is based on.

The third requirement stated that the visualization possibilities need to represent information of interest in its anatomical spatial context and that volume data should be visualized in such a way that the relation to the other available representations is made explicit. Furthermore, when a patient-specific scan is added to the system, model information needs to be represented in the context of this patient specific scan. In the first example, the linked multiple views demonstrate the fulfillment of the first two visualization requirements. The third visualization requirement is represented in the third example, by showing the surface reconstruction of the nerves only available in model space on a slice-based patient-specific CT-scan representation.

5.5 Summary

Our prototype application demonstrates that our model-based approach can be used to integrate anatomy datasets from various sources into a unified representation. The model data can then be queried in a variety of ways:

- *Structurally*: by selecting anatomical structures directly by name.
- *Spatially*: using the anatomical coordinate system and selecting a structure in an arbitrary view or using distance queries.

Furthermore, the model data can be mapped to patient-specific scans to reveal structures that are not originally available from that specific modality. The reflection section demonstrates that all technical requirements are met in the Unified Anatomical Human-system design.

Chapter 6

Conclusions and Future Work

In this final chapter we conclude this work with conclusions that can be drawn from the previous chapters and describe the future work that is envisioned for this project.

6.1 Conclusions

The Unified Anatomical Human model consists of four major components: source objects, model objects, locators and mappings. Source objects consist of original unedited anatomical information. Once they are enriched with a locator that describes their spatial extent in a single shared coordinate system and one or more mappings that describe the transformation between their original spatial layouts and the model coordinate system are added, the source objects become model objects and thus become part of The Unified Anatomical Human system. Free-form relations between model objects can also be defined in this model and are actually a first class citizen in that they form model objects themselves.

The mappings stored with the model objects are transformations that are the result of one or more registrations. These transformations can be rigid, affine, nonrigid or a hybrid that combines several of these types. It is important to note that since the source objects are stored in their pristine state, at any point, the original unmapped source object can be examined. To view the source objects in the standardized coordinate system that forms the model space, a mapping can be chosen that fits the task at hand the most.

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: The Unified Anatomical Human. 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 Unified Anatomical Human model forms a excellent foundation for future pre-operative surgical planning and intra-operative guidance applications, such as the Virtual Surgical Pelvis.

6.2 Future Work

Future work includes creating a better and more detailed pelvic model. Our proof of concept model is based on a course manual segmentation of 34 structures in a dutch female pelvis, but anatomical researchers at the LUMC are currently working on segmenting images from the Visible Korean dataset [10]. The level of detail of this dataset enables us to segment not only more anatomical structures that were not visible in the current set, but also to segment the structures more accurately. At this time, only the bony structures, the rectal lumen and muscles in the pelvis are segmented from this dataset (see figure 6.1), but more structures will be added incrementally.

Another planned improvement is enhancing the registration process. Since the registration process is such a crucial step in the practical applicability of our model, 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 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, any

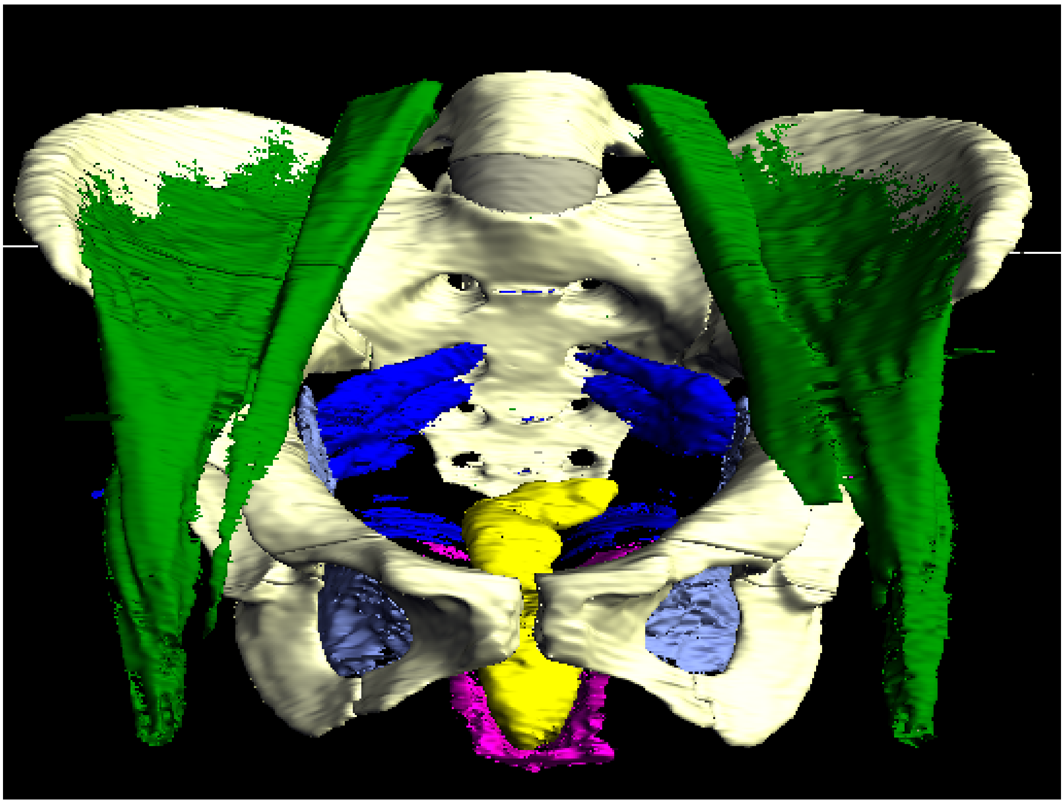


Figure 6.1: Bones, rectal lumen and muscles of the pelvis semi-automatically segmented from the Visible Korean Female dataset [10].

uncertainty regarding the exact location of an anatomical structure must be made immediately apparent to the user.

Other standard coordinate systems such as the Talairach or MNI space used in the neuroscience community [9] are already in use today and further investigation needs to be done to see how the UAH should deal with these existing standards. At first glance, it seems that mappings between these coordinate systems and our standardized anatomical coordinate systems are feasible. The source objects can then be stored in their original coordinate system and the mappings specify how this relates to our standardized coordinate system.

Furthermore, we plan to create richer visualization options for model objects. Currently, only isosurface rendering and volume slicing are available, but we would like to extend the visualization possibilities with direct volume rendering techniques. With the information available from the model objects and their relations, it will be possible to create composite custom visualizations for different clinical questions. It might even prove beneficial to allow our system to create composite visualization suggestions based on the structures of interest and the optimization of a cost function.

A webapplication that is a simplified version of the UAHViewer prototype could enable clinicians and medical researchers to view model information from any computer with internet access within the hospital. With emerging technologies such as WebGL, hardware-accelerated three-dimensional graphics become feasible. This would allow staff to interact with information in the Unified Anatomical Human without the need to install additional software or a specialized workstation.

We envision surgical and educational applications that use information from the model as a basis for surgical education and pre-operative surgical planning. The education value of a three-dimensional model that includes the complex anatomy of the pelvis is immediately apparent for anatomical education. As for surgical education, training scenarios can be created for various anatomical and pathological situations, so that the students can practice surgical procedures in a virtual reality environment. When patient-specific scans are added and the model information can be mapped to these scans, a pre-operative planning tool for procedures such as the total mesorectal excision mentioned in the introduction becomes feasible. Our work can even form the basis for intra-operative surgical guidance in the future.

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Appendix A

Glossary

In this appendix we give an overview of frequently used terms and abbreviations.

UAH: Unified Anatomical Human

UAHViewer: Prototype application for interaction with the Unified Anatomical Human database

CVH: Chinese Visible Human

TME: Total Mesorectal Excision

VCH: Virtual Chinese Human

VKH: Visible Korean Human

VHP: Visual Human Project

VSP: Virtual Surgical Pelvis