Modeling, Visualization, and Interaction Techniques for Diagnosis and Treatment Planning Support Based on Dynamic Cardiac Images

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Abstract. Due to the development new of imaging devices which produce a large number of tomographic slices, advanced techniques for the evaluation of the large amount of data are required. Computer supported extraction of dynamic 3D models of the patients anatomy from temporal series thus is highly desirable. Since the diagnostician should be able to quickly make sensible decisions based on the models, high accuracy is required within a minimum of time.

We present modeling and visualization techniques that are realized within the Cardiac Station. Results for the application of these techniques to cardiac image data are given. Besides giving information about the patients morphology functional parameters can be derived from the data and visualized together with the model. In order to verify the model with the original image data and for the planning of real intervention interaction techniques are presented.

Key words: Cardiology, Medical Imaging, Modeling, Visualization, Man Machine Interaction

German Abstract. Mehrschicht Spiral-Tomographiegeräte ermöglichen die Akquisition hochauflösender Datensätze des schlagenden Herzens. Aufgrund der hohen zeitlichen und räumlichen Auflösung liefern diese Geräte eine große Zahl von Schichten (ca. 500) weshalb konventionelle Auswertungsmethoden nicht mehr angemessen sind. Die Extraktion von Modellen aus dem Bildmaterial erscheint wünschenswert. Die Modellierung zielt auf die Erstellung eines sonst mental aus der Betrachtung der Einzelschichten rekonstruierten Modells ab. Die extrahierten Modelle sollten idealer weise eine ausreichende Genauigkeit aufweisen, um alle für die Diagnose relevanten Merkmale abzubilden. Darüber hinaus können aus dem Modell mit hier präsentierten Methoden funktionale Parameter ermittelt werden z.B. die Kammerwandbewegung oder die Konnektivität von Gefäßen. Diese können zusammen mit dem Modell in Form von Farbkodierungen der Oberfläche visualisiert werden.

Dieser Artikel beschäftigt sich mit der Modellierung, der Visualisierung des Modells und der Interaktion mit diesem. Besonderer Wert bei der Modellierung wird auf einen möglichst geringer interaktiven Aufwand seitens des Anwenders gelegt. Für die Visualisierung spielt die Geschwindigkeit und die Genauigkeit der Rendering-Ergebnisse eine Rolle. Da kein einzelnes state-of-the-art Verfahren in der Lage ist, bei hoher Geschwindigkeit genügend genaue Renderingergebnisse zu liefern, werden verschiedene Verfahren vorgestellt.

Ein weiterer Aspekt bei der Diagnoseunterstützung auf der Grundlage von Modellen ist die Interaktion mit dem Modell. Zusätzlich zum freien interaktiven Rotieren des Modells, um es aus allen Richtungen betrachten zu können, sollten interaktive Markierungs- und Schneideoperationen ermöglicht werden. Hierzu kann der Anwender auf einen Punkt der Oberfläche des Modells zeigen. Als interaktive Antwort wird der markierte Punkt innerhalb der Originalschichtbilder gezeigt, die beispielsweise auf die Schnittebene des Modells geblendet werden. Darüber hinaus können physikalische Eigenschaften wie die elastische Deformation aufgrund des Ziehens an der Modelloberfläche am Computer simuliert werden, so daß die interaktive Verformung des Modells z.B. für die Planung von Eingriffen ermöglicht wird.

Schlüsselwörter: Kardiologie, Medizinische Bildverarbeitung, Modellierung, Visualisierung, Interaktion

Introduction

Multi-slice spiral-tomographic imaging devices permit the acquisition of high-resolution volumetric data sets of the dynamic heart. Due to high spatio-temporal resolution,, these devices produce a large number of slices (ca. 500) which cannot be handled by evaluating each of the individual slices. Computer supported creation of dynamic 3D models of the patients anatomy from temporal series is thus highly desirable. The modeling aims at creating models that otherwise need to be reconstructed mentally. Regarding the distinctiveness of medical images, emphasis has to be put on modeling accuracy, speed and detail of visualization, and interaction with the model.

The accuracy of models should ideally be high enough to reproduce every detail of the original image data that is relevant for diagnosis purpose. Whereas in other areas of computer graphics esthetic aspects often are most important, in the area of medical imaging, results are to be measured by the usefulness for the diagnostician. Thus visualization has to be efficient concerning rendering speed and accuracy. Since a single method is not suitable to show every detail in adequate rendering time, two different methods are normally to be considered for medical imaging:

- *Surface rendering* which is a fast method, since it is supported by specialized hardware. Nevertheless, the rendered images may lack important details. Thus for medical applications it is suited for previewing only.
- *Direct volume rendering* which is due to its high degree of detail an established visualization method in medical imaging, which usually lacks in performance and therefore limits the degree of interactivity.

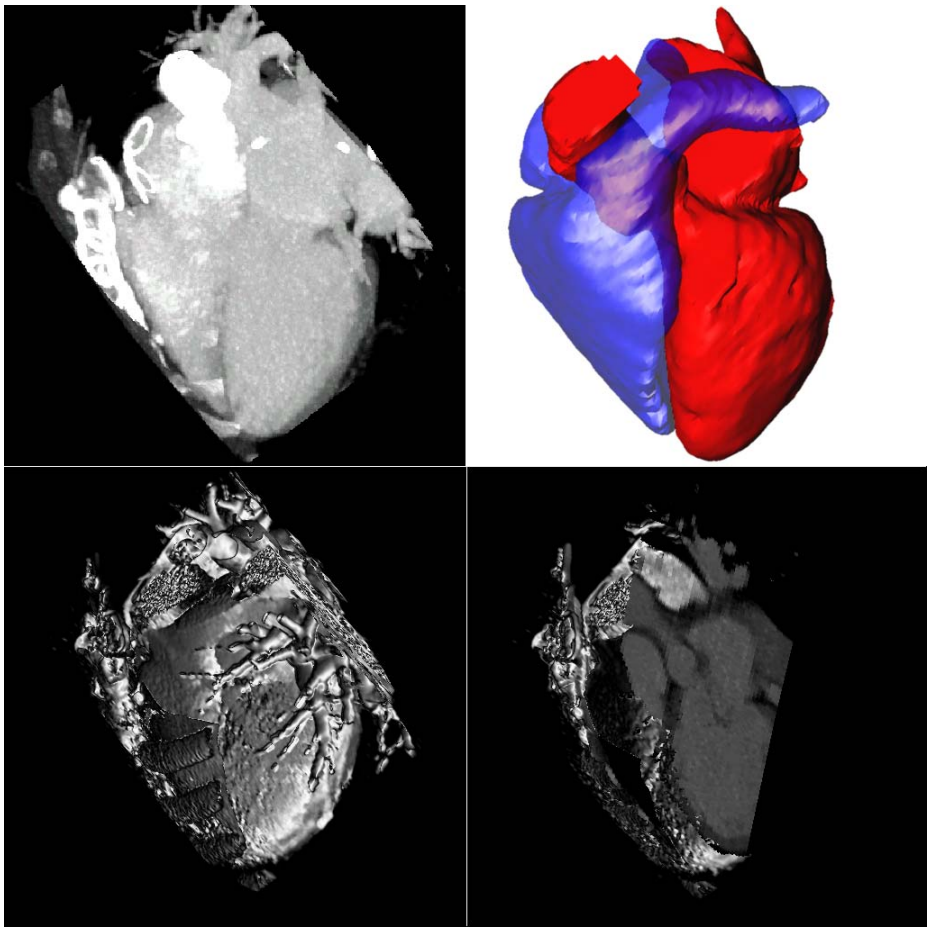

Fig. 1. Example for a visualized cardiac EBCT data set (a) maximum intensity projection (MIP) (b) surface rendered model of the left and right heart (c) extraction of surfaces (d) MPR slice mapped on an oblique cutting plane.

Besides providing an understanding of the morphology, medical imaging aims at extracting and visualizing additional information. This can be functional parameters like in cardiology the regional heart wall motion or information about the connectivity of vessels. Additional information is then derived from the image data by means of image processing methods and coded into surface color of the models. This technique is especially useful in the case of cardiology since the alteration of cardiac wall motion during systolic contraction is one of the most sensitive indicators of cardiac disease such as ischemia and myocardial infarction. Within this paper we present results of an advanced method [1] for the modeling of the left ventricle endocard motion during a cardiac cycle. As color coded visualization provides a qualitative description for regional wall motion, the diagnostician may distinguish abnormally contracting myocardium easily and quickly.

Supplementary to visualization a model can be used to quantify diagnostic measures, e.g., ventricle volumes or the ejection fraction. From models these measures can be calculated with lower error than with conventional methods since the latter are mostly based on simplifying assumptions, e.g. that a ventricle has the shape of an ellipsoid.

Beneficial for diagnosis and treatment planning support incorporating dynamic models might be a way of interacting with the model on a computer. Besides of being able to rotate it interactively in order to inspect it from all viewing directions, the navigation through the original tomographic slices can be greatly simplified by interactive pointing and slicing operations. If the user clicks on a point of the model surface the respective point should be shown in the original slices, e.g. mapped on a virtual cutting plane which is overlaid to the model (see Figure 1d). This leads to a better understanding of the relation between model and the original image information and enables the comparison with the gold standard of tomographic imaging.

Moreover during a medical diagnosis and treatment planning procedure the model can be useful by offering the following potentials:

- Models can be used to fuse information from different imaging modalities.
- They can be transferred more easily via network than the original image data for tele-consultation by a remote expert, since the model can be represented by a reduced amount of data.
- Using stereolithography highly accurate plastic models of patient anatomical structures can be created.

Processing Pipeline

In this paper we present a processing pipeline (see figure 2) that is realized within the Cardiac Station [2]. The Cardiac Station is developed within a project at Fraunhofer Institute for Computer Graphics in Darmstadt, Germany in cooperation with the Ewha Womans University in Seoul, Korea. It is made available for evaluation within clinical settings.

Within a first step the tomographic slices are read from a PACS or a tomographic device in DICOM format. These slices can be piled up to volume blocks and rendered using direct volume rendering. Conventional volume rendering methods cannot solve the problem of occluding contours. It is for example impossible to visualize just a single ventricle since the extraction of surfaces for rendering is based on the physical properties that are similar for both ventricles, thus both ventricles occlude each other. In order to avoid occlusions during visualization the slices are segmented to define contours of interest. The resulting stack of contours can in turn be integrated into a closed 3D model by triangulation. Subsequently the heart movement is tracked over the heart phase by finite element (FEM) tracking methods which results in a dynamic model. For better interpretation of the data, motion parameters can be estimated from the dynamic model and visualized with the model by encoding speed or acceleration as surface color.

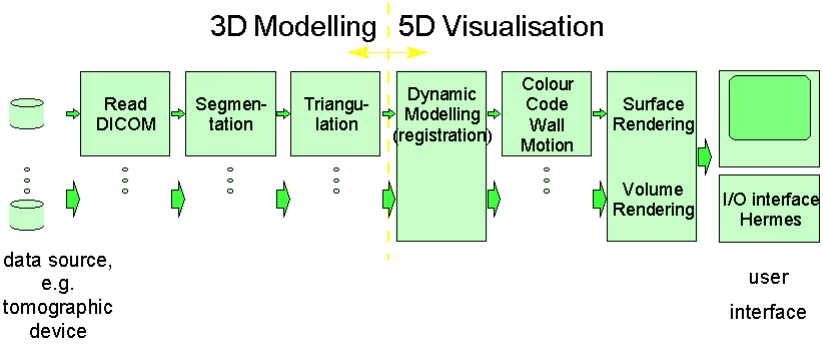

Fig. 2. Processing Pipeline of the Cardiac Station

Segmentation

Conventional segmentation techniques integrated into diagnosis and planning systems require manual outlining of structures of interest on every single slice or additionally offer simple drawing support like copying and pasting the contours from slice to slice followed by manual adaptation of the contours. In order to reduce the user interaction required for the segmentation the usage of active contour models (ACM) is realized within the Cardiac Station. These support the segmentation by integration of image features like contours and homogeneous regions.

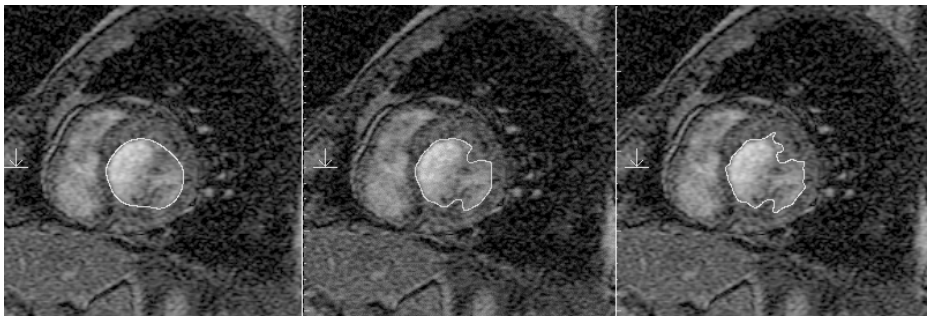

Fig. 3. Different degrees of accuracy of ACM segmentation for the same MRA slice for the endocard of the left ventricle

Segmentation methods have been developed by numerous researchers. They differ among other properties (e.g. specialization on imaging modalities) regarding the user input they require. Automatic segmentation methods seem to be most preferable. In this case the experienced eye of the diagnostician is substituted by a computer. Since most automatic segmentation methods are specialized by introducing model knowledge from a training set they produce large errors if the training set is not

representative. This fact may reduce the usability of automatic methods in clinical settings. Semi-automatic segmentation methods in contrast need some input from a supervisor and thus offer flexibility. They enable to successfully segment images even in the case of large variations from the 'normal' case. Semi-automatic methods can be beneficial if they are designed to speed up the procedure, overcome accuracy restrictions of manual input devices and enable the user to conveniently control the segmentation result. In addition they objectify results by being guided by image features. Results can thus be reproduced with predictable variances.

Among semi-automatic segmentation approaches the usage of ACMs is most advantageous since noisy images and incompletely depicted objects are completed by means of interpolation. It can be shown that ACMs are able to recover subjective contours. Subjective contours are contours that cannot be defined by local image features but are perceived from human observers due to characteristics of the human visual system as continuation of fragmentary image contours.

ACMs are based on autonomous adaptation of a given template, e.g. an approximate first sketch of the contours to be segmented or the contour interpolated from neighboring slices. By elastic deformation the curve is adapted to image contours. This behavior is attained by simulation of physical properties of an elastic material or a viscous fluid.

As can be seen from figure 3 the ACM [3] that has been developed for the Cardiac Station enables to fit to the contours to the image data to a user required degree of accuracy.

Tracking the Endocard Motion

In order to build up a at first a static 3D model of the endocard for every temporal frame within the sequence, outlined contours of the single slices are connected to a closed triangulated surface using standard triangulation methods (e.g. Delauney's triangulation). Subsequently the matching points on the surfaces for different time frames have to found. Therefore an FEM tracking procedure is performed. During this step a ventricle is represented by a single geometric primitive, a superellipsoid. For each individual heart phase the set of 3D feature points obtained from the segmentation is attached by virtual springs to the elastic dynamic model. Under the forces exerted by these springs, the dynamic model deforms to match the shape outlined by the set of feature points. As a result the FEM based deformation follows the heart motion rather realistic due to simulating the physical behavior of the heart muscle. Thus the motion parameters can be estimated rather accurately for every surface point.

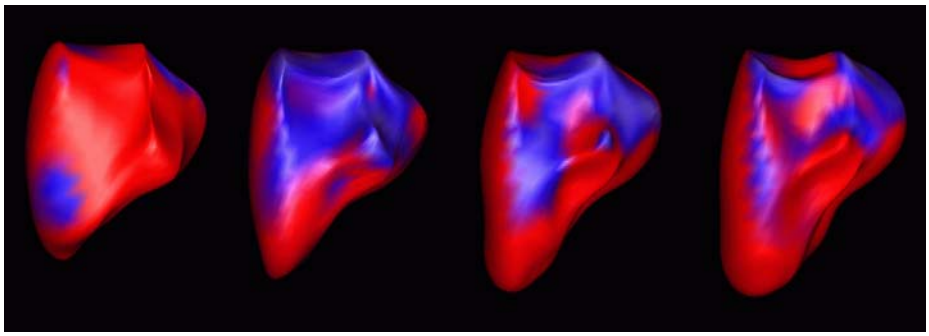

Fig. 4. Result of surface tracking coded into surface color (blue: slow motion area, red: fast motion area)

Visualization

As result of the various procedures, static and dynamic surface descriptions are generated. Therefore the system must provide techniques to visualize the polygonal data. Since the hardware of modern PC and workstation supports the rendering of 3D polygonal models directly, this description can be visualized very efficiently.

A common drawback of polygon rendering is however the necessary reduction of information compared with the original slices. In addition, modeling procedures introduce slight approximation errors. In order to make a reliable diagnosis based on 3D or higher dimensional visualization the physician should be able to see all relevant information he or she can otherwise derive from studying the slices. Polygon rendering is therefore not always appropriate to provide this diagnosis-relevant information. As a result it is more suitable to use polygonal rendering in order to receive a preview of the approximate shape, location, orientation, and movement of the given data to be evaluated. In many cases direct volume rendering can produce more accurate images, but lacks performance. Therefore both methods, direct volume and surface rendering, are included into the Cardiac Station.

Surface Rendering

The triangulation module provides one polygonal surface description per segmented object. If the number of triangles of these models is very high, the data can not be rendered efficiently and therefore an appropriate reduction method must be applied.

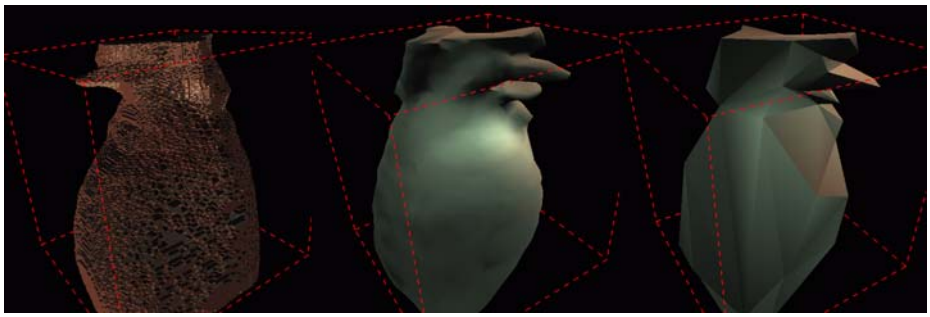

Fig. 5. Multi-resolution mesh visualization of a segmented heart (number of triangles: ca. 210,000, ca.3,000, ca.160)

The most common polygonal reduction techniques generate a sinlge static mesh based on an upper limit regarding the approximation error. Since the reduction process takes usually several minutes the parameters can not be adjusted interactively.

To control the resolution of the mesh in real-time we developed a method to generate a multi-resolution mesh from which certain triangulations can be derived. In contrast to the traditional reduction methods the system does not generate a single mesh, but a progressive mesh that includes information how to simplify the mesh by collapsing edges for a given resolution. Given this progressive mesh the user can adapt the number of polygons interactively in order to obtain a faster or more accurate visualization.

As a result of the tracking procedure the wall motion magnitudes are coded as surface color and the time-varying polygon mesh is finally visualized by a polygon renderer. For a smooth appearance the used renderer is able to interpolate between the temporal sequence of polygon meshes in real-time.

Direct Volume Rendering

Several methods for volume rendering are included which use the discrete voxel space to generate directly 2D images from the 3D data. This representation of voxel based data does not require an explicit conversion of the volume data into a surface geometry as it is necessary for surface rendering, but the information inherent in the voxel directly. However, even a relatively small volume of 256x256x256 voxels contain at least 16 million information entities that have to be processed. Therefore software based volume renderer are usually not efficient enough to produce 2D projections in real-time. To overcome this limitation we developed a 3D texture based volume renderer which cuts and blends slices through the volume block in real-time using graphics hardware (HW). However, there are two limitations of this technique. First the method requires a certain HW which supports 3D textures and second the method is limited to the blending functions which are provided by the graphics HW. To overcome these drawbacks an additional a ray caster based volume renderer is also implemented to produce high quality images for a final viewing position.

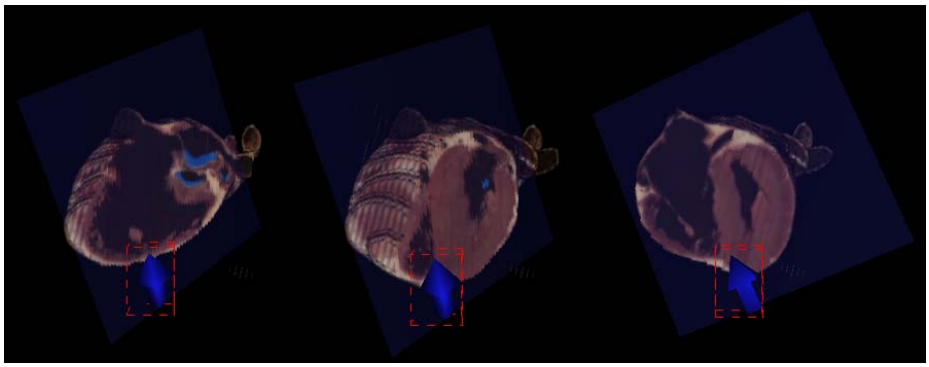

Fig. 6. Direct Volume visualization using the 3Dtexture based volume rendering method

Selective Rendering

In order to approach more realistic and detailed visualization, an innovative way of volume rendering was developed [4] that employs original volume data and model information together. This approach integrates both kind of data by selective rendering the pure volume data in a narrow area around the model surface (see figure 7). The main benefits of this approach are as follows

- portions from the volume data that would occlude the surfaces of the heart cavities are removed
- approximation errors of the modeling are compensated
- the appearance of the surface is rather realistically like that of direct volume rendering.

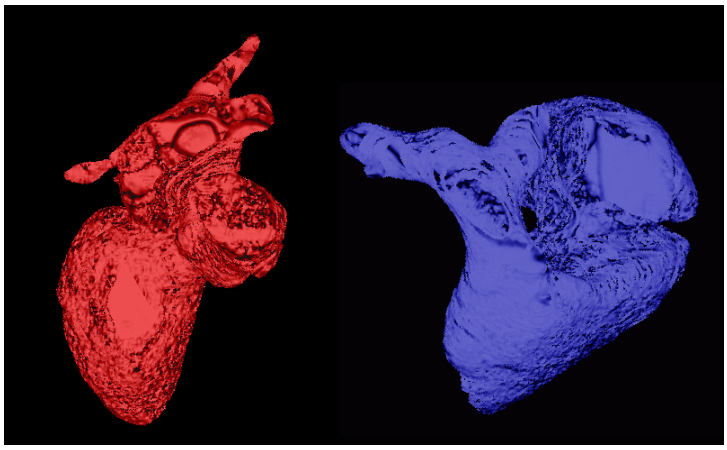

Fig. 7. Left and right ventricle depicted by selective volume rendering

Interaction with the Model

The experiments that have been performed within this project, aim at providing a realistic physical behavior of the model for surgical simulation within in the pre-operative stage in surgery. Physical based deformation methods have been evaluated and implemented to establish more realistic and real-time interaction for surgical simulation. The realistic behavior of a model during planning is aiming to save valuable time during the real intervention, by being able to predict the changes made during an intervention.

Physical based modeling based on mass-spring system worked out to be a very useful approach, since the mass-spring system is simulating the behavior of the muscle. These techniques are used to simulate the basic works of surgery like grasping, stretching, cutting or suturing of the soft tissue (see figure 8).

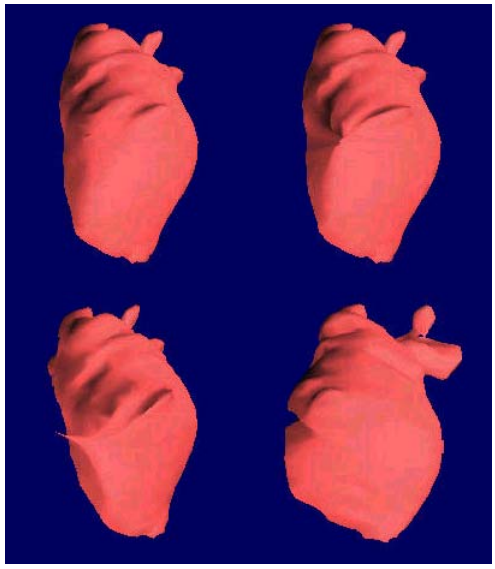

Fig. 8. Physical deformation based on the mass spring model (a) original model, (b) pushing, (c) stretching, and (d) tearing

Conclusion

We present advanced medical imaging techniques for diagnosis and treatment planning support based on cardiac image data. Since the diagnostician should be able to quickly make sensible decisions based on the imaging results, we consider several different techniques as tradeoff between calculation time and accuracy. Results of the application on medical image data are presented.

The techniques are integrated in a processing pipeline of the Cardiac Station that will be made available for clinical usage and evaluation. The results will be further evaluated by trained medical staff for usability within clinical routine.

Acknowledgements

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