

A Geometric and Textural Model of the Colon as Ground Truth for Deep-Learning Based 3D-Reconstruction

Ralf Hackner¹, Sina Walluscheck^{1,2}, Edgar Lehmann³, Thomas Eixelberger¹,
Volker Bruns¹, Thomas Wittenberg^{1,2}

¹Fraunhofer Institute for Integrated Circuits IIS, Erlangen

²Chair for Visual Computing, FAU Erlangen-Nürnberg

³E&L Medical Systems, Erlangen

`ralf.hackner@iis.fraunhofer.de`

Abstract. For endoscopic examinations of the large intestine, the limited field of vision related to the keyhole view of the endoscope can be a problem. A panoramic view of the video images acquired during a colonoscopy can potentially enlarge the field of view in real-time and may ensure that the performing physician has examined the entire organ. To train and test such a panorama-generation system, endoscopic video sequences with information about the geometry are necessary, but rarely exist. Therefore, we created a virtual phantom of the colon with a 3D-modelling software and propose different methods for realistic-looking textures. This allows us to perform a “virtual colonoscopy” and provide a well-defined test environment as well as supplement our training data for deep learning.

1 Introduction

One challenge in diagnostic colonoscopy being the endoscopic examination of the lower GI-tract (consisting of the rectum and the colon) is the limited ‘field-of-view’ of the colonoscope, also known as ‘keyhole view’. During a colonoscopic examination, the flexible video-endoscope is advanced and navigated through the anus up the rectum, then the sigmoid-, descending-, transverse- and ascending colon, the cecum, and finally to the terminal cecum, and ultimately the terminal ileum (see Fig. 1). During this insertion process, the endoscopist usually does not look for details on the colon walls, but rather concentrates on the fluent and painless insertion of the colonoscope into the lumen up to the terminal ilium.

The visual examination takes place in a second step, when the endoscope is slowly withdrawn through ascending, transverse, descending and sigmoid colon. During the withdrawal, the physician turns and bends the tip of the colonoscope for a closer examination of the colonoscopic tissue looking for possible adenomas. Even though in the past two decades, technological improvements in the field of endoscopic imaging have been proposed, such as HD, near-focus, wide-angle, or

magnifying endoscopes, the limitations of the ‘keyhole view’ still remain. Thus, the endoscopist never perceives a complete view of the colon wall and must fuse the already seen scenes together in his/her mind in order to obtain a complete, so-called ‘texture map’ or ‘image panorama’ of the colon. This subjective ‘visual impression’ and the corresponding diagnostic findings are later transcribed textually in the clinical documentation or recited from memory in interdisciplinary conferences and councils.

1.1 Panorama Endoscopy

The image-based documentation of the lower GI tract is currently limited to short videos (needing time for replay and viewing) or single images of observed lesions (usually not depicting the anatomical context). The mentioned “fused image information” of the physician is only available in his/ her mind and can hence not be used for documentation, interdisciplinary discussions or education.

In order to compensate the ‘key-hole’ effect during a colonoscopic examination, a mapping of the colon wall is desirable. Using the urinary bladder as an example of a hollow organ to be assessed with an endoscope, it has recently been shown, that it is possible to provide a so-called ‘panorama’ or ‘map’ of the bladder directly during the examination in real time [1,2], which can afterwards be used for an image-based documentation. For the computation of real time panoramic images of the colon hardly any work is known. E.g, for the stomach Liu et al. [3] have proposed an approach using electromagnetic tracker mounted at the endoscope tip. Ali [2] suggested the computation of a panorama around the pyloric antrum using optical flow between successive image frames for tracking. Approaches to do an offline reconstruction of the geometry, what can be seen as closely related problem have been done by Widya et al. [4] and Freedman et al. [5].

1.2 Objective

As the colon—in contrast to the bladder—is an organ with a much more complex (partially tubular, partially flat, partially hemisphere) and dynamic geometry, a mapping of the colon wall is related to the use of 3D-reconstruction methods such as real-time panorama mapping pipelines (SLAM, PTAM) and “Structure from Motion” (SfM) or “visual odometry”, making use of simultaneous localization and mapping of the hollow based on monocular views of the hollow. Nevertheless, for the development and extensive evaluation of such 3D-reconstruction from monocular colonoscopic image sequences, a known ground truth of the colon geometry is required. Thus, in this work, we propose the definition and application of a textured 3D phantom of the colon, in which random images with known geometry, controllable illumination, predefined textures, and even flat and sessile adenomas can be rendered as objective ground truth for 3D-reconstruction experiments.

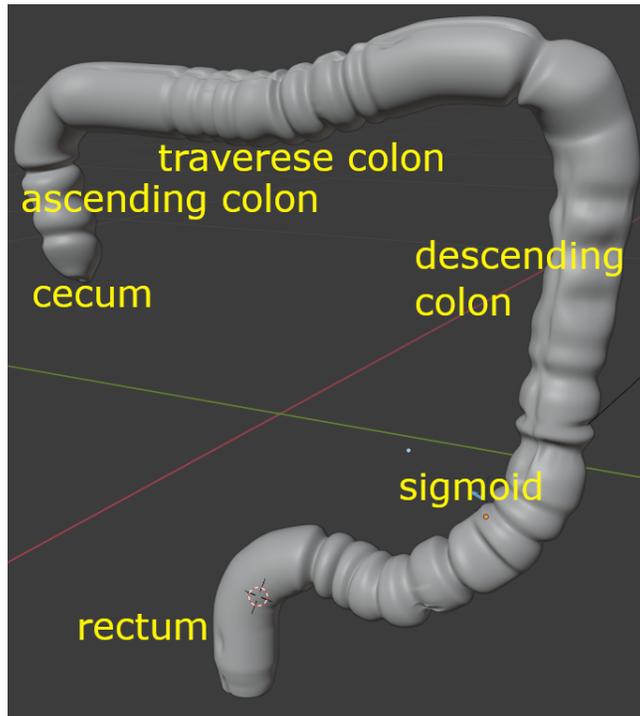


Fig. 1. geometry of the colon model.

2 Materials and methods

To model our phantom, we used the open-source 3D-modelling software *Blender*. As reference for the texture appearance we used colonoscopic video sequences from Malteser Waldkrankenhaus St. Marien, Erlangen.

The model was formed based on typical sizes [6] of a large intestine. An overview is given in Fig. 1. The average diameter is 5 centimeters, widening up to 7 cm in the cecum. The appendix is not modelled. The entire model has a total length of 1.5 m. Characteristic structures as haustra and taeniae were modelled manually.

2.1 Model Texture

The mucosa of the gastrointestinal wall is a complex structure of many tissue layers with different optical characteristics. Even a photorealistic rendering of ordinary skin is a complex task. In case of the colon mucosa, additional structures such as the intestinal villi create rough, light-scattering surface. Furthermore, the entire surface is coated by a thin layer of mucus.

We identified two primary components to mimic a surface, which is close to reality and especially contains all visual aspects expected to be important

as features for the reconstruction of the structure from monocular views. A formative element of the mucosa are the vascular trees embedded in a widely ambient, slightly translucent, blood shaded surface. The second element is the mucus coating. This coat is glossy and typically causes specular highlights in endoscopic imaging, due to light source integrated in the device tip.

To create vessel-like structures, we evaluated two different approaches: The first approach was to use our existing panorama generation software “Endorama” [1] for cystoscopy to create a number of such panoramas of real human urinary bladders. The urinary bladder wall also contains similar vessel structures. We used a common image editing software to compose these panoramas to a texture patch of the size 279×4096 . Bladder specific elements like *trigone* and *orifice* were removed. The texture can be seamlessly concatenated at its longer corner to allow a smooth loop closing, when mapping the texture to a cylindrical structure. The texture is large enough to use it without repeating, so that there is a unique vessel structure at every surface location. Subsurface rendering is used to simulate the blood shading of the tissue between the vessels.

The second approach was to generate random vessel-like structures. Inspired by an existing approach [7], we used random Voronoi textures to create vessel-like structures. Two independent textures simulating bluish and red blood vessels are combined. Musgrave textures (an algorithm, originally designed for modelling landscapes [8]) are used to slightly scatter the surface normales for a more natural look.

To simulate the mucus layer, we used a glass BSDF shader with an index of refraction corresponding to water.

2.2 Colonoscope Tip, Light and Camera

A typical colonoscope is a flexible video endoscope with a diameter between 0.8 and 1.2 cm (E.g. common devices like Olympus GIF-HQ Series [9] or Fujifilm [10]). Integrated in the tip of the endoscope is a tiny video sensor with a small fish-eye lens. A typical field of view has 140 degrees. The primary light source is outside the endoscope and glass fibers bundles are used to transport the light to the endoscope tip. A common arrangement are two fiber bundles with a distance of 0.5 cm, whose outlets are placed on each side of the sensor or slightly above. Correspondingly, we modelled a “virtual endoscope tip”, using two point light sources with a power between 25 and 40 mW and placed them 0.25 cm aside of the virtual camera. The light sources are moved through the colon together with the camera. To create a realistic impression of an endoscope withdrawal, the camera is moved on a spiral-like manner through the virtual colon with different angles and varying speed.

3 Results

We rendered about 6000 single views based on our digital model with varying textures, camera positions, light intensity and shape variations of the colon. For

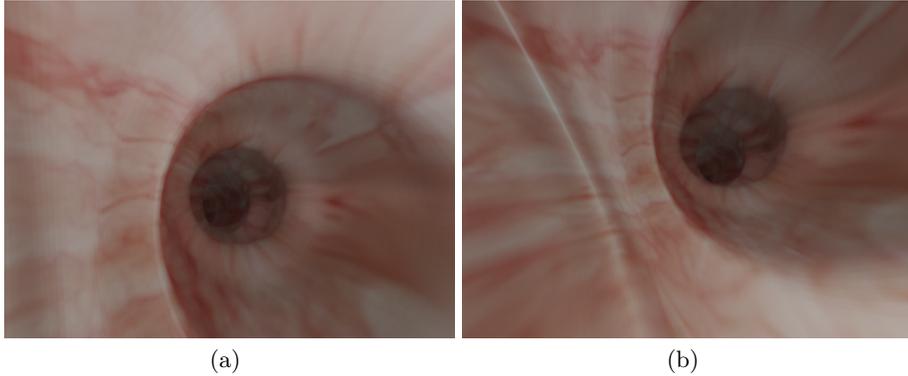


Fig. 2. Rendered images using the bladder-based texture.

every frame a corresponding depth map was generated. It contains the geometric information of the image, that can be used for purpose of training or testing a neural network. Some examples using a bladder-panorama texture can be seen in Fig. 2. Fig. 3 depicts the same frames featuring randomly generated Voronoi textures.

4 Discussion

The virtual phantom is designed for the training and testing of mosaicking applications, SLAMs and similar applications. These applications typically use surface patterns to register image tiles to each other in a correct way, where repeating patterns may lead to erroneous registrations. Thus, all patterns in both textures are strictly non-repeating as it is true for a real organ, either by using an image of sufficient size or random generated data. By providing different textures, we can also reduce the risk of an algorithm becoming too specific to the test data surface. Adding a glass shader to simulate the mucus coat created rather realistic highlights (for instance seen in Fig. 3(b)). For most image processing tasks

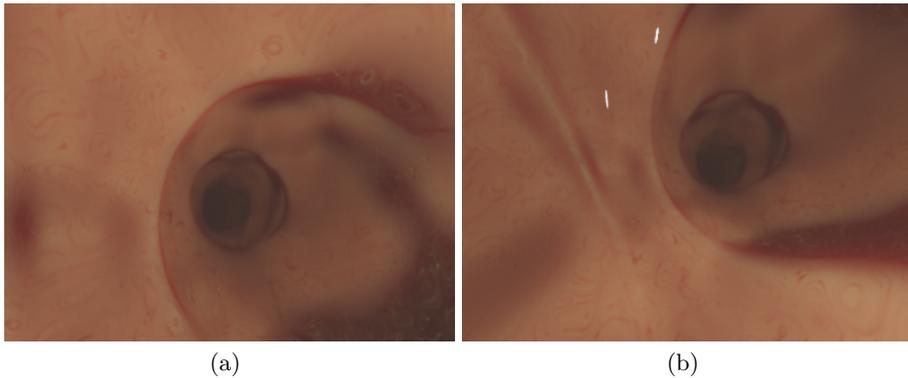


Fig. 3. Rendered images with random Voronoi textures (same positions as in Fig. 2).

these highlights are disruptive factors. For the application of depth estimation—that is a necessary step towards the geometry reconstruction—in contrast, these highlights might be useful information, since they indicate, that the surface normal is straight to the camera. The mapping between the panorama-based vessel texture is not perfect in all cases, sometimes leading to slightly stretched vessel structures (see Fig. 2(b), bottom left corner). This happens especially, when the geometry has been changed without performing a manual correction. A varying resolution for all mapped regions would be necessary to create a perfect match. The randomly generated Voronoi texture has an advantage here, since it always fits the real surface and has no predefined shape or size. Images of with both textures were shown to an expert endoscopist. He preferred the panorama-based texture, because he judged the shading in the random texture as too dominant. Both textures were considered to look slightly “wax-like”. It might be possible to reduce these flaws by fine-tuning some parameters of the shaders. When first panorama patches of the large intestine are available, it might be become possible to further improve the texture by using images of a real colon. On the long term, other fields of use might come into focus, like simulated, interactive training sessions for surgeons.

Acknowledgments Parts of the research has been funded by the Bavarian Research Society (BFS) under the project GastroMapper (AZ-1349-18).

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