Benefits of 3D Immersion for Virtual Colonoscopy

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ABSTRACT

Virtual Colonoscopy (VC) is a non-invasive clinical procedure that detects colon cancer in humans. VC seeks to supplement and improve the compliance rates for diagnosed patients, since the traditional optical colonoscopy is more painful, and less effective for cancer detection. In this paper, we discuss the benefits of using a 3D immersive user interface for VC. We discuss various design choices that we can make for such a design, leveraging the effects of the various combinations of virtual reality (VR) system components, as in previous VR empirical studies.

Keywords: Immersion, Virtual Reality, 3D Visualization, Virtual Colonoscopy, 3D Interaction, System Fidelity, Display Fidelity.

1. INTRODUCTION

3D scanning is extensively used in many scientific disciplines. Volume scanning techniques (CT, MRI, PET, and point cloud scanners) are employed for generating scientific datasets. These datasets are visualized by volume rendering and/or mesh rendering for purposes such as clinical diagnosis or geodesic analysis.

The main challenge in scientific visualization (especially medical imaging) is how to efficiently, but comprehensively, visualize all interesting features. We believe that currently used 2D displays have significant limitations for this purpose. This is because 2D displays only show a 2D projection of a 3D scene omitting 3D structures and depth cues. 2D projection doesn't allow us to see the parts of the dataset away from our direct view. The missing information can sometimes be critical for understanding valuable shape cues (e.g. curvature), leading to delays or misinterpretations.

These datasets contain large surface area and volume but few regions of interest. These regions of interest in the patients' body have landmarks of small size, which may turn into lesions. In medical imaging, by using dataset specific medial applications, doctors want to locate said landmarks and analyze their spatial relations. This may require real 3D visualization rather than a projection of an axis [3].

The merging of an Immersive Visualization Environment (IVE) with Virtual Colonoscopy (VC) aims to expand the doctors' viewing range while offering higher quality navigation. Specifically, doctors would be able to view the left, right, and even the rear view of the scene dataset more easily. We believe that this will lead to tracking more polyps, with a higher certainty, and more quickly than on a non-immersive 2D desktop.

Recent studies have found benefits of immersion in analyzing scientific datasets [12]. Immersive VR platforms provide a large virtual space, which can unclutter the dense visualization of cleansed colonoscopy data [14]. Navigation and 3D manipulation in the immersive environment merges the display and the interaction space. This improves the situational awareness [1] of doctors, leading to better spatial understanding. In this paper, we discuss ways to employ immersive VR for Virtual Colonoscopy.

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2. RELATED WORK

3D VC [10] is a non-invasive medical imaging technique, in which the CT scans of the lower abdomen of a patient are obtained and visualized. A computer system allows visualization and navigation through the colon of the patient, with visualization quality similar to that of endoscopy. Kay et al. [11] provide a nice comparison between VC and traditional endoscopy.

In recent years, research in VC has focused on real-time volume rendering of colon [25], and improving navigation and automatic detection of important features in colon, while assisting traditional optical colonoscopy [17]. For navigation, different techniques for centerline extraction have been proposed, including both automatic [26] and interactive [6] methods. More recently, Mikula et al. [19] used a curve evolution method to generate proper camera paths.

Many researchers have explored the effects of immersive environments on the analysis of scientific data visualization. Zhang et al. [28] did some early investigation on the effects of analyzing diffusion tensor magnetic resonance imaging (DT-MRI) datasets in an immersive environment. More recently, Laha et al. [13, 14] reported on the empirical effects of analyzing volume visualization of medical, paleontological, and biomechanics data in immersive environments. Recently, researchers ran some initial experiments exploring the benefits of partially immersive virtual colonoscopy [21].

In this paper, we posit that the components of an immersive system, and 3D spatial interaction [12] will produce significant benefits for critical tasks related to colon cancer screening in virtual colonoscopy. We support our argument using empirical results from prior VR experiments and visualization research related to VC.

3. VIRTUAL COLONOSCOPY

Virtual Colonoscopy (VC) employs CT scans to generate visualizations and a virtual interior navigation of the human colon. It is a popular medical imaging application, which in most cases is a possible replacement for traditional optical colonoscopy. VC greatly reduces the pain of the patients while improving the efficiency of the diagnosis. The external CT or MRI scan is far less intrusive while offering visual quality comparable to optical colonoscopy.

The first step of VC is volume data cleansing [15]. This removes water and food inside the colon, and cleans the interior of the colon. Several volume rendering methods can be applied on the cleansed volume to generate a smooth and high quality visualization mimicking real endoscopy.

Finally, the pipeline extracts the centerline inside the colon. The system uses this centerline for virtual navigation. This is regarded as a reasonable path for doctors to travel virtually through the colon to detect potential polyps, which are precursors to cancer.

Aside from visual polyp detection, several automatic techniques have been proposed. One of them is conformally mapping the volume onto a 2D surface and detecting 2D features [9].

3.1. Conformal Mapping for Virtual Colonoscopy

Conformal mapping [7] is a mathematical function, which preserves shapes (i.e. local angles of intersection) of input. It can be seen as a function f:

$$f: U \rightarrow V$$

Here U and V are in multi-dimensional domain. The shape preservation feature of conformal mapping becomes useful in many applications of computer science, such as, medical imaging [25, 26], computer graphics [6], computer vision [19], and wireless networks [21].

In VC, area preservation through conformal mapping can help the doctors in viewing the complex 3D shapes in a simplistic 2D view, which improves the efficiency in potential polyp detection [26].

After mapping the 3D volume onto a 2D graph [8], the pipeline detects special landmarks as potential polyps because they have difference in geometric features, both in 2D and 3D. Such automatic pipeline can reduce the workload of doctors and improve the accuracy of their diagnoses by reducing the number of false positives in polyp detection.

The procedure of mapping the colon wall surface to a planar domain (e.g. rectangle) is called *colon flattening*. This can be crucial for many VC applications as it can offer a global view of colon surface, while revealing the details on the wall surface including the hidden areas at once. Any mapping between this 3D surface and a planar domain would introduce some distortion such as topological noises and general changes in shapes. Recent work on virtual colon flattening using conformal mapping has created algorithms that are robust with respect to topological noises and preserves shapes locally [8, 9].

Due to gravity, the shape of the colon may change, based on the patient's orientation. Also, there are differences between supine and prone scans of a patient's colon. A registration between these two models shows the areas that are hidden in either one, and allows the viewer to find a point in both colon models. Zeng et al. introduced a pipeline using quasi-conformal mapping to register the surface mesh of both supine and prone models [27]. This pipeline contains five steps, beginning with extracting anatomical landmarks, used to cut a colon into five different segments. Next, each segment of the colon is conformally mapped to a 2D rectangle. Following that, the feature points are detected which are then used in the fourth step to find the matching points between the two models. Finally, these matched-points are used as constraints to generate a quasi-conformal mapping.

3.2. Interfaces for Virtual Colonoscopy

Figure 1 shows a 3D visualization of the interior of the colon. The user can fly through the colon centerline, shown in green. A full analysis takes about nine minutes, consisting of two fly-through animations: one from the rectum to the cecum, and then a second one, the opposite way. The areas seen during the first fly-through are marked in green, which allows the user to focus on the unmarked area during the second fly through. This method seeks to ensure a full coverage of the whole area of the colon for cancer screening.

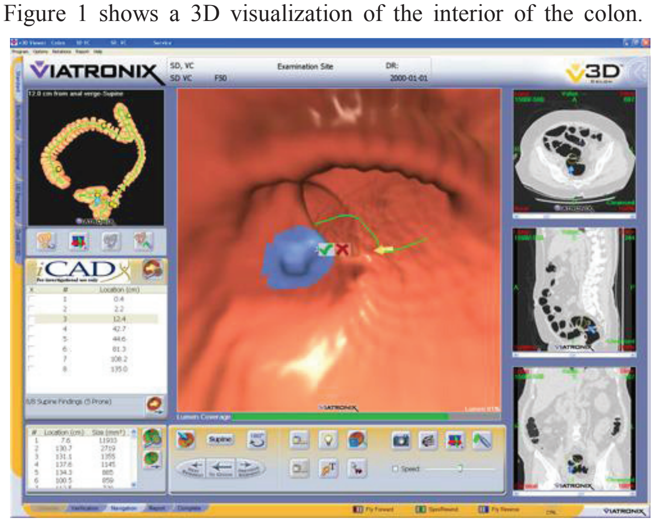


Figure 1: A 3D interface for virtual colonoscopy.

2D visualization of CT slices along three orthogonal directions is also shown – these slices are updated as the user flies through the interior of the colon, showing the position of bookmarks and the camera in the slices from CT scan. The interface also offers a variety of tools to further assist the user with exploring and measuring sections in the interior of the colon. A virtual ruler acts as a measurement tool that can be used to examine the length of patches on the colon's surface, to get a better understanding of the size of the polyps. A bookmarking tool is offered by the interface to mark any interesting patches and possible polyps in the colon. The user is able to assign notes about their position, location, and medical importance to the bookmarks.

The density of the tissues behind the surface of the colon is important because it could indicate irregularities like cancer cells. Usually a polyp contains an irregular distribution of high-density tissue. This density can be visualized by a translucent ray casting, which can help doctors in evaluating the density of each polyp and the distribution of the high-density tissue behind the polyps. This is termed *electronic biopsy* and is provided as a tool.

The geometric shape of the surface has been shown to be a very useful clue for detecting polyps, to the point that computer-aided polyp detection tools were developed around it [24]. Hong et al. introduced a fully automated pipeline for polyp detection that uses electronic biopsy in addition to shape parameters [9]. This framework first flattens the colon using shape-preserving conformal mapping. Then tissue density behind the colon is visualized using translucent volume ray casting. In the third step, a clustering algorithm is executed to find clusters of high-density tissue that would indicate polyps – any cluster smaller than five millimeters is automatically rejected because of low medical importance. Finally, false positives are reduced through shape analysis and by evaluating the curvature of each polyp. The final polyps are visualized upon the flattened colon and can also be bookmarked along the colon's surface as shown in Figure 2.

4. IMMERSIVE VIRTUAL REALITY

We define *Virtual Reality* (VR) as a 3D interactive and immersive computer generated environment [22]. The objective level of *immersion* produced by a VR system is different from the

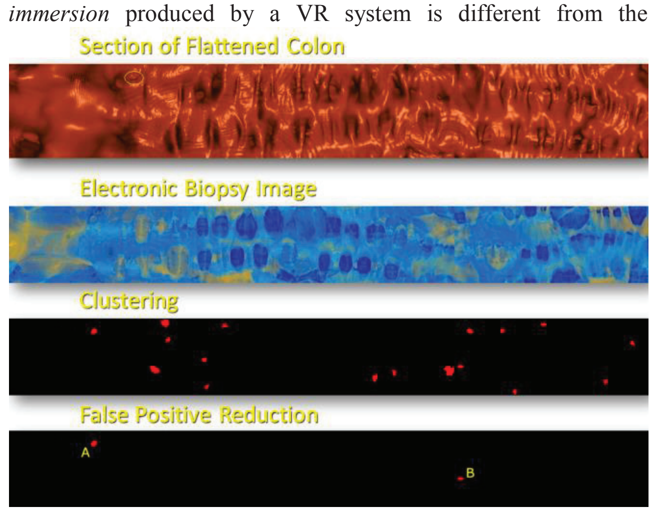
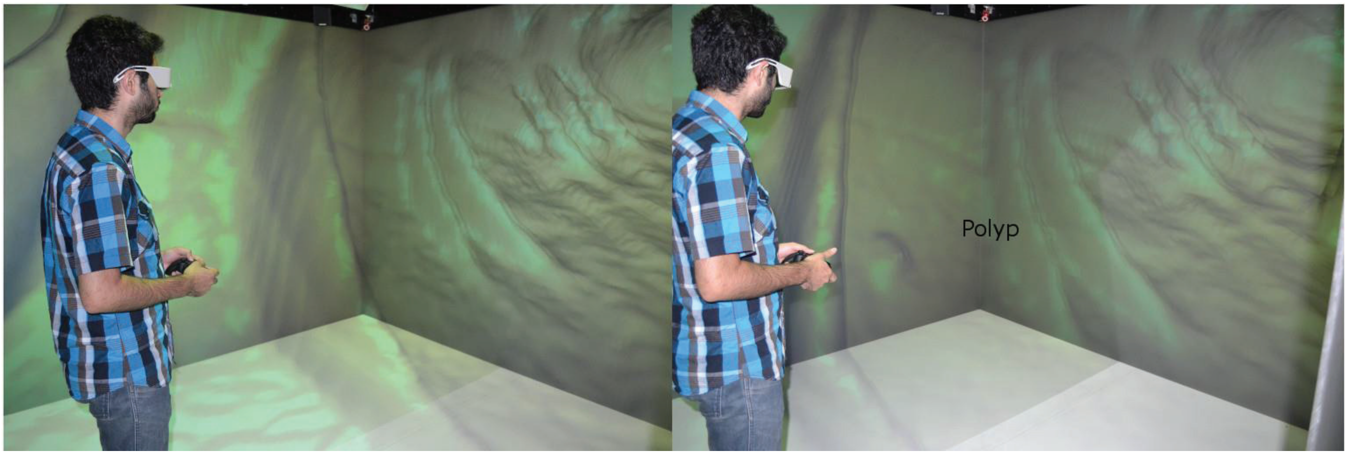


Figure 2: Pipeline of Computer Aided Polyp Detection



(a) A participant navigating through a virtual colon, looking for polyps; (b) He finds a polyp on the lower part of the left wall in the CAVE.
Figure 3: The Immersive Virtual Colonoscopy user interface.

subjective feeling of *presence* felt by users of the system [23]. A VR system consists of many sensory components (visual, auditory, olfactory, haptic, etc.), at different levels of fidelity, which produce the effect of immersion produced by the whole VR system [4]. The visual components of a VR system may include field of regard (the amount of virtual world surrounding the user), field of view (the instantaneous visual field seen by the user), stereoscopy, head tracking, resolution, display size, etc.

4.1. Effects of System Fidelity on Virtual Colonoscopy

Most immersive VR systems, such as CAVEs [5], offers a high field of regard, which can increase the virtual real-estate available to the user, during a fly-through animation. We can adjust the speed of a typical fly-through to allow the user to turn their head and look around to review the surrounding virtual area. During a colon fly-through, this may allow observing the complete surrounding wall, even behind large folds (see Figure 3). The high field of regard will enable the user to rotate their head and observe the hidden and covered areas without losing the context of the visualization. This may significantly improve the speed of completion of Virtual Colonoscopy by enabling the user to cover the entire surface of the colon with only one fly-through. The overall time of one fly-through may increase because this solution might reduce the time required for Virtual Colonoscopy by a factor of two.

The Virtual Colonoscopy scan data uses regular CT scans as input. It requires volume or mesh rendering for the purpose of visualization. The data at such scales is suitable for visualization via CAVE or other regular VR devices in terms of complexity and accuracy.

Static depth cues from stereo combined with motion parallax from head tracking can offer a high degree of depth perception, which may play an important role in detecting curvature changes and bumps on the surface of the colon. These can help improve user accuracy in shape evaluation, as prior empirical studies evaluating the effects of VR system fidelity on isosurfaces have found [13]. Since the current Virtual Colonoscopy pipeline has no quantized way of describing the shape and curvature of polyps, users must rely on their own sense of depth perception and visual cues (e.g. shadows) to extract this information. We see a significant benefit in using an immersive environment for this purpose.

A spatially immersive environment collocates the user in the same space as the data that they are analyzing. This allows leveraging physical body movements, navigation, and spatial cues leading to a natural way to explore areas of interest. For example, a user can explore areas hidden behind the ridges of the colon by simply walking around it or just turning their head in the right direction, as opposed to a traditional Virtual Colonoscopy interface, where they will need to rely on cumbersome mouse clicks and drag actions to achieve the same result. This offers an easier way of observing the whole colon area and having a closer look at surfaces of interest without losing the context or position inside the colon. It also enables users to evaluate the same patch from different angles without any need to manipulate the virtual camera, which could be very time consuming.

It is important to mention here that due to the increased sense of presence in VR environments, some users may experience motion sickness or cyber sickness, and nausea. VR empirical studies have linked cyber sickness to latency [18], field of regard [16], etc. and other components of system fidelity. We believe careful design considerations of virtual environments and the corresponding user interfaces (such as automatic, semi-automatic or user-guided fly-through) can mitigate such problems significantly. Removing rotational movement from virtual camera movement might decrease motion sickness caused by VR environments.

Meanwhile, the idea of immersive Virtual Colonoscopy is also plausible for use in other regular VR devices (e.g. Oculus Rift). Those low cost portable devices could bring the benefits of VR to remote locations but at a lower resolution.

4.2. Interfaces for Immersive Virtual Colonoscopy

Past research exploring bimanual interaction for camera control and a target selection task found that a bimanual interface could be 20% faster than an unimanual interface [2]. Bimanual gestures allow using our hands as a selection tool for measurement and bookmarking inside the colon. Further, immersive VR can offer a one-to-one mapping between physical space inside an IVR environment, and the space inside a colon. Previous research has shown benefits of matching visual feedback with kinesthetic frames of reference [1]. Merging the visual and interaction frames might make the selection task more natural and accurate, and may improve user accuracy in interacting with colon surface and measurement tasks. A similar technique can be used to select an area for the electronic biopsy and all other tools that require an interaction with the colon's surface.

Head orientation can be a strong predictor of user's gaze direction, according to Kai and Rainer [20]. We can thus use head tracking to mark out areas covered by the user so that in the second fly through, if necessary, the user can focus on the remaining parts, highlighted by visual or audio feedback. Gaze tracking can be used in combination with head-tracking to increase the accuracy of this procedure.

A tablet device, in addition to an IVR Enviroment, can be used to show the user position globally in the colon and also show the 2D visualization of CT slices. This can be used to improve user understanding about their exact position in the virtual environment, thus providing a valuable context for user navigation, and identifying polyp locations inside the colon. Additionally, it can also offer an interface for fast movement inside the VR environment, such as for jumping to points of interest or to bookmarks, which can improve the speed in navigation tasks, especially when reviewing a previously visited surface.

Results from computer-aided polyp detection can be overlaid on top of current visualization, to improve predictability in polyp detection. This can be done by overlaying glyphs or color marks over their positions, regardless of whether they are hidden behind a wall or not. All possible polyps that are closer than a certain threshold can have their position overlaid as glyphs onto the current visualization, which can ensure that there are no false negatives. In immersive VR environments, doctors will be able to detect polys more precisely because polyps can be visualized in 100% view angles rather than the 75% prevalent in current 3D VC. Moreover, textual information and measurements from previous observations or CAD software can be overlaid in the glyphs. For example, information such as size, maximum density, or medical importance of a polyp can be overlaid on it using a glyph and color maps, which would reduce the interaction required by the user to explore this information, and also ensure that the user will observe this information.

As mentioned before, registering both supine and prone CT scans generates the volume used in virtual colonoscopy. Due to gravity, there could be differences between these two scans. Colon movement between these scans can show the softness of colon tissue, which can also be viewed through color mapping. This can give a better understanding of tissue structure and increase the accuracy of the procedure, while also reducing both false positives and negatives.

Petkov et al. introduced a framework [21] to conformally map a full surrounding view of the colon to the displays of a given visualization system (e.g. four sided cave). This mapping preserves the shapes for polyps, and can effectively optimize and improve the speed of the virtual colonoscopy, as the user can cover the entire colon at a higher speed, limited only by her visual scanning speed. However, this mapping would create some distortion in the final image, which could cause motion sickness and also interfere with the user's understanding of the colon.

Conformal mapping also removes the distortion at the edges, when the visualization is done in an immersive environment [21]. For example, in an CAVE environment [5], due to the 90° gap between any two screens, the shape may look deformed. But, conformal mapping preserves the shape even at those edges–the visualization looks natural and keeps the shape undistorted.

Amplified camera rotations through head tracking can be used to rotate the scene, to facilitate visual scanning by the user. This can produce quicker and comprehensive horizontal coverage of the colon surface, when navigating virtually inside the colon. Such cameras can give doctors better and natural controlling experience because they do not have to press buttons in gamepads or keyboards when visualizing and detecting polyps. We can customize the amplification factor for each user, as this can potentially cause some discomfort and nausea, but may vary between users.

The UI would differ in other VR environment because portable devices may not be suitable for large deformation controller like joints tracking.

5. Conclusion

We provided a detailed background on virtual colonoscopy, and on the current state-of-the-art user interfaces, associated with it. We then discussed a variety of choices that we can make in designing an immersive VR interface for cancer screening in virtual colonoscopy. We discussed the choices in the light of existing empirical findings on the effects of VR system fidelity and 3D interaction techniques on human task performance for volume data analysis. We believe that a carefully designed immersive VR system and user interface has the potential to significantly improve cancer screening in VC by improving the accuracy, or the speed of polyp detection, or some combination thereof.

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