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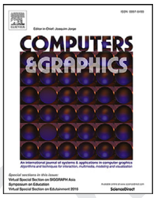

Technical Section

Improving spatial perception of vascular models using supporting anchors and illustrative visualization☆

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Incorrect spatial interpretation of 3D vascular models is a main perceptional problem in medical visualization. For improved depth perception, we propose supporting anchors between vascular trees and a cylindrical cutaway that serves as an insight for a virtual resection surface or a path for a tumor ablation. The supporting anchors are optimally arranged in a circular manner such that the depth can be perceived without time-consuming interaction. For improved shape perception and distance-encoding, we additionally employ a novel and fast hatching approach that produces results comparable to state-of-the-art techniques. The advantages of our new visualization approach are demonstrated using the example of laparoscopic liver surgery and confirmed in a quantitative user study with 81 participants. The results show that participants were able to assess relative distances more precisely and were most confident using our illustrative visualization approach.

1. Introduction

During medical interventions, it is often important to understand the morphology of vascular structures and its spatial relation to surrounding risk structures such as tumors. Therefore, high-quality vascular 3D models, reconstructed from computed tomography (CT), are applied using direct or indirect volume rendering techniques [1] and medical augmented reality visualization [2–4]. The vascular models often portray complex geometries and therefore demand cognitive effort and user interaction.

While the interaction with a 3D model (scaling, rotation, panning) can be easily integrated in surgery planning, such interaction is hard to perform during an intervention due to the constraints of a sterile room [5]. This is complicated by the fact that physicians often request a multilayer visualization to display different depth layers of an anatomical object, e.g., vascular structures and tumors underneath an organ surface, in which layers are rendered on top of each other. An effective multilayer visualization of the depth layers that represents the medical image data during an intervention is hampered by structures (vessels, organ surface, tumors, etc.) that occlude each other. Adding object transparency may aggravate the perception of relative depth distances between virtual 3D objects (layer clutter). Therefore, a visualization to support medical interventions should encode essential information as the location, spatiality, and distances to important anatomical structures in a clear and non-misleading way.

In this work, we introduce an illustrative visualization approach that faces the above-mentioned problems and aims to improve spatial perception for medical augmented reality visualization. We introduce *supporting anchors* that are based on *supporting lines* introduced by Lawonn et al. [6]. *Supporting lines* proved to be a strong depth cue in 3D vascular visualization. However, this approach cannot be applied to augmented reality visualization, as they used a floor to project their supporting lines onto, which entails a direction that is not given. Another disadvantage of their approach is that the lines were placed manually. To improve upon this method, we present an algorithm that automatically finds the optimal positions for the supporting anchors. In addition, we present a new hatching technique for complex vascular structures. Compared to state-of-the-art hatching approaches, the new technique enables lower memory usage and faster computation time, while showing comparable visualization results. In this work, the hatching technique is utilized to convey shape and encode the distance between vessels and tumors.

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The advantages of our approach were confirmed in a quantitative user study with 81 participants. Because Kersten-Oertel et al. [7] rated pseudo-chromadepth rendering as the best depth cue for vascular visualization, we compared our illustrative visualization technique with pseudo-chromadepth rendering [8], and Phong shading [9] without an explicit depth cue.

2. Related work

Incorrect spatial interpretation is the most common perceptual problem in augmented reality (AR) applications [10]. The need to assess spatial information from superimposed 3D models precisely during an intervention has led to the development of several techniques that improve spatial perception in AR.

2.1. Improving spatial perception for medical visualization

Stereoscopic vision improves the spatial assessment of computer-generated images [11–14]. Therefore, autostereoscopic monitors or head-mounted displays can be of great value in the operating room (OR). For many surgeons, additional hardware is cumbersome or difficult to use within the constraints of the OR [15]. In addition, the benefit of stereoscopic vision is task-dependent, and the results of Kersten-Oertel et al. [15] indicate that it does not provide effective spatial cues for the depth judgment of 3D vascular models.

Computer-generated monoscopic depth cues have been proposed to improve spatial perception. Kinetic depth, especially motion parallax, provides depth cues in many AR applications [16,17]. A virtual window was introduced by Sielhorst et al., which simulates a view of the patient's viscera [18]. The window plane is slightly textured to improve spatial perception through partial occlusion when using a tracked head-mounted display. Projection of guidance graphics, such as entry points and surgical plans, onto an organ surface while tracking the operator's head using projector-based AR has been proposed [19,20]. A disadvantage of kinetic depth is that the operator's head needs to be tracked. This leads to additional hardware in the OR, and forces operators to continuously move their head to improve the spatial impression.

Color coding can also be employed to encode depth and inter-object distance in AR. Ropinski et al. [8] introduced pseudo-chromadepth rendering as an enhancement of the chromadepth rendering, where the number of hues were reduced. According to a user study by Kersten-Oertel et al. [15], pseudo-chromadepth rendering allows for the best relative depth assessments for vascular structures. However, a recent study by Lawonn et al. [6] showed that illustrative rendering techniques could improve depth assessment results over pseudo-chromadepth rendering. In addition, multiple viewports are proposed as a method to improve the spatial perception for AR. To visualize inter-object distances in AR environments, seamless switching between an AR view and a virtual reality (VR) view was proposed [21]. Bichlmeier et al. [22] presented *virtual mirrors*, a render-to-texture approach, which provides additional views of the model. The interpretation of partial self-occlusions inside complex models is particularly improved.

The correct display of *occlusion* between 3D virtual models and real objects, e.g., patient, operator, and instruments, on a 2D surface is important to convey spatial relations. An information filter based on intra-operative distance measures was introduced to reduce occlusion of anatomical structures by virtual overlays [23]. Fischer et al. [24] propose providing a distance map of the real scene using a time-of-flight (TOF) camera. By performing registration between the distance map and virtual 3D models, the distance map is used to decide which objects are rendered at the front and to control the rendering style. A common approach is to change the rendering style for occluded objects, e.g., using a wireframe representation [25] or transparency [26].

2.2. Improving spatial perception using line drawings

Feature Lines. Line-drawing techniques illustratively visualize the object's shape. These can be divided into two groups: feature lines and hatching. The first view-independent approach was presented by Interrante et al. [27], who used curvature measures to determine the ridges and valleys of the surface. Because this approach is not view-dependent, DeCarlo et al. [28] introduced suggestive contours. Their method cannot depict salient regions of convex structures. Thus, Judd et al. [29] combined the ridges and valley method with a view-dependent curvature measure to detect even convex structures. An illumination-based approach was introduced by Xie et al. [30]. They used the shading of the surface to determine the most prominent regions. As this approach is only based on shading, it is possible to influence the result by adding more light sources such that noisy regions are illustrated with less clutter. A similar approach was introduced by Zhang et al. [31]. They generalized the Laplacian-of-Gaussian, a well-known technique that illustrates features in images, to surfaces. This approach was then adapted to the difference-of-Gaussian that was known in image-space before by Zhang et al. [32]. Feature line techniques can enhance spatial cues on the surface, but they cannot give a spatial impression of the surface [33].

Hatching. Most hatching methods use principle curvature directions (PCDs) to orient the directions of the lines. Hertzmann and Zorin [34] determined the PCDs and smoothed them afterwards. Then, they generated streamlines to obtain a hatched result. Praun et al. [35] presented a real-time hatching method. They built *lapped textures* which represent the different shading levels on a surface and projected them onto the surface. Zander et al. [36] presented a hatching method which is based on generating streamlines around the whole surface. For this, the PCDs were calculated and smoothed accordingly. Then, they were used to generate the hatching strokes represented as streamlines. In addition, the PCDs ensure that neighboring streamlines have a minimum distance, to prevent too many streamlines from occurring in a region. Tietjen et al. [37] presented examples for the combination of classical and illustrative rendering techniques on surfaces and volumes to provide expressive focus-and-context visualizations for medical applications.

Lawonn et al. [38] presented ConFIS – a hatching technique that illustrates the surface at feature regions and at the contour. The work of Ritter et al. [39] is close to our work and is guided by a similar set of requirements and application scenarios. They introduced a hatching method which is not applicable in a frame-coherent manner. In addition, they presented a distance-encoding stripe texture which requires distortion-free texture coordinates. For complex vascular structures, as in our case, these are hard to calculate automatically, which limits the applicability of their approach. Furthermore, the stripe texture covers the whole object surface and thus can hardly be combined with other illustrative rendering techniques [4].

Focus-and-context visualization. Illustrative rendering techniques can also improve the spatial perception for focus-and-context visualization. Different cutaway approaches to achieve interactive frame rates were introduced by Diepstraten et al. [40]. Viola et al. [41] proposed a technique to illustrate view-dependent cutaway surface generation. Their method is based on volume rendering, where segmented objects have an importance, which is used to define the cutaway. An approach where the user needs to cut a hole in the surface to reveal the underlying objects was presented by

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