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Virtual Endoscopy in Research and Clinical Practice

Dirk Bartz

Visual Computing for Medicine Group
University of Tübingen
Email: bartz@gris.uni-tuebingen.de

Abstract

Virtual endoscopy is among the most active topics in virtual medicine and medical imaging. It focuses on the virtual representation of minimally invasive procedures for training, planning, and diagnosis without an actual invasive intervention. In the past few years, virtual endoscopy modes have been transferred from research systems in virtually every commercial medical imaging software, but with varying quality and flexibility.
This report covers concepts used in current systems in research and products, and how they might be applied to daily practice in health-care. Specifically, I will start with an introduction into virtual endoscopy and the related medical field. This will also include typical scenarios of virtual endoscopy applications as they appear in clinical practice. This part will be followed by a discussion of the technical issues of virtual endoscopy and how they are addressed in currently available systems. Among these issues are navigation through the respective body organ and the orientation aids for the users. Furthermore, I will highlight the different rendering techniques used and its impact on rendering speed and quality.

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1. Introduction

Minimally invasive procedures are of increasing importance in medicine because they have less deleterious effects on the patient. In particular, these procedures are used in gastroenterology, surgery, neurosurgery, (interventional) radiology, and many other fields. Usually, these procedures are performed using an endoscope, which is a fiber optic that is moved to the target area. The fiber optic itself can be flexible or stiff, depending on the size and other requirements of the endoscope. For instance, a typical endoscope for neurosurgery has a small diameter in order to minimize the impacted brain tissue. The small diameter reduces the possibilities to transport sufficient light through the fiber to the endoscope head. Building a stiff fiber to allow a maximum of light[31] compensates this effect. Beside the light source, an endoscope consists of the optic for a camera to transport the acquired image to a monitor, and has one or more "working tubes" that are used to move tools such as pliers, to the target area. Cameras in the tip of the endoscopes have usually a large opening angle in order to provide a sufficient overview. Unfortunately, this also aggravates optical effects such as the fish eye view[37].

Other tools for minimally invasive interventions include (micro-)catheters, which are moved to the target area using a guidance wire – which gives the very flexible catheter stiffness – and fluoroscopy/xray control that provides an overview of the current localization of it. A specific application area of catheter are (usually arterial) blood vessels. Note that typical endoscopes cannot be used inside the examined blood vessels, since they are too large. Therefore, imaging is limited to the fluoroscopy images, or generated by a virtual endoscope, since a virtual camera cannot be too large.

Several drawbacks are associated with minimally invasive procedures. They are usually very unpleasant for patients, they are expensive (although they are still cheaper than "traditional" open surgery), and some areas of interest cannot be reached by the endoscope or catheter (due to folds and plaits). Especially in (neuro-) surgery, these procedures lack the fast access for open surgery in case of serious complications, such as strong bleeding. Therefore, careful planning and realization of these procedures is essential, in order to avoid such complications. This problem aggravates, because handling and control of many of these endoscopes is quite difficult. These difficulties are mainly due to limited flexibility of and limited field of view through the endoscope, a very limited depth perception, and the sensitive nature of the brain tissue.

In contrast, virtual endoscopy is a convenient alternative. It is based on a 3D scan of the respective body region. Examples for these scans are CT (Computed Tomography) scans, MRI (Magnet Resonance Imaging) scans of the abdominal area, the heart, the head, the lungs, or rotational angiography of blood vessels in various body parts. Based on the resulting volumetric data, the organs of interest are visualized and inspected from interior ("endo") viewpoints. Depending on the original endoscopic procedure, which is mimicked by virtual endoscopy, different goals can be achieved. These goals range from

- teaching: providing unusual insights into the anatomy of living patients,
- diagnosis: inspecting organs for (shape) defects, indicating unusual organ geometry,
- intervention planning: providing insight into the potentially complicated and non-standard anatomy of the patients and the individual organ location, and
- intra-operative navigation: currently, the position of a "real" endoscope is tracked by an infrared-based 3D navigation system and mapped into the image stack acquired previous to the operation. With virtual endoscopy, this position and orientation information can be exploited to generate a coupled visualization of optical and virtual endoscopy. In particular the virtual endoscopy can provide information which is not available to the optical endoscope, due to the limited flexibility and field of view.

In the next section, we discuss important display and navigation requirements that are imposed on and options that are available for virtual endoscopy. Furthermore, we propose a taxonomy of virtual endoscopy, based on these requirements and options. We will also classify the various approaches into that taxonomy. After presenting a brief overview of virtual endoscopy in Section 3, a more in depth discussion of some approaches will be presented in Section 4. We will also discuss a variety of applications, where virtual endoscopy systems have been successfully used (Section 5). Finally, we briefly discuss the advantages and shortcomings of virtual endoscopy in Section 6.

2. Requirements and Options for Virtual Endoscopy

2.1. Perspective Rendering

Mimicking endoscopy requires the rendering of the dataset with a strong perspective view inside of the dataset. Unfortunately, not all rendering algorithms – in particular the acceleration methods – can cope with these boundary conditions, and all algorithms suffer from the large magnification factors of perspective views inside of datasets and close to the rendered structures. Undersampling problems are almost always present and the limited resolution of the scanned datasets becomes often obvious. Some algorithms, however, are less prone to these problems. Isosurfaces reconstructed by the Marching Cubes algorithms[55] can be rendered with perspective views at no additional costs using graphics hardware. However, the large magnification factors and viewpoints close to these surfaces expose the typical diamond artifacts caused by the trilinear interpolation. Furthermore, the number of graphical primitives (triangles) generated by this approach is usually large. Several million triangles for large datasets are not uncommon. Therefore, the straightforward rendering of the triangles may be not possible at interactive framerates. Acceleration techniques like occlusion culling[63, 48, 16] or surface simplification[88, 56] can ease that problem. Nevertheless, these techniques need to be applied with care, if image quality is traded off for the acquired additional speed. Also, surface rendering techniques like MarchingCubes require a decision what is going to be rendered before the surface extraction process starts. While this is not really a problem for virtual endoscopy – the characteristics of the datasets are usually already known –, this can be a problem for general rendering tasks. Finally, the representation of multiple segmented data objects requires a little bit more effort for transparent rendering (ie., polygon sorting) than with direct volume rendering methods.

Adaptive ray-casting[69] can cope with the undersampling problem by adaptively oversampling the isosurface in these regions at the cost of lower framerates. Splatting[95, 65] enables filtered reconstruction of the voxels, but can also increase the blurriness of the representation[61]. The shear-warp algorithm [51] uses a base-plane approach that is generally not suited for large magnification factors encountered in virtual endoscopy, since the base-plane has the same resolution as the respective face of the volume dataset[61]. Even more recent improvements do not really allow these large factors[85].

Texture-mapping-based Volume Rendering

Texture-mapping-based volume rendering[27] suffers from various problems. Among them are limited accuracy in the compositing pipeline of older graphics subsystems (but has been overcome in high-end graphics accelerators that became available at the end of 2003 with a full floating-point rendering pipeline), limited texture/graphics memory that does not accommodate the whole dataset, and sampling problems[61] that are successively reduced.

Many research contributions have investigated the use of texture mapping graphics hardware for volume rendering. In 1998, Westermann and Ertl presented 3D texture mapping-based volume rendering with isosurface shading[94]. Meißner et al. extended this approach with advanced clipping methods and shading of volumetric data[60]. In the past four years, many more researchers have improved the visual quality of texture mapping-based volume rendering. Engel et al. have coined pre-integrated volume rendering to address high reconstruction frequencies in transfer functions[33], which also enables to reduce the sampling rate to some extend (and is applicable to other direct volume rendering as well). Other approaches use also the programmability of modern graphics hardware to improve the quality and the speed of this volume rendering approach[59, 42].

However, one of the major limits of texture-mapping-based volume rendering remains; since the full dataset rarely fits into the texture/graphics memory of the graphics accelerator, various swapping – ie., bricking – and compression methods need to be applied[42]. Overall, it still does not provide sufficient high-quality performance for interactive endoscopy applications. More details can be found in tutorials on texture-mapping based volume graphics[50, 32].

In summary, most virtual endoscopy systems use either an isosurface-based rendering using the graphics hardware, or an accelerated ray-casting approach. In particular the latter one involves the exploitation of many auxiliary datastructures, like distance fields, which need to be generated in a pre-process. The only system that uses texture mapping hardware is the Vitrea2 system of Vital Images, but it generates insufficient image quality for virtual endoscopy[71].

For a discussion of the cause and visual appearance of data and rendering artifacts[22], please refer to [11] (only in German).

2.2. User-Interaction and Navigation Paradigms

Besides rendering, the used camera navigation paradigm determines the usability of a virtual endoscopy system. Controlling the camera in a virtual endoscopy application is not an easy task. The various approaches can be roughly classified into three classes[48]: automatic navigation, manual or free navigation, and guided navigation[39].

Many systems use a planned or automatic navigation, which generates an offline animation of a fly-through after specifying a camera path. This simple scheme reduces the interaction to a VCR-like functionality, requiring a costly refinement of the camera path (and of the animation), if the structure of interest is not well covered. In this context, Dachille et al. noted that only approximately 70% of the colon surface are covered by a single direction fly-through and up to 95% for a fly-through in both directions[28]. For the remaining parts, interactive camera control is required. A variation of the planned navigation is “reliable navigation”[44], in which a complete “visit” of all structures of the organ is guaranteed. However, this also means that user interaction is limited and that irrelevant regions cannot be easily skipped. As an important cross-reference to the used rendering technique, automatic navigation does not require an interactive rendering technique, since without any user interaction, no rendering lag obstructs the navigation.

A manual or free navigation approach is another popular option. Unfortunately, the complexity of the anatomical structures commonly found in the datasets is very high. Even for a specifically trained physician, it can be difficult to navigate to the target. Furthermore, the unrestricted movement through the dataset imposes many view control limitations that render this approach difficult to use[66]. For similar reasons, semi-automated fly-throughs[48] cannot be easily integrated into free navigation frameworks. Collision avoidance requires costly query operations and are therefore frequently not available in these systems. In contrast to automatic navigation, free navigation requires a highly interactive rendering technique, since a significant lag between interaction and rendering will severely disturb the user interaction.

Our final option is the guided navigation paradigm[39] that enables full navigation flexibility, combined with user guidance and an efficient collision avoidance scheme. Different techniques can be used to implement guided navigation. Galyean suggested a spring-based model to compute the respective constraints[39]. However, specific implementation details were omitted in this publication. In contrast, Hong et al.[48] used several potential fields and a set of kinematic rules to implement their guided navigation system. While the original idea is to provide additional guidance to the user, it can also be more constraint. Vilanova et al.[5] describe a guided navigation system where the location of the camera is fixed to a pre-computed path, while the camera orientation can be selected freely.

Guided navigation benefits from interaction rendering, since user interaction has an important role for the camera control. However, the guidance constraints are damping lags between user interaction and rendering. Therefore, a not very interactive rendering technique might be still usable. Nevertheless, a very slow rendering technique that produces less than five frames per second is still not suited for guided navigation.

2.3. Taxonomy of Virtual Endoscopy Systems

In our taxonomy, we will focus on the rendering techniques and camera navigation models used in various systems. However, there are many more important features of the various systems, which we will not include in the taxonomy. Among these other features are: How well multiple materials/segmented objects are supported? How well the system is integrated in a PACS viewing system (a criterion that is very important for the daily clinical practice)? How much pre-processing is required?

Table 1 gives an overview of the various systems classified by our taxonomy.

Rendering Technique: Navigation Paradigm	Polygonal Surface Rendering With Accel.	No Accel.	Direct Volume Rendering High Quality	Reduced Quality
Automatic Navigation		VESA[56],VirEn[5], 3D Slicer[40], FreeFlight[88]	VI VoxelView[77], PMS Endo3D, SMS Syngo	GE Navigator, SMS Virtuoso
Free Navigation	VBC[64]	FreeFlight[88], 3D Slicer[40]	PMS Endo3D, VI Vitrea2, SMS Syngo	GE Navigator, CRS4[41], SMS Virtuoso
Guided Navigation	VICON[48], VIVENDI[16]	VirEn[5]	Viatronix V3D Viewer, Tiani's J-Vision	

Table 1: *This table shows an overview of many of the available virtual endoscopy systems and their classification according to our taxonomy. Note that available information on the various virtual endoscopy systems can be somewhat undetailed. Hence, some of the presented information might be inaccurate.*

3. Overview on Virtual Endoscopy Systems

Research on virtual endoscopy is one of the most active areas in virtual medicine. The various developed methods of virtual endoscopy have been applied to colonoscopy[86, 48, 52, 5] (and other parts of the small and large intestines), bronchoscopy[64, 87, 35, 73, 93, 58, 46], ventriculoscopy[2, 17, 18], and angioscopy[29, 20, 41, 19, 14]. Other applications also include the ear/nose cavities[97, 75]. A more complete listing of applications of virtual endoscopy is provided by Rogalla et al.[74, 76]. Due to the sheer number of published work on (mostly applications of) virtual endoscopy – Google Scholar found more than 2600 references on the topic virtual endoscopy –, I can focus only on a rather small subset of research contributions.

As mentioned before in Section 2.1, different rendering options can be used to trade off quality and rendering speed. Standard graphics hardware is used to render surface models[63, 88, 56, 48, 16, 5, 66], extracted with the Marching Cubes algorithm[55]. However, the high geometric complexity of the extracted organ models frequently exceed the interactive rendering capabilities of most of the available state-of-the-art graphics accelerators, thus requiring either high-end systems[48, 88], algorithms to reduce the rendering complexity[48, 16, 45], or to relinquish interactive performance[20, 5].

Hong et al.[48] implemented a decomposition of the colon along its centerline. The resulting cell/portal structure is used together with a framebuffer-based visibility test to reduce the geometric complexity of the dataset to approximately 10%. To overcome the limitations to single-tube-like organ topologies, Bartz et al.[16] utilized an octree decomposition of the volume dataset and its isosurface in junks of roughly similar size. A hardware supported occlusion test is used to reduce the geometric complexity to 5-8% for a large variety of different organs. Hietala and Oikarinen[45] applied a mixed technique, where a variation of template-based ray-casting[96] provides visibility information later employed for Marching Cubes-based polygonal rendering of tubular organ datasets (aorta and colon).

In contrast, volume-rendering techniques are used, partially for better visual quality, partially for interactive speed[82, 47, 29, 98, 41, 81]. Unfortunately, interactive speed has almost always compromised visual quality, general applicability, or flexibility. In [82, 77] and [47], key-framed animations are generated offline, which frequently leads to the time-intense refinement of the key-framed animation if the current camera path is not suitable. You et al. used a 16 processor SGI Challenge for parallel volume rendering of isosurfaces[98, 90]. However, image quality was still poor. In contrast, Gobbetti et al. employed the 3D texture mapping hardware abilities of high-end graphics systems for volume rendering[41]. Here too, image quality was significantly reduced by the lack of shading. In Vital Images Vitrea2, also a texture-mapping approach was implemented, which however also offers shaded rendering.

The Navigator software of General Electric uses isosurface ray-casting with roughly a few frames per second. Even if the performance of the 1996 results (one frame per second) has significantly improved, it hardly can be viewed as interactive[29, 35, 3, 2]. Similar solutions are provided by the Syngo platform of Siemens Medical Solutions (SMS) (Virtuoso was the previous 2D-texture-mapping based solution) and by the EasyVision Endo3D option of Philips Medical Systems[74, 22] (PMS) with similar performance of a few frames per second and varying image quality. Another variation was presented by Wegenkittl et al.[93], where six offline generated volume rendered movies were combined into a cubic map to provide interactive rendering speed on low-end PCs similar to Chen's QuicktimeVR[25]. Fast high quality direct volume rendering has been implemented for Tiani's J-Vision and Viatronix V3D Viewer.

In terms of camera navigation paradigms, the various systems employ all three options. Automatic navigation is employed in numerous systems[86, 47, 56, 77, 20, 44, 66] to generate an offline animation of a fly-through after specifying a camera path. Many systems with purely automatic navigation use direct volume rendering techniques, which offer high quality at quite low framerates[47, 77].

A free navigation approach is followed by Vining et al.[88, 86], Gobbetti et al.[41], and Nain et al.[66]. Typically, it is combined with the polygonal rendering of an extracted surface representation of the organs of interest[88, 66], since it requires interactive rendering performance. Most current commercial systems (GE Navigator, SMS Syngo, PMS EasyVision Endo3D) also provide a free as well as an automatic, path-based traversal of the structures of interest.

Finally, guided navigation[39] is used by Hong et al.[48] and Bartz et al.[16, 19] with full navigation flexibility. If no user-interaction is involved, the virtual camera moves along the pre-computed centerline to a specified target point. A more restricted fashion of guided navigation was introduced by Vilanova et al.[5]. Another variation of this more restricted guided navigation was presented by Wegenkittl et al.[93], where a cubic map was utilized to generate an interpolated image from the pre-rendered six face of the cube, organized in six movies. Another image-based approach using a cubic map was presented by Serlie et al.[81], which also combined a front and back view.

An interesting variation of virtual colonoscopy has been proposed in [43] and further developed in [8, 6]. Here, the colon is stretched and unfolded to provide an inspection mode similar to pathology. This way, the whole colon can be examined without traversing it, therefore, no camera navigation model is required. Unfortunately, this technique is not easily adaptable to more complex organ systems with no simple tube-like structure like the colon. Even other tubular structures like blood vessel trees are not easily unfoldable by these techniques.

The presented virtual endoscopy systems are by no means a complete list of available/developed systems. However, this section gives an overview on most of the systems that have been described in a publication.

4. Detailed Look into Systems for Virtual Endoscopy

In this section, we will take a more detailed looked into a subset of available research systems for virtual endoscopy. In particular, we will examine the FreeFlight system of the University of Wake Forest[88], Endo3D of PMS, Syngo of SMS, VESA of GE Corporate Research, and Development, the VICON family of systems at the University of Stony Brook (SUNY Stony Brook)[48], the VIVENDI system of the University of Tübingen[16], and VirEn system of the Technical University of Vienna [5]. In addition, we will also briefly discuss a few other systems that have been developed.

Please note that detailed information of commercial products – as research spin-off or company developments – are usually not available. Therefore, some of the information provided in the next sections on these systems is by nature inaccurate and not necessarily describing the most recent state of these systems.

4.1. FreeFlight – University of Wake Forest

The FreeFlight system has been developed at the University of Wake Forest and is next to Mori's VBE system[64] one of the oldest systems[88]. It is based on the OpenInventor API toolkit[83], which FreeFlight uses for interaction and rendering.

After the segmentation of the respective organ, a surface representation is generated using the Marching Cubes algorithm[55]. This surface representation is then used for the endoscopic examination where the user utilizes the interaction techniques of OpenInventor to explore the polygonal organ model. In addition to this free navigation mode, an automatic mode is also included. It is based on a centerline algorithm that moves the camera through the organ cavity.

Next to the polygonal endoscopic view, FreeFlight is an early adopter of texture-mapping-based volume rendering[27]. However, its capabilities are limited by the size of the available texture memory and by the lack of shading. Finally, it provides the three orthogonal cross-sectional views of axial, sagittal, and coronal orientation. FreeFlight offers the reduction of the volume dataset resolution to adapt to the actual rendering capabilities of the employed graphics subsystem. However, the involved quality reduction can severely impact the proper representation of features such as polyps.

Overall, FreeFlight has the characteristics of a free navigation system with an isosurface-based rendering. The most severe drawback is surely the free navigation model that hardly offers sufficient functionality for an intuitive and easy to use interface for the potential users.

4.2. EasyVision Endo3D - Philips Medical Systems

PMS has integrated virtual endoscopy functionality into its EasyVision product. It is based on a first-hit ray-casting scheme that renders the images in a lower resolution, while moving through the scene and in full resolution for still images. Both low and full resolution rendering modes are currently significantly below interactive rendering rates (on SUN Ultra 60 workstations). As navigation modes, path oriented and free, slice oriented navigation are provided.

As a special option, Endo3D offers an unfolded view[81] of the scene. Here, a panorama-like view of 360^o is rendered into a cube that is unfolded into its six faces. The rendering of these six directions is done in a preprocess and offers a functionality similar to the automatic navigation, providing a VCR-like interaction.

4.3. Syngo – Siemens Medical Solutions

Syngo is the overall platform for the imaging workstation of SMS. The volume rendering functionality is partially based on software, and partially based on TeraRecon's VolumePro technology[70] (originally developed by Mitsubishi Electric Research Labs (MERL)). In an earlier version of the SMS imaging workstation ("SMS Virtuoso"), volume rendering used 2D texture mapping with all its inherent limitations, including poor or no shading.

According to SMS, virtual endoscopy on the Syngo platform is performed using ray-casting with space leaping as major acceleration technique. It also provides an automatic navigation mode. Depending on the dataset and the computing platform, the virtual endoscopy function allows a framerate of up to 10 fps.

4.4. VESA – GE Corporate Research and Development

About the same time as FreeFlight has been developed, a similar system was developed at General Electric Corporate Research and Development. It was also based on the polygonal surface representation of a segmented organ. Algorithms from robot motion planning were utilized to generate a flight path through the organ, which then was used to move the camera through the organ model. Potential performance bottlenecks due to the large number of triangles in the surface representation could have been overcome with polygonal simplification algorithms. However, this also involved the reduction of rendering quality and henceforth needed to be applied with great care.

By now, GE offers the Navigator module as the virtual endoscopy option for their Advantage Windows system. Based on the volume data of a patient, a first-hit ray-casting approach is used to render the surface at a speed of a few frames per second[29, 3].

4.5. VoxelView/Vitrea2 – Vital Images (VI)

Also in the early years of virtual endoscopy (1994-1996), Vital Images developed the VoxelView system that was based on (texture-mapped) direct volume rendering[82, 77]. Preprocessing of the data volumes included the definition of the 8bit data window (from 12bit scanner data) and the resampling of the possible anisotropic volume into an isotropic grid. After the specification of the classifications through four transfer functions, a camera path was generated based on dedicated viewpoints, specified by the user, and a keyframe interpolation scheme. Afterwards, a video animation was generated in a time-intensive offline process. While the system offered a reasonably good image quality due to the used volume rendered method, it provided only a VCR like functionality of playing/replaying the video animation. If an important feature was not visible from the generated viewpoints of the camera path, it could not be seen in the animation. Furthermore, a possible needed refinement of the camera path required the regeneration of the animation, which took several hours at the time.

By now, Vital Images provides a different system in their Vitrea2 software, but also with non-interactive manual navigation. This navigation mode is controlled by the cross-sectional viewer of Vitrea2 and steps slice by slice through the cavity. This conservative way of navigation is motivated by the traditional way radiologists examine data and is in contrast to most other virtual endoscopy systems, which utilize either a world-frame control setting (ie., FreeFlight) or an endoscopic-frame setting. The rendering is based on a 2D/3D texture-mapping based volume rendering utilized in Vitrea2.

As in most commercial systems, not only the software but the whole system at large is delivered in a completely configured computer system. Therefore, the rendering functionality is carefully tuned to the capabilities of the used graphics system. Currently, they are using a WildCat graphics accelerator.

4.6. VICON – SUNY Stony Brook

Early development in the VICON family of virtual endoscopy systems started in 1994 in the Vislab at the SUNY Stony Brook. It has its origin in an automatic navigation approach that generated an animation of a fly-through on a defined camera path[47]. In a pre-processing step, the start and end point of the camera path were specified by the user. After segmenting the respective colon region using a 3D region growing approach, the camera path was computed by calculating a centerline of that segmentation. The used "onion peeling" algorithm implemented a thinning approach, which successively removed outer voxel shells from the segmentation until only a one voxel wide connection remained. Thereafter, the direct volume rendering stage generated the respective animation.

Later, this approach was modified to adopt a guided-navigation paradigm[48, 39], in which the user can roam through the virtual colon as flexible as preferred. The used submarine model for intuitive guided navigation mimics the submarine in the academy-awarded movie "Fantastic Voyage" where a miniaturized submarine traverses the blood vessel of a patient. Two (three) distance fields – interpreted as potential fields – are used for navigation purposes. The first one (two) implements a forward (backward) stream from the start point to the end point, similar to the blood flow. The final distance field implements a collision avoidance system to prevent penetrations of the surface of the colon, based on the distance to the surface of the segmented voxels[78]. The distance field generation itself is interpreted as a single source graph problem where all voxels of the dataset represent the nodes of the graph and the voxel cell edges represent the graph edges. We used Dijkstra's minimum path algorithm to calculate the forward (backward) distance field on the segmentation.

Together with a set of kinematic rules, which emulates the engine of the virtual camera/submarine, this model enabled an interactive and intuitive navigation through a colon. The distance fields are calculated on a 26-neighborhood of the segmentation of the colon. The default camera path – which the camera is following along the forward (backward) stream – is defined on a centerline calculated on the maxima and ridges of the collision avoidance (and forward) distance fields. This way, it enables a smooth path in the center of the colon, if the influence of the two distance fields are parameterized accordingly[48, 9]. The very same approach was later re-discovered by the same group and described in [21] and yet again in [89]. After the segmentation and camera path have been calculated, the VICON system generates a subdivision of the segmented colon volume based on split planes of the three orthogonal orientations (axial, sagittal, coronal)[9, 48]. The isosurface is extracted using the Marching Cubes algorithm[55]. For the rendering of the isosurface during the interactive traversal of the colon, the split planes and remaining voxel segments are used as portals and cells for a potential-visible-set-based visibility algorithm[1]. Basically, this approach tests the intersection between the current and next portal from the current viewpoint for visibility. Here, contributions to the framebuffer are tested to establish if the geometry behind the next portal, represented by the respective cell, is visible and henceforth has to be rendered. Otherwise, it is skipped from rendering. Overall, this approach enabled a reduction of polygonal complexity of about 60% and enabled interactive rendering of more than 10fps on a SGI Challenge with an Infinite Reality graphics subsystem[48].

The VICON system has been constantly improved since the original, polygon-based approach. You et al. suggested to employ ray-casting in parallel on a 16 CPU SGI Challenge[98]. Wan et al.[92] used the distance-to-surface distance field – originally intended for collision avoidance – to compute step sizes for empty space leaping, a technique that was originally proposed by Zuiderveld et al.[99]. Yet again, this approach was presented by Wan and Kaufman in [91]. In 2001, Li et al. also improved the rendering performance of the ray-casting volume approach significantly. The original portal/cell approach is improved by employing cache coherence and the texture-mapping functionality of the graphics hardware[54] to limit the ray casting sampling to the visible surfaces. This way, he achieved a significant increase of rendering speed.

4.7. V3D Viewer – Viatronix

The technology of the previously described VICON system has been widely utilized in the V3D Viewer/Colon module of Viatronix. While the navigation module is still mostly based on the submarine guided-navigation system of VICON, its rendering technique has been improved quite a bit since the initial versions. Currently, V3D uses a variation of ray-casting with a space leaping approach based on the distance field transform. Specific acceleration techniques exploit the close proximity of the inner organ wall, which saves empty samples of the rays casted from the viewpoint. Unfortunately, the high framerates break down, once the rendered surface becomes semi-transparent, requiring the sampling of the volume behind it.

Overall, V3D Viewer uses a highly optimized ray-casting approach for rendering and – more or less – the previously known camera navigation paradigm of VICON.

4.8. Interactive Virtual Angioscopy – CRS4

An early texture-mapping-based approach[27] was presented by Gobbetti et al.[41]. Here, the volume data is rendered using 3D texture-mapping hardware, available on high-end graphics at the time. To adapt the distances between the slices to perspective projection, the slice space has been chosen inversely proportional to the actual distance. Furthermore, texture lookup tables are used to adapt the opacity of the samples accordingly[41]. The free navigation is accompanied with a force/friction model, which is coupled with the opacity of the data samples. If the samples become opaque, this model detects collision and the respective collision reaction is calculated.

Overall, this system provided a few frames per second as rendering performance based on the texture-mapped volume dataset. If the volume dataset does not fit into the texture memory, a bricking technique is used to swap-in required parts of the dataset. In terms of quality, the system suffered from the typical poor rendering quality of the early texture-mapping-based volume rendering systems[27, 24] that lacked shading. Interaction follows to some extent the guided navigation paradigm, since collision avoidance is implemented based on the voxel opacities in the direction of the movement. Otherwise, it is a regular OpenInventor-type free navigation model.

4.9. VIVENDI – University of Tübingen

Similar to the V3D Viewer of Viatronix, the VIVENDI system developed at the University of Tübingen has its roots in the VICON system. It branched off after I left SUNY Stony Brook in late 1996 and has been modified and improved ever since. The major goals of the VIVENDI project were twofold; the first goal was the reduction of the pre-processing times (which at the time required 10-16 hours) and second to overcome the topological limitation of VICON to tube-like organs (its occlusion culling algorithm is based on the segments of a colon). Furthermore, it integrated new functionality to navigate through complex multi-model scenes. Basically, the only similarity to the VICON systems is now the guided navigation systems, which is based on its submarine model[48].

The non-optimal data structures were one of the major problems of the pre-processing stages of the VICON system. Consequently, we improved the heavily used priority queues by employing state-of-the-art structures of the LEDA library. Instead of the previously implemented FIFO queues, which are unsuited as implementation of priority queues with a large number of elements, we are now using Fibonacci heaps that reduced the computational complexity to $O(logN)$, in contrast to the $O(N^2)$ of the FIFO queue-based implementation[16]. Since the priority queues are used by Dijkstra's algorithm to compute the centerline and the forward (backward) distance fields, the respective run time could be reduced tremendously from many hours (almost one day) to an one digit number of minutes, even for large datasets. Similar results have been rediscovered by Wang[89].

To overcome the focus on tube-like organs, we replaced the centerline-based decomposition of the segmented volume by a spatial decomposition, based on an octree. Depending on the number of relevant voxels (voxels that contain the specified isosurface), the granularity of the leaf nodes of the octree is determined. This octree-based spatial decomposition ensures the independence of the hierarchical data structure from the actual topology of the organ of interest, roughly balanced by the number of relevant cells that correlates roughly with the number of triangles. During run time, VIVENDI performs a hierarchical test on the tree nodes to establish if they are located within the view-frustum. This operation returns a front-to-back sorted list of the geometry organized in the leaf nodes of the octree, which is passed to the occlusion culling stage. Since the first 10% of nodes are rarely occluded, they are rendered without any occlusion test. All successive nodes are first tested for occlusion, based on their bounding volume, and depending on the result of that query, they are rendered or skipped.

Currently, VIVENDI supports multi-object and multi-material interaction. Therefore, it can differentiate data from different segmentations with different connotations[18, 38, 15].

VIVENDI has been successfully applied to a large number of different virtual endoscopy applications. See Section 5 or the Eurographics State-of-the-Arts report[12] for more details. For an indepth discussion of the architecture of VIVENDI, please refer to [16].

4.10. VirEn – Technical University of Vienna

VirEn[5, 93, 4] has been developed over the past four years at the Technical University of Vienna in conjunction with Tiani MedGraph, a PACS system company. Similar to the previous system, it is based on a surface model of a segmented organ in a volume dataset. It uses the Marching Cubes algorithm[55] to extract the surface model of the organ. In addition, it offers ray-casted rendering of current viewpoints with better visual quality at significantly higher rendering costs. The rendering performance of the surface rendering depends on the selected graphics accelerator and might not be able to provide interactive framerates for large datasets.

The adopted navigation mode is a guided navigation, based on the centerline of the organ model. In contrast to VICON[48] and VIVENDI[16], the user navigation is limited. The virtual camera moves along the centerline of the organ. Only the view direction can rotate around the current camera position. The centerline itself is generated by topological thinning, a process similar to the onion peeling[47], where voxel layers of a segmentation are successively removed as long as they preserve the topology of the set of voxels. This operation is computationally quite expensive and is done in a pre-process.

A variation of this rendering approach was presented by Wegenkittl et al.[93]. Here, the image generation is based on a cubic map of the volume rendered images of six viewing directions represented by the directions of the viewpoints along the camera path. Similar to Chen's QuicktimeVR[25], these six images are combined to generate the image of the current view direction. In Wegenkittl's approach, the views of the six view directions along the path are stored in six movies that are generated offline in a pre-process. At run time, they are interpreted as a cubic map to generate the display image. A similar approach has been proposed by Serlie[81], which in part is also integrated in the EasyVision system of Philips Medical Systems.

While VirEn uses a ray-casting approach for direct volume rendering, the authors also suggested to utilize volume rendering hardware to accelerate the rendering. Since the used VolumePro system[70] does only provide parallel projection views, they decompose the volume in view direction in several slabs of several volume slices. These slabs are independently rendered by VolumePro and warped to simulate a perspective projection[7]. If the number of slabs is too low, the image quality suffers badly from the error introduced by the parallel projected slabs and their warping to fit the perspective projection[7]. To provide an acceptable quality, more than 130 slabs need to be used for a relatively small dataset of $256 \times 82 \times 105$ voxels. However, the multi-pass rendering of the different volume slabs reduces the performance of VolumePro significantly, since this is similar to the rendering of multiple volume datasets. For the mentioned number of required slabs (>130), the performance is less than 10 seconds per frame, a performance that is similar to high-quality software volume rendering systems.

An interesting variation of virtual colonoscopy is unfolding the generated dataset into the plane. Vilanova et al. have proposed two different approaches how this unfolding can be achieved, while maintaining size ratios and overview in the generated images[8, 6]. Unfortunately, there are some situations where a colon fold can occlude a small polyp or other features. In these cases, the presented approaches will not represent that polyp in the unfolded colon properly. As noted before, this approach cannot be easily adapted to other organs with a more complex topology.

4.11. J-Vision – TIANI

Starting from the developed systems at Technical University of Vienna[93], TIANI developed the J-Vision system that integrates regular PACS-based 2D exams with 3D visualization on a plugin basis. The 3D plugins also include a virtual endoscopy application that is based on a ray-casting-rendering-engine in Java. Based on the specified thresholds (transfer functions), the first sample of a ray that crosses the iso-contour of the threshold is rendered (first hit). Due to the used traversal scheme (first hit) and the exploitation of image/object space coherence[67], J-Vision achieves near interactive framerates on a state-of-the-art laptop/PC. A more recent implementation of a fast ray casting technique is described in Bruckner's master's thesis[23].

Also, in contrast to the previously developed system, J-Vision allows a flexible navigation and is not limited to a specified path. It offers automatic, free, and guided navigation.

4.12. 3D Slicer – MIT and Brigham's and Women's Hospital

3D Slicer[40] is a joined effort of the AI Lab at MIT and the Surgical Planning Lab at Brigham's and Women's Hospital in Boston. It is software for medical imaging, which performs segmentation of organ structures from volume data, and the respective 3D rendering of these structures. In addition, it provides the traditional 2D orthogonal cross-sections of the volume dataset. 3D Slicer itself is based largely on VTK[80] and offers no additional acceleration techniques to improve the rendering performance beyond the offerings of the used graphics hardware. However, VTK also offers surface simplification mechanisms that can be applied to generated a simpler model of the organ, which in turn also reduces the fidelity and accuracy of the generated surface model.

Nain et al.[66] recently added a virtual endoscopy viewing mode to 3D Slicer, which uses a surface model of the segmented organ to render the endoscopic view. As a special feature, the previously mentioned cross-sections are not necessarily aligned with the volume dataset, but can be reformatted into multi-planar representations (MPR) that are aligned with the current viewing orientation.

Three different modes of navigation are provided; two automatic navigation modes, and one free navigation mode. The first automatic mode is based on a key-frame interpolated path of viewpoints ("landmarks"[66]). The derived viewing direction depends on the travel direction. Unfortunately, automatic navigation usually suffers from the gimbal lock, since the roll of the virtual camera remains unspecified[48]. The second automatic navigation mode is based on a centerline generation, using temperature distribution functions and their finite-element-based numerical solution[66]. While the authors claimed that this centerline can be generated within minutes on a Sun Ultra 10 workstation for a dataset of approximately 100K triangles, the performance on recent datasets of more than a million triangles per dataset remains unclear.

Finally, 3D Slicer includes a free navigation mode. While the authors described similar difficulties of freely navigating through a model as with the FreeFlight system, they proposed to use a 3D gyro structure to aid the user for accurate navigation[66]. Furthermore, they provided an endoscope local reference frame that also improves the handling of the virtual camera. Collision avoidance was implemented by measuring the distance from the current viewpoint in view direction to the surface. If the user-specified threshold is reached, the appropriate reaction is calculated.

Overall, 3D Slicer provides a surface-based rendering model with a performance that completely depends on the polygonal complexity of the model and on the rendering capabilities of the employed graphics hardware. The adopted free navigation approach only eases the problems of free navigation. The used 3D gyro and the local reference frame still appear to be more cumbersome than the submarine model utilized by VICON[48] or VIVENDI[16].

5. Applications of Virtual Endoscopy

In Section 3, we briefly outlined various applications of virtual endoscopy. In this section, we will take a short tour into these applications. Interested readers are directed to the respective Eurographics State-of-the-arts report[12], Rogalla's book on applications of virtual endoscopy[76], or to the respective original papers.

Most applications focus on planning aspects for minimally invasive procedures, while others focus on diagnosis, teaching, or training. In this section, we will look only into systems for diagnosis and planning.

Among the oldest applications of virtual endoscopy is virtual colonoscopy[86, 47, 77, 48, 52, 5]. It aims at being a diagnostic tool to identify and locate polyps. If a sufficiently large polyp is found, an optical colonoscopy becomes necessary to remove it. If, however, no polyp is found, no other procedure is necessary. The value of virtual colonoscopy as a planning tool is limited. While it generates quite accurate information on the relative location of the polyp within the colon, the highly mobile organ systems of the abdomen is changing the absolute position and the shape of the colon significantly.

Virtual bronchoscopy has already shown that it cannot significantly improve the detection of tumors[74, 76, 15], so its value as a diagnostic tool[64, 87, 35 84, 73] is limited. However, it is an excellent tool for endo-bronchial visualization for various purposes, ie., the distribution of inhalation drugs[26], for possible resection planning[15, 57], and planning of a trans-bronchial biopsy[93, 46].

In virtual ventriculoscopy, the ventricular system of the brain is examined. While it can be used for diagnostics[2],

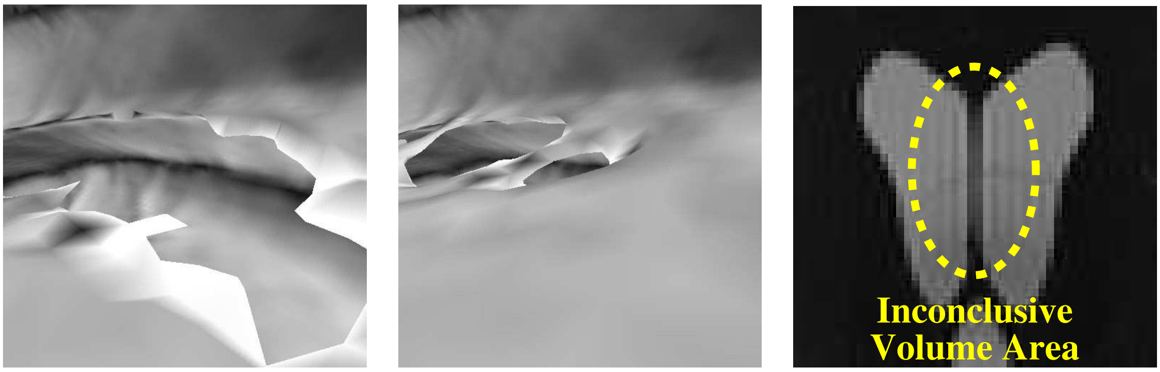

Figure 1: *Hole of different sizes in ventricular septum (of the brain); isovalue in (a) is lower than in (b). (c) shows a magnified slice from the original volumetric data of that area.*

its actual value is in planning a complex endoscopic intervention[17, 18, 13]. For this purpose, the visualization of risk structures (usually arterial blood vessels) is important to reduce the risk of a serious complication[18]. If virtual endoscopy is combined with optical endoscopy using an image-guided surgery system[13, 36], it can also be used for intra-operative navigation.

Another popular application field for virtual endoscopy are examinations of the vascular system, like cerebral arteries[20, 19], the Aorta[29], other arteries[41], or of the heart[14, 10]. Here the main purpose of these applications is diagnosis (ie., assessment of an occlusion or stenosis) or the planning of minimally invasive intervention (ie., coiling of an aneurysm or placing of a stent).

A more recent application has been presented by Neubauer et al., where virtual endoscopy is used as a tool to plan a complex endoscopic procedure to remove pituitary tumors[68] and to consequently reduce the risk of serious complications.

Other applications include the cavities around the nose, the paranasal sinus[97, 75, 79], where virtual endoscopy is used as a planning tool for minimally invasive surgery.

6. Discussion of Virtual Endoscopy

The different objectives of the virtual endoscopy applications impose specific requirements on the virtual endoscopy system. An educational objective focuses more on the visual quality that demonstrates the general topological and geometric aspects of the specific patient anatomy. In contrast, the accuracy of fine details is only of limited importance, if the details are not the subject of the examination. However, this is different for a clinical objective where the accurate rendering is one of the major factors that determine the usability, where an incorrectly represented blood vessel connection might have a fatal impact on the medical intervention. If virtual endoscopy is used for planning an intervention, it is important that relevant anatomical structures are represented appropriately, since otherwise the planned access path (ie., in virtual ventriculoscopy) might be occluded in the "real world" anatomy. Similarly, the visual representation must be highly accurate and up-to-date for intra-operative navigation to provide usable information to the surgeon.

There are several sources of errors that can lead to an inaccurate visual representation of anatomical structures in virtual endoscopy. Most notorious are partial volume effects and undersampling which generate false connections between the various caverns that are actually not connected, or holes in connected structures. Furthermore, motion artifacts can reduce the visual quality severely or distort the actual anatomical geometry. These artifacts are generated by movement of the patient during a (long) medical scanning procedure. Another example is scanning of fast moving body parts, ie., the valves of the heart, which still cannot be traced properly by modern volumetric scanners.

Even if these effects do not reduce the accuracy of the volumetric representation, the quality of the visualization depends heavily on the quality of the segmentation process. Isovalues that are not selected with sufficient particularity lead to holes in surfaces, if the isovalue is too low, and vice versa. In Figure 1, the hole in the ventricular septum between the two lateral ventricles varies in size, depending on the isovalue. However, the question of which isovalue is correct is not easy to answer in this case, because the volume data in that area is inconclusive (Fig. 1c); due to partial volume effects, the exact size of the hole is not clear. In Bartz[11], I provide a more detailed discussion of the various sources of artifacts.

Besides visual quality, interactivity is a major issue for virtual endoscopy. A rendering speed significantly below interactive rendering (10 fps) is usually not well accepted in the medical community. If virtual endoscopy is used for intra-operative navigation, no measurable rendering lag is acceptable. The virtual endoscopy system must deliver real-time rendering performance to represent the geometry of the current view of the endoscope immediately with every movement of the endoscope. These requirements are usually not met with most virtual endoscopy systems. Even the VIVENDI system does not provide sufficient performance for all applications; virtual angioscopy of the heart allows only a few frames per second. The widely visible inner geometry of the left and right ventricles of the heart allows only a culling rate of 80%, which still leaves a high polygonal complexity for rendering. For all other applications, however, VIVENDI meets the requirements for interactive exploration and in particular for intra-operative real-time navigation of ventricular MRI datasets.

Virtual Endoscopy versus Optical Endoscopy

The more general question of whether virtual endoscopy provides more scientific or medical insights, more patient safety or comfort, or an economic benefit is more difficult to answer. As for most scientific problems, the answer depends on the actual goal of the procedure, the qualities of alternative medical procedures, and various costs of the procedures.

In all procedures that require a histological examination of a tissue sample with a microscope, virtual endoscopy is not able to compete. The data resolution of modern 3D scanners does not reach anywhere close to the resolution of a microscope, although it is already in a sub-millimeter range for rotational angiography. Furthermore, texture information, such as structure, color, and reflections is also not captured by 3D medical scanners. All applications that heavily depend on this information will not succeed with virtual endoscopy. Similarly, if the medical procedure includes the removal of tissue (ie., lesions or tumors), or other objects, invasive or minimally invasive procedures cannot be replaced by virtual endoscopy, since it does not interact with the actual body of a patient.

However, if the relevant information can be represented as geometric shape (ie., a polyp of virtual colonoscopy), virtual endoscopy can be used for diagnostic purposes. Furthermore, it provides insights into body parts that might not be accessible to current medical procedures. The virtual representation based on scanner data enables access to virtually all scan-able body parts. Physical limitations of optical endoscopes – ie., the limited flexibility and navigation of the endoscope used for ventriculoscopy, the insuperable obstruction of folds in a colon for optical colonoscopy – are not shared with virtual endoscopes. Similarly, virtual endoscopes do not share the frequent unpleasantness of optical endoscopes. The patient interaction is limited to the scanning procedure, and is therefore providing much more patient comfort and acceptance. In addition, data acquisition and the actual virtual procedure are not necessarily at the same location. This geographical decoupling allows tele-medical procedures, which are not possible with optical endoscopy, where data acquisition and procedure are inseparably combined.

From an economic point of view, virtual endoscopy does produce fewer costs than the optical or conventional counterpart, since usually no sedation, patient preparation, or even hospitalization is required. This, however, is somewhat different for virtual colonoscopy that usually requires at least partially patient preparation. The necessary computational expenses can be seen as additional post-processing of the volume reconstruction of the scanner. However, procedures, which combine virtual and optical methods, ie., ventriculoscopy, do not benefit from these costs; the goal of this combination is to reduce the risk of complications and to increase the success of the intervention.

A study on the accuracy of virtual colonoscopy compared to conventional colonoscopy has been presented by Fenlon et al.[34] The authors found that the performance of virtual colonoscopy (based on CT data) is comparable to optical colonoscopy, as long as the data resolution is sufficient to detect polyps of the respective size. Only polyps with a size close to the sampling rate were not detectable as easy as larger ones. Problems arose also from residual stool, which often was the cause of a false positive finding. A more recent study by Pickhardt et al.[72] essentially confirmed the results (also based on CT data), but stated a better performance of virtual colonoscopy compared to optical colonoscopy. Reasons for this observation were an "unblinding", where the colonoscopist was informed on the results of the virtual colonoscopy, in particular to confirm if polyps only found in virtual colonoscopy were indeed polyps. Only for small polyps (closer to the sampling rate), optical colonoscopy had a slight advantage.

The authors also explained[72] their significantly better results compared to previous studies. Essentially, many studies (not the one by Fenlon et al.[34]) used virtual colonoscopy not in 3D, but only by inspecting 2D slice images and with a larger slice distance (space between two axial slices), resulting in much less axial resolution, and of course a much worse representation of the colonic interior. Another reason for the reduced false positive polyp detection in virtual colonoscopy was the use of digital tagging and fluid removal methods[53]. Also, there is a significant difference in quality depending what virtual colonoscopy tool is utilized. Pickhardt et al.[71] compared the results of the GE Navigator, the Vital Images Vitrea2, and of the Viatronix V3D Colon system and observed that the latter system had by far the best results, while Vitrea2 had the poorest performance.

An interesting observation is however, that none of the mentioned studies used a digital biopsy for analyzing the polyp tissue. This basically confirms my statement that there is usually not enough resolution in the scans to generate sufficiently meaningful information compared to a histological examination.

Future Trends for Virtual Endoscopy

As described in Section 5, virtual endoscopy has been applied to different parts of the human body (and even other biological structures[49]). The typical goal of these applications was either diagnosis, anatomical teaching, or planning for complex interventions.

Future challenges of virtual endoscopic applications lie in the integration into the actual surgical intervention as navigation aid[62, 13, 30, 46]. Of particular importance will be the integration of intra-operative imaging modalities, such as ultrasound, endoscopic laser scanners, full-field MRI, x-ray scanners, and many more to provide an up-to-date view on the current situation of the various organs.

7. Conclusions

In this report, I have discussed several virtual endoscopy systems that are used in research and clinical environments. These systems address different objectives and are using henceforth different rendering techniques and adopt different camera navigation paradigms.

I also presented several applications of virtual endoscopy in the clinical practice. While some of these applications aim at support for "traditional" interventions, some try to replace their real world counterpart, ie., colonoscopy. However, it still remains to be shown in most applications that virtual endoscopy actually provides an added value. This however, holds for most advanced medical imaging techniques.

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