VES: VIRTUAL ECHOCARDIOGRAPHY SYSTEM

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ABSTRACT

The objective of the VES project is the research and development of innovative techniques and solutions for the achievement of a virtual examination environment in echocardiography. One crucial point is the development of realistic geometric models representing the diseased human heart. For this purpose we decided to use real echocardiography findings as a starting position. The modelling and visualisation of a human heart based on findings requires initially the elaboration of an ontological framework for echocardiography findings and heart-beat descriptions at the medical and at the geometrical level. In this paper we present our work on ontologies and how geometric models can be derived from them. We go on to explain how these techniques can be combined to achieve a virtual examination environment. In this way we show that VES serves as a case study for ontology based visualisation.

KEY WORDS

Visual Information Systems, Surface Reconstruction, Medicine, Intelligent Tutoring Systems

1 Introduction

Sonography has become a very useful diagnostic tool in almost every medical field after it was introduced in the late 1950's. At present real-time scanners are in routine use, which depict a continuous two-dimensional picture of medical structures on a monitor screen. According to the diagnostic question very high frequency sound waves of 2.5 megahertz are used for this purpose. Repetitive arrays of ultrasound beams scan the region of interest in thin slices and are reflected back onto the same transducer. The information obtained from different reflections is recomposed into a sequence of pictures.

Because of the high expressiveness of the images obtained by sophisticated computer technology, examination of the structure and function of the heart and great vessel structures by ultrasound, hereby referred to as echocardiography, is becoming of increasingly better quality. Due to the non-invasive nature of ultrasound and the expansion of the roles of cardiac technicians and radiographers, ultrasound scanning is becoming a fast and readily available modality, which is able to give immediate results at relatively low cost.

Although echocardiography plays an important role in clinical diagnostics, there are still some major drawbacks associated with this technique. Due to clinical routine the time for monitored and guided examinations is quite limited. Many potential findings are rare compared to the number of examinations done every year but may have lethal consequences nevertheless. After completing the one year training the student will still have seen only up to 80 % of the possible findings. In consequence, partially untrained medical personnel are doing every day clinical routine far before they have acquired a thorough experience in the vision process. Therefore, computerized education and training will become particularly important with the increasing role played by echocardiography in the management of patients.

In this respect, the long range objective of the Virtual Echocardiography Project (VES) is the research and development of innovative techniques and solutions for the achievement of a virtual examination environment for educational purpose in echocardiography. Applying the VES technologies, medical students and echo cardiographers can take part in training sessions and further education to improve their technical and clinical skills in the field of echocardiography.

This paper describes the design of the VES architecture, and presents the methods and techniques necessary for developing it. In particular the formal representation of medical knowledge and anatomical modelling in the field of echocardiography will be addressed.

First we give a brief overview on related work concerning anatomical modelling. In the next section we present an overview over the knowledge management techniques that were used and we describe how these methods were applied in the design of our system. In section 4, we describe the development of appropriate geometric models for the visualisation step followed by an overview over the system architecture.

2 Related Work

In the field of knowledge management lots of current research is spent in the modelling of anatomical and medical structures. Examples for taxonomical structured medical vocabularies are MeSH [1] and UMLS [2]. A project that also follows the idea of building an ontology of human anatomy is the Foundational Model from the University of Washington ([5] and [6]). Although all these project are dealing with very similar terms they do not or only rudimentary provide information about the spatial relationships between different anatomical structures. Due to this fact, the generation of satisfactory geometric models for the visualisation of complex objects only from the ontology is not possible.

Regarding geometric heart modelling in [1] the left ventricle is modelled using CSG primitives (free form objects). The main aspect is the reconstruction of the myocard. [2] constructs a hybrid phantom of the left and right ventricular cavity based on anatomical and geometrical phantoms. In contrast to most projects concerned with heart model creation the main purpose of this project is to build a dynamic model of the complete heart, thereby preserving as much geometrical information as possible.

[3] reconstructs a mesh of the left and right ventricle in order to solve the inverse problem of electro-cardiology. The same background holds for [4] where the anatomy of individual heart features is reconstructed from few cross-sectional CT images based on a prior model. Some other projects approximate heart structures by ellipsoids or other geometrical primitives. Most projects model the left and right ventricle solely. These models, however, can only be used in a dedicated manner, e.g. motion analysis, change in volume and many others. They are not suitable to give an insight into the complex geometrical structure of the heart.

3 Formal Representation of Medical Knowledge

3.1 The Term Ontology

In the field of artificial intelligence, ontologies are used to formally describe information and concepts from a particular domain and to gather relationships between these terms. The literature contains lots of different definitions of the term ontology, many of them contradicting one another. Since we decided to use the ontology editor Protégé-2000 [3] for our design, we restricted the notion of ontology for our purposes to the definition used in the context of Protégé-2000. In this manner, an ontology consists of classes each representing a particular set of objects with common properties or structure. A single object of a class is called instance. Each class has a set of attributes (or slots) describing the classes' properties. When creating an instance of a class, the slots are filled with values. The range of valid slot values can be restricted by attaching facets to the corresponding slot like cardinality, value type, etc. Another aspect characterising an ontology is inheritance. Classes can be derived from superclasses where the subclass inherits all attributes of its superclass. The subclass is related to the superclass via an is-a relationship. More detailed information about the Protégé-2000 notion of ontologies can be found in [9].

[1]http://www.nlm.nih.gov/mesh/meshhome.html
[2]http://www.nlm.nih.gov/research/umls/
[3]http://protege.stanford.edu

3.2 The Ontology Framework

The development of a parametric heart model describing a human heart is essential for a virtual examination environment. In order to store the information gained by an echo-cardiographic examination of a patient, we also need to model the structure of such a finding. This conditions led to a framework that consists of three different ontologies.

- a finding ontology representing an echo-cardiographic finding.
- a heart ontology that gives a detailed description of a healthy human heart.
- a third ontology operates on a meta level and is designed to merge a certain finding with the healthy heart to generate a model of an individual existing heart.

An overview of this framework is given in figure 1. All ontologies were developed and maintained with Protégé-2000. In the following we are going to have a closer look at the different ontologies.

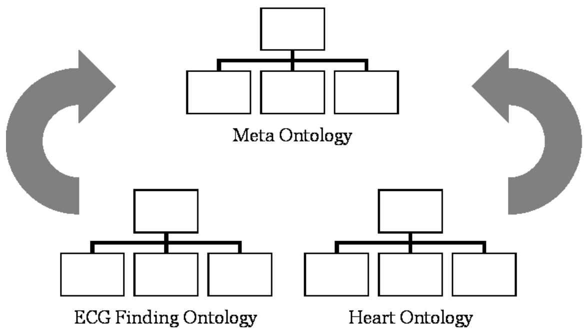

Figure 1. Different ontologies and their correlation

3.2.1 Finding Ontology

The basis for the design of a finding ontology is a common notion of the term echo-cardiographic finding in medicine. This basis was established by the recommendations of the German Cardiac Society that determine a set of about 600 parameters used to describe an echo-cardiographic finding [7]. The finding ontology is derived from this recommendations. To allow for a better matching of the finding to our heart model, the structure of the finding ontology is closely related to the anatomical structure of the heart. According to the heart structure, a finding is divided into sub-findings for the different anatomical parts like mitral valve, tricuspid valve, left atrium, left ventricle, right atrium, right ventricle, each of which is again divided into subparts. Additionally, the model contains some general information about the patient and the examination.

3.2.2 Heart Ontology

The objective of the heart ontology is to describe the anatomical structure of the healthy human heart and in particular to build a framework that allows for the generation of a geometrical model for visualisation purposes. We designed a new model of anatomy to represent all necessary qualitative and quantitative data needed to obtain geometrical and spatial information of the different anatomical entities.

Since the extension of the ontology to other structures than the heart might be target of future work, special attention was paid not to restrict the model too much. Although only the heart anatomy is integrated, so far, the ontology is not limited to that and the framework allows the development of arbitrary organs and organ systems.

The heart itself consists of many anatomical entities which are correlated to one another via relations of different kind, see Figure 2. All these relations need to be reflected by the ontology. In addition, the model links anatomical entities to geometrical objects like meshes or free-form surfaces that can be used for visualisation. The example in figure 3 shows a simplified part of the heart ontology where only some particular relations are displayed. In our example, we summarise all boundary segments necessary to define the left ventricle by tracing the graph. For combining these individual segments additional information is needed. To obtain this information a framework for storing topological information was integrated into the ontology. We have introduced the concept of so called *Abstract Edges*. These edges are used to connect different anatomical parts of the heart ontology, e.g. the different wall segments from the example are equipped with edges while the entity *Wall of LV* knows which edges have to be used to connect two wall segments to one another. The implementation of the edges depends on the implementation of the geometric primitives that are used to represent anatomical entities.

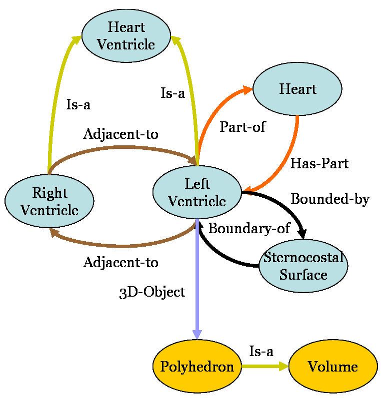

Figure 2. Relationships between different anatomical structures of the human heart

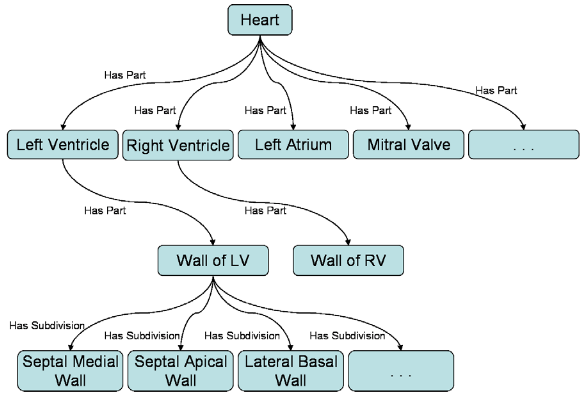

Figure 3. Simplified view of the heart ontology

3.2.3 Meta Level Ontology

Not only the structure of the healthy heart is required, but also the information which parts are essential to visualise a particular finding and how the finding impacts the heart structure. Because of this, a mapping between the ontologies has to be carried out to obtain a reasonable representation of the heart. The framework for this mapping is provided by a meta level ontology. This meta ontology has access to the anatomy and the finding ontology and is able to combine data from these two domains. In addition, the meta ontology consists of a set of rules providing two different functionalities. On one hand it selects anatomical entities crucial to illustrate a particular finding, e.g. to represent a finding describing a perturbed wall movement it is essential to include the affected wall segment. On the other hand the rules manipulate anatomical entities depending on the finding. The finding module is equipped with default values for the different medical parameters. Whenever a current finding value differs from the default value, a rule fires, implying, for example, the manipulation of an anatomic structure.

4 Geometric Modelling and Visualisation

For visualisation purposes the heart ontology is combined with a geometric model. Visualisation supports the exploration of the highly complex ontological structures, since human users are trained to perceive and reason in three dimensions. A crucial point is that the geometric model is consistent with the ontology, even if the latter is altered by the meta ontology.

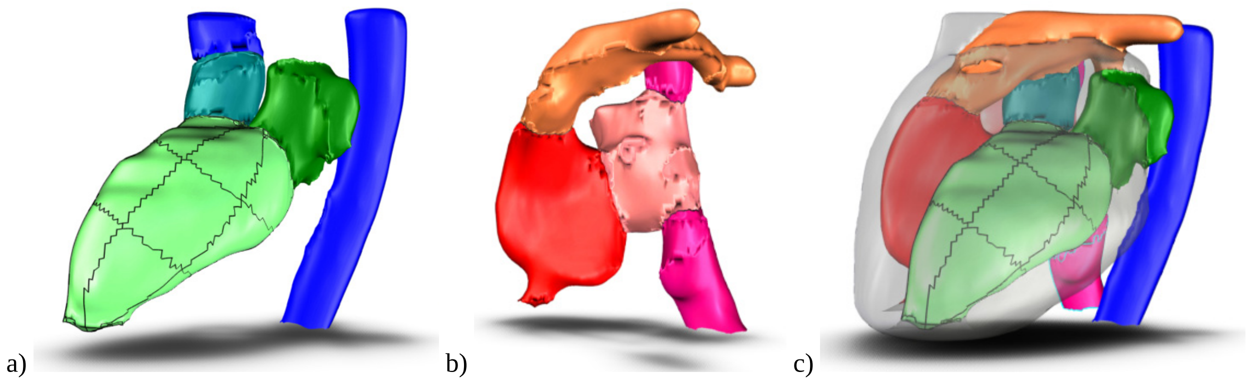

Figure 6. Combining extracted meshes to functional units. a) left ventricular complex; b) right ventricular complex; c) combined heart model with domain boundary (transparent).

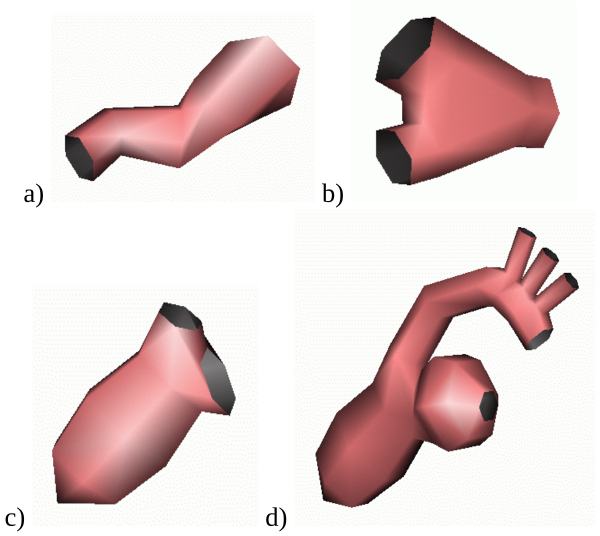

Figure 4. Simple building blocks for the geometric model. a) vessel; b) junction; c) ventricle; d) left ventricular complex.

4.1 A Topological Model for Cavity Structures

In a first modelling approach we defined simple building blocks, such as vessels, vessel junctions, ventricles, etc. that can be merged to larger components, see figure 4. The first model was designed to carry a minimum of geometric information while representing the topology of cavity structures. Vessels, for example, are described by a spline curve with radius, and a ventricle simply consists of an ellipsoid. All primitives are connected in circular (or elliptical) slices serving as plug-ins. For rendering, all primitives are subdivided into triangles, enforcing consistency at the plug-ins.

Due to the adaptivity of this modelling system, individual components can be exchanged or altered by additional rules complementing our meta ontology with respect to the geometric model. These rules guarantee consistency with the heart ontology altered by a specific finding.

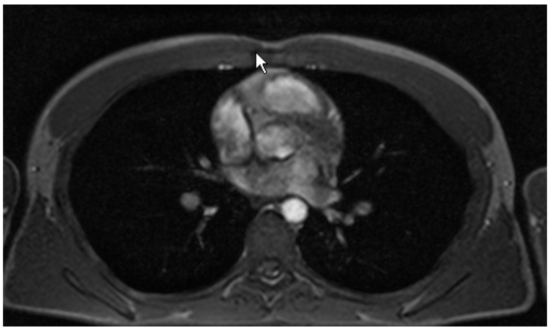

Figure 5. MRI slice of a human heart.

4.2 Reconstructing Geometry from MRI Data

In a second approach, we used time-varying magnetic resonance images (MRI's) of a healthy patient's heart to build a geometric model composed of meshes. The MRI recording was triggered by the r-wave of the echocardiogram, such that slices from different heart cycles were be combined to a time-varying volume data set (MRI is too slow, to do this interactively), see figure 5.

The individual slices were manually segmented such that all voxels corresponding to a cavity structure represented in the ontology are associated with a corresponding "material". To extract a surface model from the volume for every time step, we implemented the following pipeline:

- Volume fairing based on signed distance functions.
- Extracting a mesh component for every pair of adjacent materials.
- Constrained Laplacian smoothing.

- Combining meshes into functional units based on the ontology.

The volume fairing is necessary to reduce mismatches of of adjacent slices which may have been recorded within different cycles. Therefore, we construct a signed distance function (SDF) for each material. SDF's have already been used for interpolation by Jones/Chen [15]. We found that they also provide an excellent fairing tool. The initial SDF's for each slice were replaced by a convex combination of the SDF's of multiple slices, for example averaging three slices with the weights $\{\frac{1}{4}, \frac{1}{2}, \frac{1}{4}\}$. The smoothed data set is obtained by filling each voxel with the material whose SDF is minimal in absolute value among all other materials.

The mesh extraction is performed by a variant of marching cubes, described in [14]. We construct a mesh component for every pair of materials, producing feature lines where three or more materials meet. The meshes are smoothed by Laplacian smoothing, where the range of movement for each vertex is restricted by a maximal distance from its initial position. This fairing method is similar to the approach of Gibson [16], where binary volumes (without multiple materials implying non-manifold structures) were considered.

In the last step, we use information of the heart ontology to combine meshes automatically to functional units. For example, the left ventricle may be adjacent to multiple materials. We simply take the union of all meshes bounding this ventricle and subtract the two valves (mitral and aortic valves). The result is a topologically correct, highly detailed heart model, depicted in figure 6.

Modularisation of our model allows to exchange any part. For example, the left ventricle is subdivided into 18 surface segments, each of which can be replaced to represent a certain disease. Even topological degeneracies can be modelled by exchanging the participating structures. Since we do not have MRI data available for any potential finding, we manipulated the degenerated meshes using a surface editor, like 3D Studio Max. The degenerated parts are then simply replaced in the model, according to the finding. Again, this process works fully automatic.

5 System Architecture

The VES architecture is organised in modules because this allows for a general basis to be extended in application directions. The architecture starts with the Finding Module (FM), which enables the entering and administration of echocardiographic findings. A relational database is used to store the finding data where the database schema is derived from the finding ontology. The direct correspondence between the database schema and the ontology provides the knowledge of the findings structure and allows the usage of the meta level ontology for further processing of the finding data. Beneath the Finding Module resides the Modelling Module (MM). This module offers functionality to create a dynamic heart model based on a formal description derived from the FM. The next module is the Administration Module (AM). This module contains components to administrate the different users of the system and their user authorizations. The last module is the Tutoring Module (TM) that currently provides the functionality for a basic examination environment. It offers a suitable case selected by a human tutor or the student himself. The case is a description of a particular medical finding in conjunction with the heart model created out of it. Based on this information a dynamic heart model will be displayed on the monitor. Figure 8 shows the viewer with a visualisation of the heart on the left side of the viewer. The viewing plane of an artificial ultrasound transducer is displayed on the right side. The position and orientation of the transducer is currently set manually, whereas the resulting image is computed as cross-section with the heart model in real-time.

In a later version the position data will be gathered from a real transducer equipped with a 6-DOF position sensor and an artificial ultrasound image will be computed out of the cross-section. Based on the artificial ultrasound data the student can enter a finding into the Finding Module, which will be compared to the original finding to judge the performance of the student.

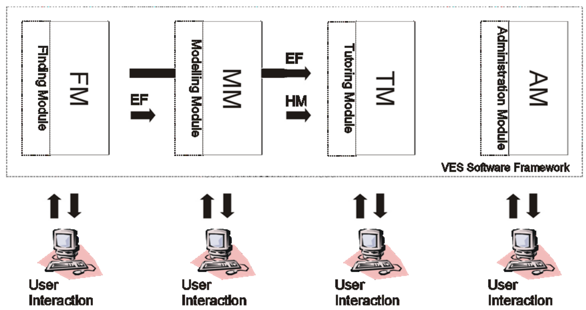

Figure 7. Overall System Architecture

6 Conclusion

Over the years to come, virtual examination environments will play an important role in medical education. In this work we have proposed a new approach to obtain geometric representations of anatomical structures based on formal descriptions. The geometric model of the healthy heart and the ontological framework enables us to derive any medical reasonable representation of a diseased heart for virtual examination. In contrast to conventional modelling techniques based on medical data sets this approach is fast and delivers models of the diseased heart without any image data.

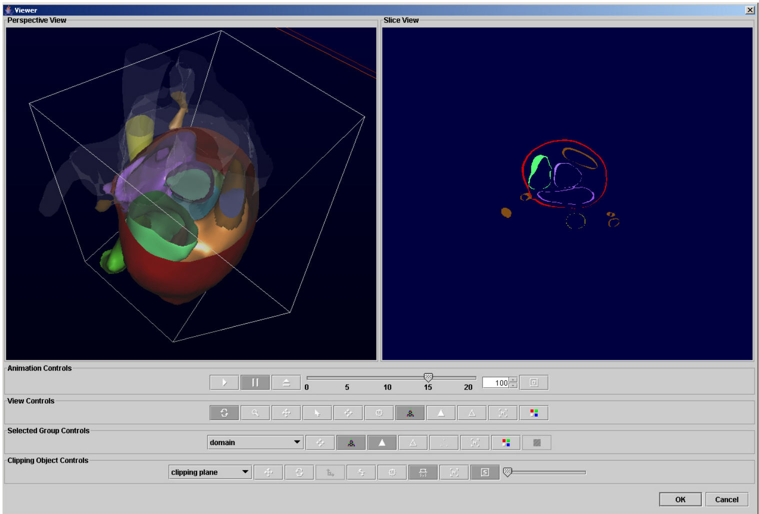

Figure 8. The 4D Anatomy Viewer

7 Acknowledgments

This work was supported by the German Federal Ministry of Education and Research (BMBF), under contract number NR 01 1W A02, through project VES. We thank the members of the DFKI Knowledge Management Group for stimulating discussion and comments during the preparation of this paper.

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