NIHmagic: 3D Visualization, Registration and Segmentation Tool

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ABSTRACT

Interactive visualization of multi-dimensional biological images has revolutionized diagnostic and therapy planning. Extracting complementary anatomical and functional information from different imaging modalities provides a synergistic analysis capability for quantitative and qualitative evaluation of the objects under examination. We have been developing NIHmagic, a visualization tool for research and clinical use, on the SGI OnyxII Infinite Reality platform. Images are reconstructed into a three-dimensional volume by volume rendering, a display technique that employs three-dimensional texture mapping to provide a translucent appearance to the object. A stack of slices is rendered into a volume by an opacity mapping function, where the opacity is determined by the intensity of the voxel and its distance from the viewer. NIHmagic incorporates three-dimensional visualization of time-sequenced images, manual registration of two-dimensional slices, segmentation of anatomical structures, and colored-coded re-mapping of intensities. Visualization of MRI, PET, CT, Ultrasound, and 3D reconstructed electron microscopy images has been accomplished using NIHmagic.

Keywords: 3D visualization, volume rendering, texture mapping, interactive segmentation

1. INTRODUCTION

In recent years, the biomedical imaging modalities such as MRI, CT, Ultrasound, as well as electron microscopy, etc., have become essential in identifying, diagnosing and localizing structures and abnormalities. Traditional methods for evaluating data required the viewer to mentally reconstruct a volume from a series of radiographic films or two-dimensional images.

The advent of real-time three-dimensional visualization has enabled interactive examination of the internal and external structures from any viewpoint. Three-dimensional visualization assures better accuracy of measurements, detection of structures, assessments of their shapes, etc. We present a system for the visualization of three-dimensional biomedical images incorporating a sophisticated user interface, real-time object manipulation, manual registration, interactive segmentation, quantization of segmented objects, and volume rendering with texture mapping with gray scale or color look-up tables. This comprehensive tool will enhance medical treatment planning.

In the cardiology community, MRI is utilized as a gold standard methodology to measure myocardial volumes. This acceptance is largely based on the ability to image all the cardiac chambers in volumetric acquisitions that do not require any geometric assumptions. Additionally, a large number of studies has validated the techniquet[8]. NIHmagic has addressed the problems of cardiovascular MRI by providing an interface for manual registration of the long and short axis images in three-dimensional space allowing accurate segmentation and determination of myocardial volumes.

The long-term goal of this project is to develop a generic tool for the visualization of three-dimensional biomedical data. NIHmagic will include automated procedures for registration and segmentation applicable to a comprehensive variety of imaging modalities.

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2. METHODS

2.1 Volume rendering

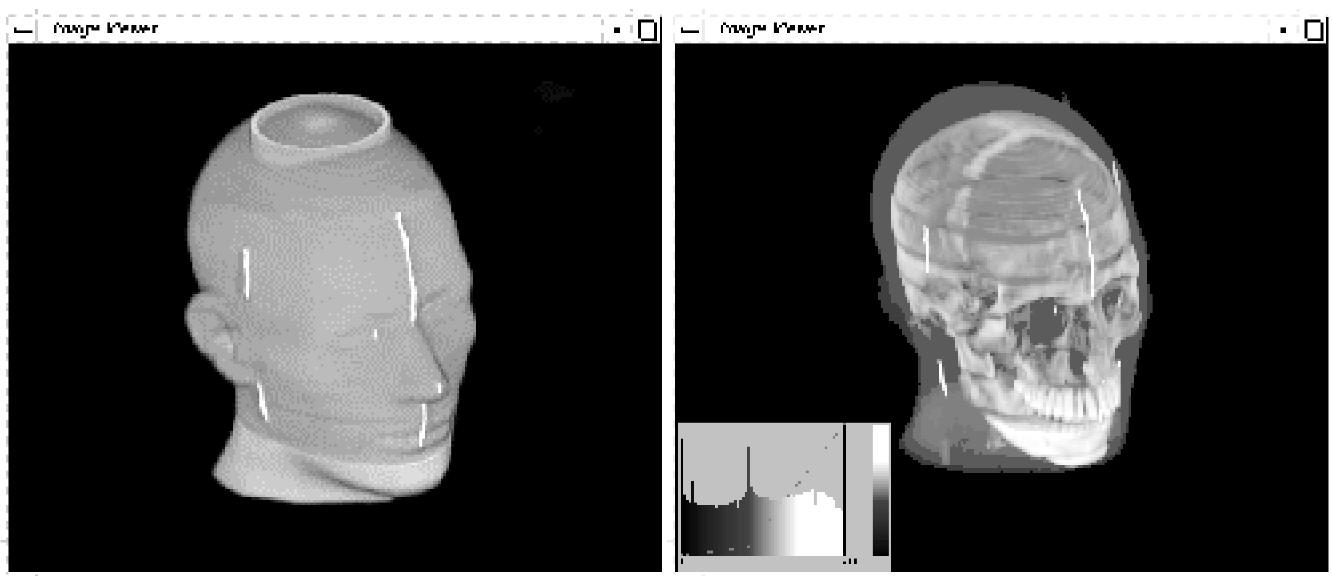
Volume rendering is a direct representation of a three-dimensional data set[2,5,6]. Unlike surface rendering, this technique does not require a priori knowledge of the surface for intermediate generation of geometrical representation. A geometric approximation of a surface within a volume set is formed from a cross connection of data points of equal value or density specified by a threshold value[14,17]. Volume rendering does not use geometric representation of the volumetric data, thereby including all the data points in the volume[9]. Such an approach significantly reduces the number of falsely identified surfaces characteristic to surface based methods resulting from hard decisions about the inclusion of boundary voxels in noisy or poorly defined features using some form of thresholding.

The rendering is done from back to front by ray casting, and each voxel is blended with the previously drawn voxel using transparency[10,21]. The transparency is calculated by interpolating the individual intensities of the voxels along the line of sight. The opacity of voxel *k* is:

$$\mathrm{O}_k = \frac{\mathrm{I}_k - \mathrm{I}_{k-1}}{\mathrm{I}_{k+1} - \mathrm{I}_{k-1}}$$

where I_{k-1} and I_{k+1} are the intensities of the voxels in front of and behind the k^{th} voxel respectively. Voxels in the back of the volume are partly obscured by voxels in front. If the opacity for a voxel is zero, that voxel becomes transparent and contributes nothing to the intensity; when O_k is 1, the voxel is opaque and transmits no light.

NIHmagic allows the user to specify and interactively adjust opacity transfer functions (Fig. 1b) in order to assign low opacities to regions of the volumetric set, which are of lesser importance and high opacities to regions of interest. A variety of adjustable gray scale and color look-up tables are provided.



(a) (b)

Figure 1. (a) Rendered gray scaled CT volumes (b) with adjusted transparency level

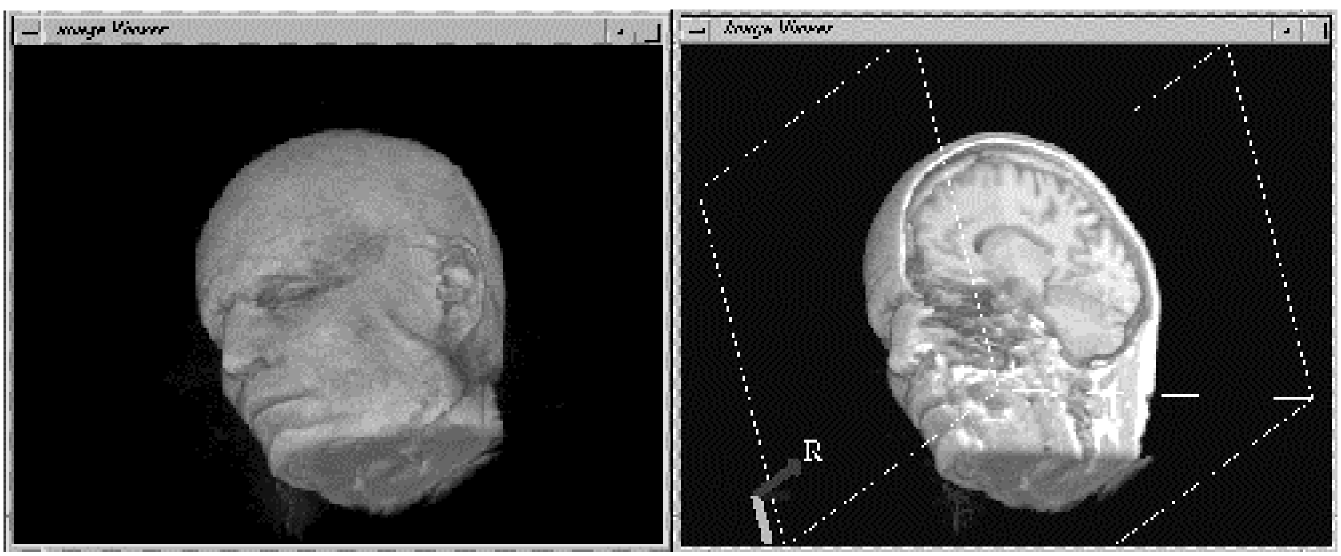
2.2 Texture mapping

Traditionally, texture mapping has been used as a technique for reducing geometric complexity and for adding realism to a computer-generated scene. In recent years, this technique has moved from the domain of slower software rendering systems to high performance graphics hardware providing real-time rendering.

In the NIHmagic program, texture mapping is used as the fundamental graphics primitive for volume rendering. The basic principle behind three-dimensional texture mapping[11] is to apply an image (the texture) onto a three-dimensional polygon in a scene. The volumetric data is copied into the three-dimensional texture image, also called texture space, and then displayed back to front, with sufficiently small intervals, as a stack of parallel slice planes. Each slice plane of the object is drawn by sampling the data in the volume along the plane of the slice and by mapping sampled texture coordinates onto the polygonÕs vertices[18]. The transformation of the sampling polygon is independent from the three-dimensional texture. Consequently, either the volumetric texture or the polygon may be reoriented. Manipulating the orientation of the polygonÕs vertices and then applying corresponding texture coordinates to it or resetting the volumetric texture and mapping it onto the polygon performs accelerated geometric transformations of the entire volume. Since the texture memory needs to be loaded only once, real-time object manipulation can be realized.

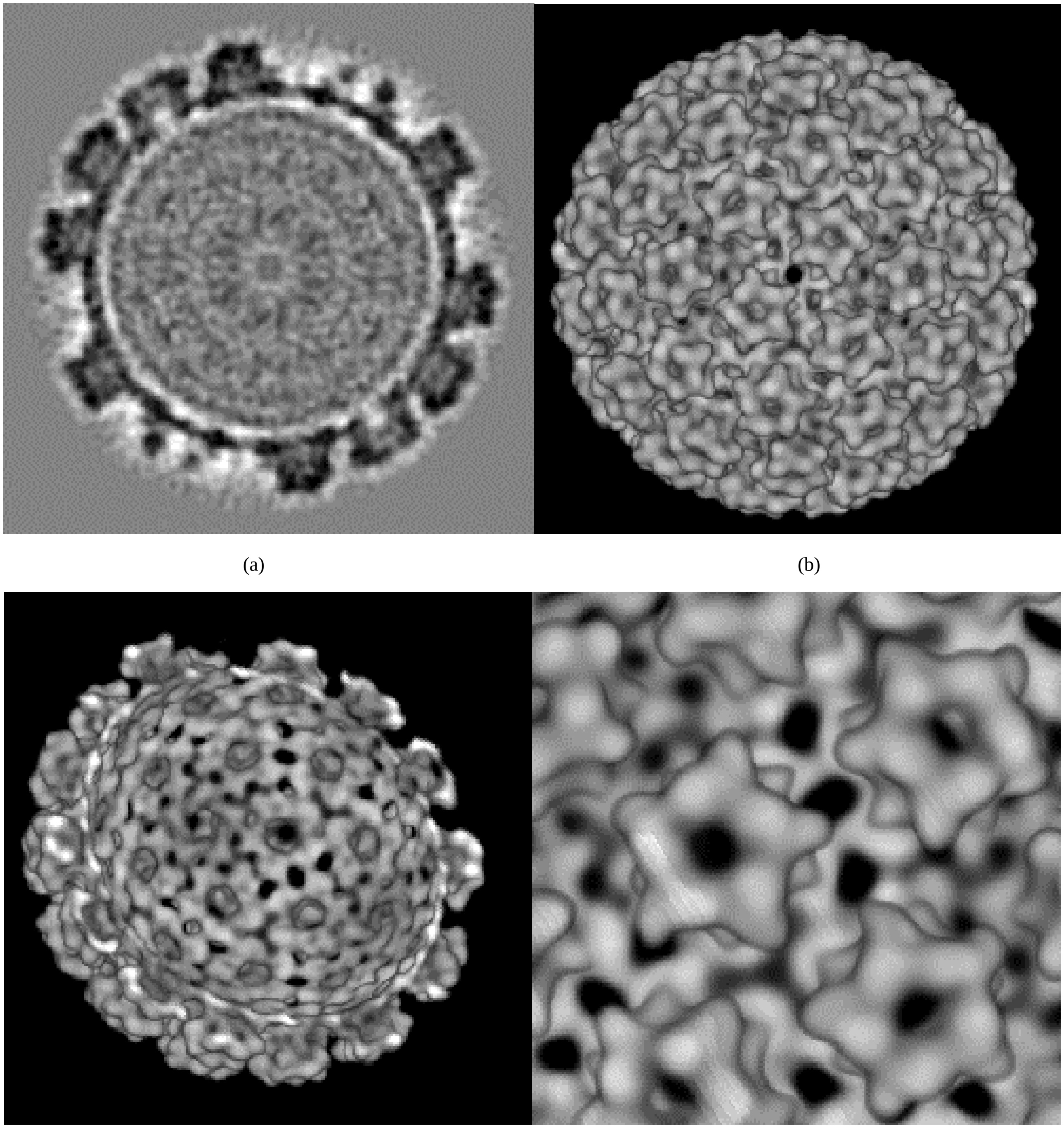
Figure 2(a) shows rotated MRI volumetric data constructed of slices centered on the origin of the texture space within a bounding cube. Figure 2(b) displays the same volume with an outlined bounding cube and a plane cutting through the volume. Mapping from the texture space onto the real three-dimensional space is linear, therefore any object or texture manipulations are linear as well. However, in order to insure that the volume content is not deformed during rotation or zooming, trilinear interpolation is applied to the texture following such manipulation.

This method requires hardware with a three-dimensional texture mapping capability[1].



(a) (b)

Figure 2. (a) Rendered MRI volume (b) with surface structure removed by using a clipped plane



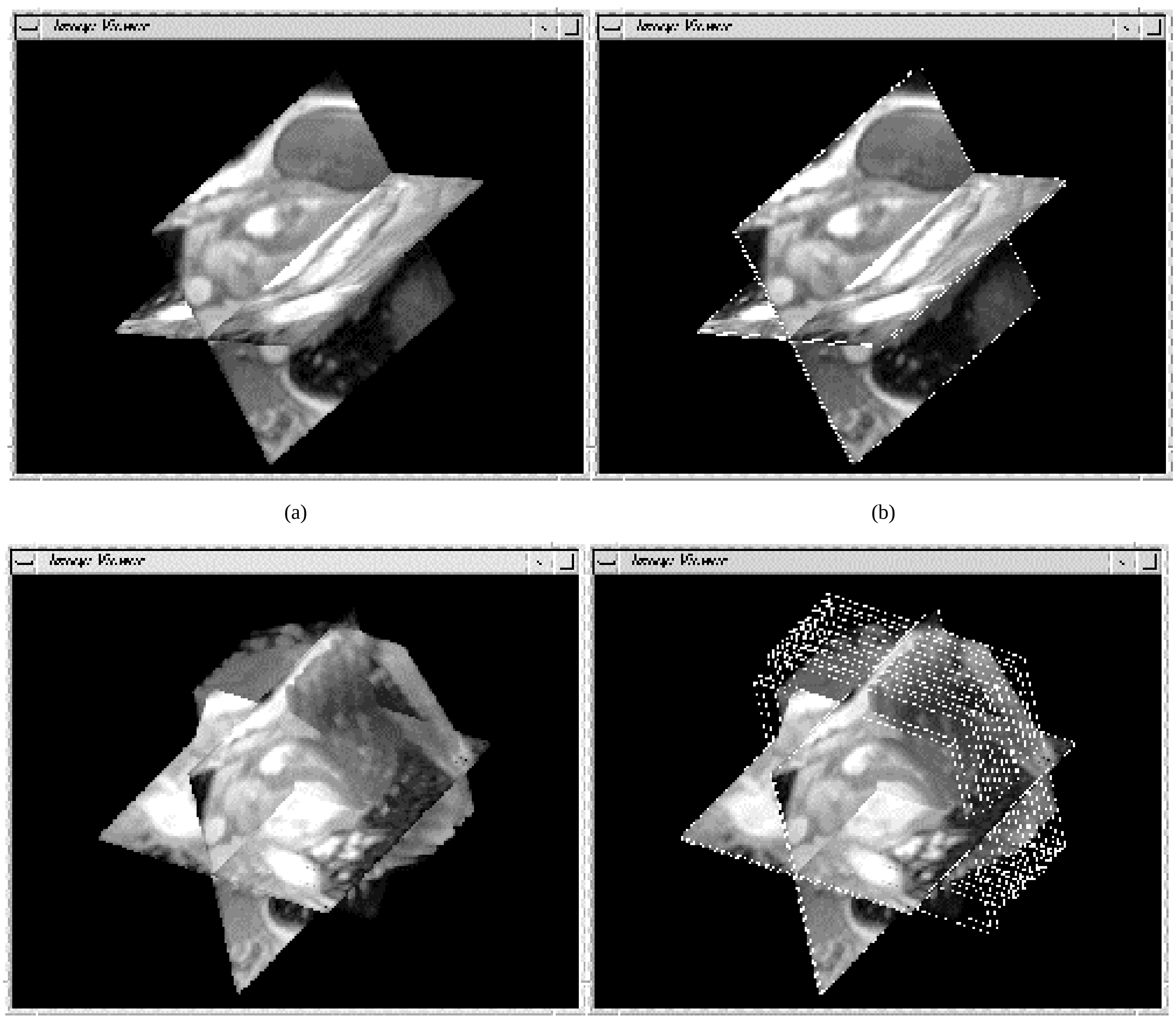
(a) (b) (c) (d)

Figure 3. (a) single (central) section through a 3D reconstruction of the papillomavirus capsid[20]. (b)The capsid visualized using texture mapping. (c) The inside surface of the capsid can be visualized using a clipping plane (d) or zoomed to examine fine details on the outside.

2.3 Registration

Patient motion is a frequently encountered problem in medical imaging. Perhaps the most problematic case is cardiac motion during cardiovascular MRI. It is not yet possible to eliminate cardiac motion, maintain high spatial resolution, and achieve high image quality in three-dimensional acquisitions. Thus, conventional approaches use sets of multiple parallel-plane two-dimensional imaging experiments where each slice is imaged in all phases of the cardiac cycle, resulting in 20 three-dimensional volumes[8]. Sampling of the consecutive slices is ECG gated, and the entire data set is acquired over the span of 10-15 minutes considering time needed to setup. In order to compensate for respiratory motion artifacts, patients are instructed to hold their breath during each set of two-dimensional acquisitions. However, the accuracy of volumetric data is dependent on the reproducibility of end expiratory diaphragm position. In some patients, the variation in diaphragm position from breathhold to breathhold is enough to shift the heart by more than an imaging plane, resulting in either a duplication or omission of the slice at the base of the heart. Since the basal slice can represent 10% of the myocardial volume, errors of this magnitude are significant. Accurate determination of myocardial volumes requires a registration of long and short axis images in 3D space.

Using the NIHmagic© set of interactive tools for object manipulation, registration for cardiovascular MRI is accomplished by manually aligning anatomical features in orthogonal cross sections of the heart volume. Orthogonal cross sections along the long axes of the heart are aligned first (fig. 4a and 4b). Slices along the short axes are sequentially aligned to the previously registered slices (Fig. 4c and 4d).



(a) (b) (c) (d)

Figure 4. (a) orthogonal cross sections along long axis of heart (b) with optional borders added as a visual aid for the user. (c) and (d) Slices along short axes are registered sequentially by manually matching anatomical features.

2.4 Segmentation

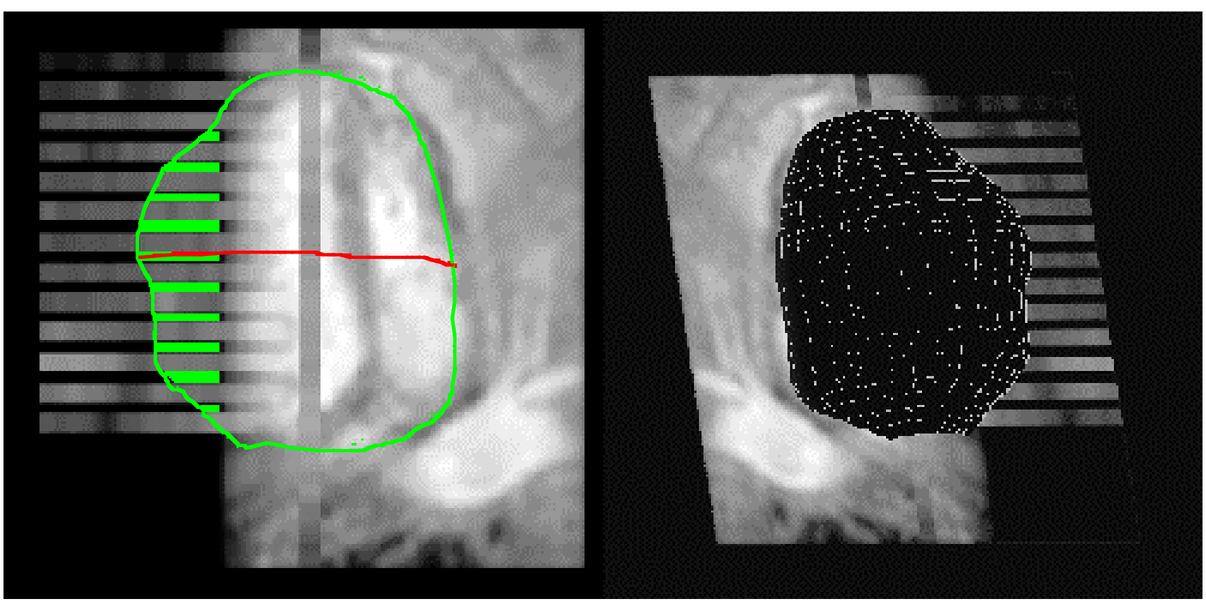
NIHmagic features an interactive tool to segment a volumetric object by manually tracing the objectӨ boundary. The system enables the user to traverse through the volume and trace an object on an arbitrary cross section through the data volume. The cross section is represented by the Slice View (Fig. 5a), which is always perpendicular to the viewing direction. The traced boundary of the object is displayed as a contour within the given slice.

The three-dimensional surface of the object is reconstructed instantaneously using a cylindrical surface representation, which is the projection of the surface onto a cylinder[15]. Interpolation of the surface in the cylindrical coordinate domain provides curvature in the surface around the main axis, and the boundary conditions can be set to a point at the apex and/or at the base. The cylindrical raster map-based surface reconstruction method is able to handle sparse sampling points of the surface of an object and incorporate geometric characteristics of the object to compute values for the non-sampled areas of the surface. The process of reconstructing the surface on the object from a set of traced points consists of the following steps:

- Establish the object coordinate system.
- Transform the data point (x, y, z) into the object coordinate system (x_o, y_o, z_o).
- Transform (x_o, y_o, z_o) into a cylindrical coordinate system (r_o, θ_o, z_o).
- Record (r_o, θ_o, z_o) onto a two-dimensional raster map where θ_o and z_o are the two dimensions and r_o is the recorded value.
- Extrapolate recorded values onto the two-dimensional raster map where data is not available.
- Compose the surface from the interpolated two-dimensional raster map based on a cylindrical surface representation where the raster map represents a bounded discrete surface.

The resultant two-dimensional array of values, or raster map, contains the radial distances from the main axis for a given angle and height. By formatting the unorganized set of points onto a regular grid, the raster map provides a context within which point-to-point comparisons between two surfaces and the quantification of specific aspects of a surface can be done in a straightforward manner[12,16]. Such a representation transforms the three-dimensional reconstruction problem into a more manageable two-dimensional interpolation problem.

The three-dimensional surface of the segmented object is displayed instantaneously on the Rendered View (Fig. 5b), providing an immediate response as to how the shape of the mesh fits the volumetric object with each added data point.
In the Rendered View, the slice is embedded within the traced three-dimensional surface.



(a) (b)

Figure 5. (a) The Slice View and (b) the Rendered View.

3. FUTURE WORK

Manual segmentation and registration are labor-intensive and subject to possible errors in reproducibility and to each user’s skill and ability to analyze a given data set. Therefore, a major development in NIHmagic will include semi-automated and automated image registration and segmentation methods. NIHmagic was initially developed to analyze cardiac images using a cylindrical coordinate system. However, for many biomedical images, other coordinate systems may be more appropriate or useful. A variety of additional models for surface representation (e.g. spherical coordinates) will be added to the existing interactive segmentation tool to accommodate objects that cannot be accurately represented in a cylindrical coordinate system.

The current version of NIHmagic has a real-time frame rate for volumetric data sets less than 32 MB. This limitation is imposed by the 64 MB of texture memory available on the existing Infinite Reality pipes. An accelerated visualization method for volumetric data sets larger than 32 MB, based on eliminating voxels outside the viewing area, is under development and will be incorporated into NIHmagic in the near future.

4. IMPLEMENTATION

NIHmagic is written in C++/OpenGL using the ImageVision Library (IL) toolkit and runs on a Silicon Graphics Onyx2 Infinite Reality (1 R10000 250 MHz CPU, 1 Raster Manger with 64 MB of texture memory). Real-time performance is achieved for multimodal volumes less than 32 MB, where the remaining 32 MB out of the total 64 MB of texture memory are used for alpha-blending.

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