New Metaphors for Interactive 3D Volume Segmentation

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Abstract

This paper describes on-going research at the Swiss Federal Institute of Technology to develop new paradigms for interactive segmentation of medical 3D volume data. In our segmentation system we are using a haptic device as a 3D mouse with force-feedback. The paper introduces the basic components of our framework and the ideas behind our multi-modal approach. On the one hand we are trying to increase the sense of immersion of the user by allowing him to interact in a natural way with the presented data, on the other hand we are using force-feedback as an additional channel to mediate information. The segmentation of linear structures in the human body serves as a case study for our system. We successfully used our approach to extract the skeleton of a radiological colon data set, which then served as the basis for a full segmentation of the object of interest.

1 Introduction

Over the last decades, computer imaging techniques have become an important tool in the practice of modern medicine. In medical imaging, large voxel data sets, containing information about the internal anatomy and/or physiology of a living patient, are obtained from a variety of tomographic imaging modalities, such as Computer Tomography (CT) or Magnetic Resonance Imaging (MRI). Before any high-level reasoning, for instance radiation treatment planning, can be applied to this data, it has to be broken down into its major structural components. The process in which the data sets are subdivided into their constituent parts is called segmentation. The algorithms used in this step can be classified with regard to their degree of automation:

- Manual segmentation:

  This approach is highly insensitive to noise, tolerant of incomplete information and in many cases sufficiently precise. Nevertheless, it is very time consuming and has to be done in a tedious pixel-by-pixel manner. Furthermore, it lacks reproducibility.

- Automatic segmentation:

  This term refers to computer algorithms which can segment an image without manual interaction. These methods can only be applied successfully within exactly defined bounds. This is mainly due to the difficulty of formalizing the a priori knowledge of the examined anatomical structures as well as incorporating this knowledge into the segmentation process. Unfortunately, none of the so far published algorithms is robust enough to provide general purpose, fully automatic data segmentation.

- Semi-automatic segmentation:

  In between the former two approaches lie semi-automated algorithms, which try to merge the advantages of both worlds. Rather than attempting to duplicate the complex and poorly understood human capability to recognize objects, they try to provide an interactive environment in which users control the segmentation process and exploit their expert knowledge.

The developed methods can be further classified according to the underlying interaction paradigms in either two or three dimensions. In a two-dimensional approach the segmentation is done in a slice-by-slice manner, making a subsequent reconstruction step necessary, in which the previously segmented contours are combined into a three-dimensional structure.

More seldom are systems that exploit the possibilities of interactive 3D segmentation [18, 17, 8, 19, 11].

This is often justified by the problems that arise due to adding another dimension to the user interaction:

- Editing, controlling and interacting in three dimensions often overwhelms the perceptual powers of a human operator.
- Todays desktop metaphors are based on two-dimensional interaction and can not easily be extended to three dimensions.
- The visual channel of the human sensory system is not designed for the perception of volumetric data.

These major drawbacks are valid in terms of interactive systems that are based on two-dimensional Window-Mouse-Icon-Pointer (WIMP) interfaces that solely rely on the visual sense of the human operator.

In the presented project these limitations are alleviated by enhancing the segmentation process with additional sensory feedback. Properly applied, the use of more than one sense to investigate complex data sets promises to improve the user's understanding of the data and their ability to interact with them [13, 9].

Possible approaches for multi-modal interaction stemming from virtual reality applications are the addition of auditory as well as haptic feedback. In this work we focus on providing additional perceptual information to the medical expert by using force-feedback technology.

2 Related Work

Though the need for understanding the influence of human-computer interaction on semi-automatic segmentation is recognized, only very few research has been done in this direction. The only work we know of investigates this problem for 2D segmentation [16].

Other related research mainly focuses on separate aspects. New 3D interaction paradigms, that can assist the end user in navigating in volume data sets have been evaluated in [8, 19, 11], but this work only focuses on visual interaction with the data. Nevertheless, the results show, that novel ways of interaction can enhance the navigation in the data. The application of force-feedback to improve the understanding of volume data sets in a medical setting has been done in the field of surgical planning [6] and navigation [4]. In both projects only the navigation is enhanced with force-feedback. The necessary segmentation of the medical volumes is still done with traditional methods.

The usage of haptic feedback to augment human performance in graphical user interfaces is investigated from a more general point of view in human-computer interaction research projects. In [1] it is shown that a mouse with force-feedback can aid a user in targeting tasks. The usage of a haptic device to lessen the information overload of graphical displays is studied in [15].

The addition of force-feedback to facilitate the understanding of multi-dimensional data was used in [5]. Complex relationships between different currencies are rendered visually as well as haptically.

Generally, using multi-modal interaction in volume visualization is not a widely studied subject and only a few research groups have begun to investigate the possibilities of such an approach. A good introduction to using haptics for volume visualization is given in [2]. Also in [14] the benefits of haptic rendering of volume data have been recognized. Mainly, research is carried out in the field of visualization of geoscientific data [7, 3, 12, 20].

3 Segmentation Tool

To understand the effects of adding force-feedback to a segmentation program we followed two different approaches. Firstly, we investigated how exploration of 3D data could be improved by haptic rendering. Although the main goal of our research is to improve segmentation, these initial studies gave us an insight into the way humans interact with a multi-modal interface. Secondly, we examined a haptically assisted segmentation process. The reconstruction of tubular objects in the human body served as a case study for our system. The segmentation of these structures is of great medical interest and has several areas of application, for instance the reconstruction of the nervous and the vascular system or the bronchial tree. While haptic cues ease the three-dimensional interaction and orientation in the tubular structures, we present an optimal 2D cross-section for visually guided contour extraction.

3.1 Haptic Data Exploration

To give a user a more thorough understanding of the volume he is interacting with, we mapped the gray values of the medical data to different haptic representations. We have to mention, that instead of giving a user a "realistic" feel of body tissue we only tried to mediate information about 3D cursor localization and tissue densities. To this end we combined haptic volume rendering to encode tissue borders with viscosity or vibration effects to display density values. Due to the limited continuously exertable force of the haptic device and the JNDs of the haptic effects, we chose to discriminate only between three types of densities, i.e. bone, soft tissue and air.

A force field derived from image gradients gives us information about the border location between the tissue types by resisting the motion from an area with small density to an area with a larger one. After thresholding, we approximated the gradient vector field of the resulting data set by central differences. Moreover, to ensure the stability of the computed forces, we smoothed the obtained gradient map with a 5x5x5 binomial filter. This force field was precomputed before the actual interaction, to ensure a fast enough haptic update. Because the gradient vectors are located at discrete voxel positions, we have to do a tri-linear interpolation during the interaction to obtain the continuous gradient force map $\vec{F}_{grad}$ needed for stable haptic interaction.

Apart from the gradient map we encoded the tissue density itself, using vibration and viscosity. The vibration effect is created by sending a sinusoidal force with frequency and amplitude depending on gray values to the device. One interesting observation regarding this approach are the unintended audio signals that were generated by the vibrating haptic device, which gave a user additional information about the densities. The viscosity was computed according to Stokes Law, which holds at low velocities in fields free from turbulence:

$$\vec{F}_{visc} = 6\pi r \vec{V} \eta,$$

where r is the radius of a sphere moving with velocity $\vec{V}$ through a medium with viscosity η. The viscosity parameter was again adjusted according to densities.

Linearly combining the gradient field with the viscosity rendering

$$\vec{F} = \alpha \vec{F}_{grad} + \beta \vec{F}_{visc},$$

allowed a user to do a haptically enhanced data exploration. Additionally to the force display, the medical volume is also volume rendered in stereo and sagittal, transversal and frontal slices of the data set are shown. Furthermore, the 3D mouse can be used to place a free oblique slice in the volume. During some limited experiments with this setup users reported, that tasks like tracing the tubular structure of the colon, were much easier accomplished by relying only on the haptics cues. This was mainly due to the complex task of integrating the 2D slices of the volume into a 3D representation, which required a lot of visual attention distracting from the actual task.

The described framework helped us to understand more about the psychophysics of haptic interaction in order to design a system using a force-feedback device in a segmentation process.

3.2 Multi-modal Segmentation

The initial step of our multi-modal approach is the haptically assisted extraction of the centerline of a tubular structure. We create forces that guide a user on a path close to this centerline. In the optimal case of good data quality, the user "falls through" the data set guided along the 3D ridge created by the force-feedback. While moving along the path, the user sets control points which are used to approximate the centerline with a spline.

The segmentation of tubular structures can be optimally facilitated, if all cross-sections of the object are orthogonal to the centerline. Therefore, we use the interactively generated spline to determine the appropriate orientation of slice planes through the data volume. In a subsequent step an active contour model [10] is used to extract the 2D cross-section of our structure of interest from these slices. The re-orientation of the cutting plane allows us to make a rough assumption about the shape of the cross-section, which should be approximately circular. Furthermore, as we always update the slice orientation, we can use the segmentation of the previous step as a fairly good initialization for the next cross-section. This can be done, because the deviation between subsequent cross-sections in a tubular structure is usually small.

To create the force field that is guiding the user, we adopt an approach similar to the one used by Bartz for enhanced navigation [4]. Instead of using the gray values directly, we first compute an Euclidean distance map of the data set S that resulted from the thresholding step: For each $(x, y, z) \in S$, the map value

$$DM(x, y, z) = \min_{(x_i, y_i, z_i) \in S} d[(x, y, z), (x_i, y_i, z_i)],$$

is determined, where d denotes the Euclidean distance from a voxel that is part of the tubular structure to a voxel of the surrounding tissue. In the next step the 3D distance map is negated and then processed similar to the gradient rendering approach. Additionally, to ensure stability, we apply a low pass filter to the computed forces over time.

In the case of sufficient data quality this approach works very well, nevertheless, more interesting is the case of poor image quality, because conventional segmentation algorithms do not suffice in this situation. Here a user can be assisted by the forces to bridge a gap in the linear structure. We have to mention that a decrease of data quality comes along with an increased user interaction time and effort. We intend to overcome this shortcoming with more advanced gap closing mechanisms.

4 System Overview

Our setup (Figure 1) consists of two main components: an SGI Octane and a haptic device. The Octane is equipped with two R10000 processors running at 195 MHz and 512 MB memory as well as an MXI graphics board with 4 MB texture memory, allowing us to render 128x128x128 volume data sets in real-time.

We are using a distributed architecture for our current prototype to ensure the necessary update rates for the visual and haptic display. The separated processes exchange data via a shared memory with semaphore functionality.

Only within the last few years suitable force-feedback devices became accessible for the development of multi-modal applications using touch interaction. In our project we are using SensAble Technologies' PHANToM as a sophisticated 3D force-feedback mouse. The lack of rotational forces is not a problem for our application, as we only need point force creation for our current approach. Nevertheless, in order to haptically encode the orientation of the cross-sections we are going to change to a haptic device, which also allows the creation of rotational feedback.

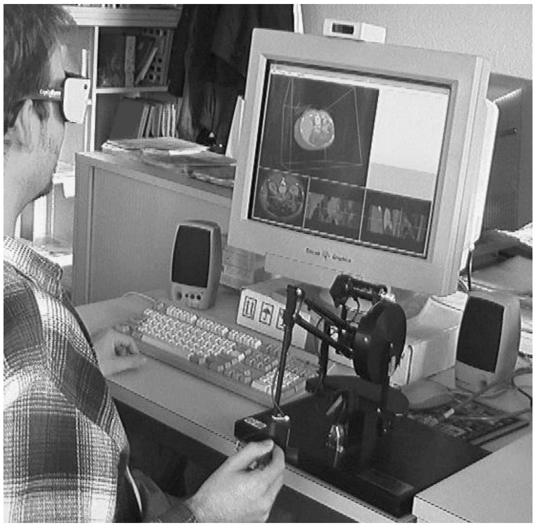

Figure 1: System setup

5 First Results and Future work

In this paper we presented a new paradigm for interactive segmentation which allows the handling of medical data in a natural way. Additionally, we described how multi-modal interaction can enhance the process of interactive segmentation. We used this approach to extract the skeleton of a linear structure which then served as the basis for a full segmentation of the whole object of interest. In order to reduce the interaction effort we have to evaluate more sophisticated algorithms for gap closing.

Moreover, we will study if providing force-feedback to both hands can improve the interaction. Another aspect in this direction is the usage of different haptic devices, for instance a glove with force-feedback could be used for the non-dominant hand to hold and manipulate the data. Additionally, we are going to investigate the possibility of including other perceptual cues. The most obvious addition would be the auditory sense.

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