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NAVIGATIONAL ASPECTS OF AN INTERACTIVE 3D EXPLORATION SYSTEM FOR CARDIOVASCULAR STRUCTURES

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Abstract

This paper describes a system which allows the exploration of a detailed geometric 3D model of the cardiovascular tree in a scalable virtual environment in real time. Positioning a virtual camera inside the vascular structure for a virtual fly-through can provide a better understanding of the global structure. Vascular bifurcations of high curvature with acute angles and narrow pathways can be easily detected. Especially in a 3D environment, steering and navigation using traditional devices, such as keyboard and mouse, is not always intuitive. This article addresses this need and describes a novel approach to guided, interactive navigation utilizing a multi-functional gamepad for controlling camera and viewpoint.

KEY WORDS
Virtual model, cardiovascular system, fly-through, navigation, gamepad, endoscopy.

1 Introduction

Virtual biomedical models can help better understand how diseases affect the function of parts and organs of the human body. By thoroughly exploring such a model, scientists and surgeons are able to analyze the effects of different treatment options, and ultimately find more appropriate ways to prevent diseases. Specifically a virtual model of the vascular system of the heart can aid in finding out more about the way the heart functions, and might give insights in what causes conditions such as coronary heart disease (CHD), which still is the number one killer in the United States.

Therefore, this paper describes a system which allows scientists and surgeons to explore a detailed virtual model of a geometric 3D representation of the cardiovascular tree. Users can position a virtual camera inside the vascular structure for a virtual fly-through to detect and analyze vascular bifurcations of high curvature with acute angles and narrow pathways. To ensure intuitive and interactive exploration of the vasculature in real time, various navigational aspects are discussed in this paper and a system for detailed inspections of the internal view of the vascular tree on traditional desktop environments with a multiple-degree-of-freedom input device is introduced.

2 Related Works

A number of approaches have focused on 3D tree visualizations from an external viewpoint, investigating tubular internal organs, such as vessels, esophagi, or colons. The datasets mainly differ in size and resolution. While for some applications 3D tree visualizations from an exterior point of view are sufficient, endoscopic views of the inside are helpful, especially for radiotherapy planning or training, surgery planning, rehearsal, and delivery of computer-assisted surgery.

In general, a camera model describes point of view, orientation, aperture angle, and direction and ratio of motion. A general system for camera movement based on the specification of position and orientation of the camera is presented in [1], while Gleicher et al. [2] choose an approach where through-the-lens control by solving for the time derivatives of the camera parameters is applied. The concept of walkthroughs in simulated virtual worlds using a flying metaphor has first been explored by Brooks [3]. Other commonly applied metaphors for navigation in virtual environments (VEs) such as ”eyeball in hand”, ”scene in hand” and ”flying vehicle control” were introduced by Ware and Osborne [4].

For camera and viewpoint navigation in virtual endoscopy systems, various aspects have to be considered. While free manual navigation in 3D generates the problem of potential disorientation, proceeding automatically on a planned path is often too constraining. Planned navigation with automatic path planning by specifying camera parameters at key points has been explored for example by Nain et al. [5]. A mix between manual and planned navigation is called guided navigation. While Galyean [6] applies a river analogy for guided navigation in VEs, Hong et al. [7] among others utilize guided navigation paradigms with a combination of distance fields and kinematic rules for collision avoidance. Lorensen et al. [8] describe the use of a virtual endoscope for several types of data. Internal views of the data are explored by generating camera paths with key framing and robot path planning algorithms. Kaufman et al. [9] enhance their endoscopy system (volumetric environment) with automatic fly-through capability based on flight-path planning with the possibility of an interactive walk-through. Application areas for virtual endoscopy[10] are, for example, virtual colonoscopy [11], virtual angioscopy [12], and vessel visualization and exploration of the vasculature of the human liver [13].

The goal of the method described in this article is to provide scientists, physicians and radiologists with tools for exploration and exact measurements. In addition, statistically generated data is to be verified and appropriate tools for validation and measuring of the vascular system are provided. The ViVa project [14] presents visualization solutions for virtual angioscopy and provides simple tools for measuring single distances inside the vessels.

Sobel et al. [15] present a visionary system featuring novel visualizations and views of bifurcations. In addition, the blood flow is depicted by particles visualized as glyphs. Since the visualization aspect concentrates on non-photorealistic visualization techniques, no textures are used and no complex surface details are visible. This might be a restriction for physicians who are used to traditional (realistic) visualizations and real-life endoscopic images. In contrast to that approach, the methods described in this article address the need for more photo-realistic, yet quantitatively accurate visualization.

The structure of this article is as follows: initially, an overview of the used 3D input device is given. Subsequently, we discuss what implications the internal structure properties of the vasculature have for generating the virtual geometric 3D model. Then, various exploration methods for virtual fly-throughs in real time are shown. Finally, forthcoming challenges and future work are discussed.

Figure 1. The Logitech© WingMan® Cordless Rumblepad™ seen from the top.

Figure 2. Front view of the Logitech© WingMan® Cordless Rumblepad™.

3 Input Devices

Traditional desktop environments usually utilize only keyboard and 2D mouse for interaction. For steering in a 3D scene, a 2D input device obviously has its limitations. To address this limitation, an additional cordless USB input device for navigational control is added to the desktop. For the given application, a Logitech© WingMan® Cordless Rumblepad™ was chosen as main 3D interaction device, depicted in figure 1, since it features several buttons and different analog joysticks facilitating very advanced steering capabilities.

The Rumblepad™ has 12 buttons and 9 axes. The six main action buttons labeled A, B, C, X, Y, and Z are located on the right side of the pad designed to be pressed using the right thumb. Four front action buttons L1, L2, R1, and R2 are located on the front of the device, so that L1 and L2 can be accessed by the left index or middle finger, and R1 and R2 by the right index or middle finger [figure 2]. The START button is the smallest button on the device and located in the center of the device top. Of the detected axes of the Rumblepad™, seven can be used for user input. The device features one digital joystick (axes 5 and 6, eight positions) and two analog joysticks with four axes (axes 0 and 1 for left analog input and 3 and 4 for right analog input). While the digital and analog joysticks register 2D input in x and y direction, the analog slider/throttle, which is located on the right front side of the pad above button R1, only generates 1D data.

The implementation described in this paper focuses on the two analog joysticks for directional input and for positioning and orienting the camera. The slider is used for speed control, while the front action buttons select the various interaction modes. The number of buttons used in the implementation is to be kept to a minimum, since the user should be able to completely concentrate on inspecting the vascular structure on screen without having to look at the gamepad to find the right action button. Since the interaction should be as easy and intuitive as possible and without unnecessary distraction, the buttons on the top of the device are not used with the exception of the Z button, which can be easily reached by the right thumb. By pressing it, the user can switch between the different navigational modes that are available. Using the two analog inputs, a navigation with six-degrees-of freedom (6dof) is achieved, enabling realistic and unconstrained movement in the 3D space of a virtual environment.

In a traditional desktop environment, navigation methods provide the use of a 3-button mouse in the dominant hand, allowing for 3D movement by means of common 2D interaction methods for navigation in OpenGL. Several functions can be activated with the non-dominant hand through modifier keys. In contrast to keyboard and mouse, which can be used simultaneously since they each allow one-handed interaction, the gamepad needs to be used with two hands due to its design, size, and weight. Since the Rumblepad™ features a sufficient number of controls, no other input device is required for the navigation. Similar properties apply to other gamepads. Therefore, this approach provides an easy to use bimanual camera navigation interface which can not be realized to this extent by traditional setups.

4 Fly-Through

In order to explore the internal structure of the vasculature, the user needs to be able to fly through the vessel tree and explore its interior anatomy in real time.

A heart of a pig was used as a test specimen. The heart was extracted and scanned with a regular CT scanner at a resolution of 0.6 mm resulting in a three dimensional volume. Using the commercial software tool *Analyze*[1], the geometry of the specimen was extracted based on a topology preserving erosion process [16]. The tool generates a list of points representing the center lines of the vessels found in the 3D volume. In addition, radius information is computed by the software at these points.

In a vascular tree, a segment can branch into several child segments. In most cases, a segment has one or two children; but three or even more child segments may occur as well. Therefore, the topology of the vascular system compares to a tree with several branches. Consequently, one frustum may have more than just one successor in this tree. When connecting subsequent frustums with the current one at such a bifurcation point, these subsequent frustums share a common circle at their starting point. Since the circles at the other end of these frustums are not identical, the frustums intersect each other so that the path inside these frustums is occluded. Because of the short length of the frustums there may be more than the two frustums generated by the current bifurcation involved in these occlusions. To completely avoid occlusions in the interior path through the vessels, the overlapping areas of all these intersecting cylinders are computed and then removed. In addition, subsequent frustums can cut into preceding ones at bifurcation points so that these intersections need to be removed as well.

[1] http://www.analyzedirect.com/Analyze4.0/

Evidently, a vast number of frustums need to be intersected in order to compute all the crossing areas of the frustums and remove the occlusions. Consequently, a fast algorithm is required to determine these areas. For visualization purposes, the frustums are represented in the geometry as triangle strips. We can exploit this fact for the intersection algorithm as well. Assuming that the frustums consist of a bunch of triangles, the algorithm only needs to compute the intersection between a few lines and triangles to get the desired result. This approach has two advantages: first, it results in a fast intersection algorithm and second, it avoids cracks in the geometry.

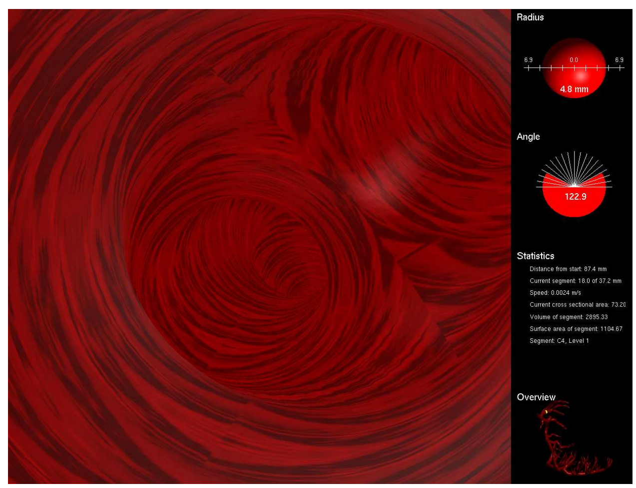

Figure 3. A flight through a cardiovascular tree, left circumflex (LCX) coronary artery.

In figure 3 a screenshot of the dynamic fly-through simulation is given. A non-realistic texture is used for the walls of the vessels which has a rather complex pattern. It was observed that a more detailed texture better reveals the layout of the vascular tree structure and improves accuracy of manual navigation. In analogy to the often used rectangular grid in virtual 3D spaces, the textured vessel walls provide the user with a valuable navigational aid. Navigation is either automated by a smooth and guided traversal through the tree on the center line of the vessels, or it can be set so that the user has complete manual control over camera position and orientation.

4.1 Guided Mode

In the guided mode, the user can change the speed of the camera as it advances through the vessels at all times and even move backwards to further investigate a certain area. The camera always stays close to the center line of the vessel on a wall-collision-free path. The view point is set to a fixed distance ahead on the center line so that the camera smoothly follows each vessel segment or turns when approaching a bifurcation. This results in a guided navigation.

Two different options are available at vessel bifurcations: either the camera follows a pre-defined path or the user picks the next path interactively. In the latter case, the camera continues to move until a bifurcation is reached. There, it stops and moves back and forth between the two or more choices. When a new direction is chosen through user input (button or key pressed), the fly-through continues following the way closer to the current camera position. To avoid unsteady camera navigation, the camera smoothly moves back to the center of the vessel and then continues flying further into the cardiovascular structure.

4.2 Manual Navigation

At any time during the guided fly-through, the user can switch to manual navigation to interactively explore the internal structure. In this mode, the 3D scene can be inspected by freely controlling the position and orientation of the camera (eyeball-in-the-hand). The direction of the camera movement can be changed independently from the viewing direction, and it is in no way limited by 1D constraints through sliders or mouse movement as for example in Nain et al. [5]. By using a gamepad like the Rumblepad™ we overcome the limitations of traditional input devices with limited degrees of freedom.

In analogy to the movement of flying birds or swimming fish, a metaphor similar to the one seen in first-person-shooter computer games is incorporated to create an immersive experience for flexible and effective exploration of the interior of the vascular tree. This simulated flight approach is similar to the river metaphor described in [6]. The camera and viewpoint move while the object stays fixed, thereby providing a driving experience which lets the user drift in a given direction through the tubular structure, where she or he can stop anywhere and move closer to inspect an object by changing the viewpoint to point towards the region of interest.

Several input and navigation modes are imaginable. So far three different navigation modes are implemented, which allow smooth, continuous and unconstrained movement in 3D. These are (i) *camera mode*, (ii) *viewpoint mode*, and (iii) *mixed mode*.

The *camera mode* lets the user control the location of the camera, while the viewpoint stays at a fixed distance relatively to the camera. The camera can be moved horizontally, vertically, and back and forth from its current position. Driving is controlled by the left analog joystick of the gamepad. The y direction of the left stick controls acceleration and deceleration of forward and backward motion, and the x direction moves the camera sideways. If the right analog joystick is moved in y direction, the camera moves vertically.

The *viewpoint mode* leaves the camera at a fixed position, while the viewpoint, i.e. the location where the camera is pointing at, can be moved sideways, up, or down. Thereby pitch and yaw functionalities are given, while simulating roll is not necessary in an endoscopic environment. To keep this mode similar to the 'camera mode', the x direction of the left joystick again controls the horizontal movement, comparable to moving the nose of an airplane sideways (yaw), while the y direction of the right joystick controls the vertical movement (pitch). This mode is particularly useful for a closer inspection of a region of interest.

The *mixed mode* is a combination of the two previous modes. The left analog joystick controls the camera movement (sideways as well as up/down panning) and the right analog joystick controls the viewpoint (pitch and yaw). The camera always moves forward and backward in the viewing direction. The motion speed of the camera can be controlled with a slider: at the leftmost position, the speed is zero, at the rightmost position maximum speed is reached. Buttons L1 and L2 let the user change the direction of movement, where button L1 moves the camera forward, while L2 changes to backward movement. This mode is useful for quick navigation, while still being able to look around.

Mode changes can be performed at all times by simply pressing the front action buttons on the Rumblepad™. Button R2 activates the *camera mode* and R1 the *viewpoint mode*, while L1 and L2 jump to the *mixed mode* with the camera moving in a forward or backward direction, respectively. During the fly-through, collision with vascular walls is prevented by observing a 'safety margin': the camera is not allowed to get closer to the outer wall than a fixed distance defined by a chosen threshold, which is set in such a way that the view is always constrained to the interior of the vessel.

4.3 Graphical User Interface

During navigation through the vasculature several instruments are available to the user to read specific information about objects contained in the data set. All these instruments are positioned on the right side bar of the display as can be seen in figure 3. The instrument at the top shows the current radius of the vessel. The user can switch between a

Figure 4. User interaction with the Logitech© WingMan® Cordless Rumblepad™.

regular and a logarithmic scale that automatically adapts to the minimum and maximum radii of a given data set. The current radius is symbolized by a balloon which is inflated and deflated according to the change in radius. Below the radius, a goniometer displays the angle at the last bifurcation. This angle indicates how much the consecutive vessel segments deviate from a straight line. Besides geometrical information, this angle can give a hint of the likelyhood for the occurance of plaque deposits and calcifications at that bifurcation.

Below the two instruments, statistical information is shown, including the distance from the point of entry, and the current speed of the camera during the fly-through. The distance from the point of entry, for instance, would correspond to how far the physician had inserted an endoscopic device into the tubular structure. Also displayed are the size of the cross-sectional area at the current camera position, the relative position inside the current segment between two bifurcation points, the total length of that segment, the volume of the segment, and the surface area defined as the area of the vessel walls of that segment.

To ensure that the user does not get disoriented while flying through and locally inspecting the inside of a massive vascular tree, an overview map is displayed in the lower right corner of the screen. This map provides global information by showing the entire cardiovascular tree with the current camera position marked by a yellow ring. The user can rotate, zoom, or pan in this overview in the same way as in the regular view. Therefore, the user is allowed to reposition the vascular tree in the window to get an optimal view of the current position as indicated by the marker.

The marker itself follows exactly the camera movement. This means that not only the camera position but also the location the camera is pointing at are considered. This is particularly helpful when the user is required to choose between two or more possible options at a bifurcation during the guided mode. The marker then slowly alternates between the respective segments and always points towards the vessel segment that would be followed if the user would continue in that direction. Consequently, the user can always easily identify the branch that would be followed if she or he would continue at that particular moment in time when the marker is in the right position.

5 Conclusion and Future Work

In this article, various navigation methods embedded into a visualization system for vascular trees were presented, enabling interactive data exploration in real time. A fly-through mode was described and implemented that dynamically displays similar detail information about the vascular system. Three intuitive navigation modes that ensure continuous smooth exploration of the internal vascular structure were included in the system. The described system employs a gamepad as a precise input device that has proven to be much more useful in 3D environments than conventional keyboard or mouse.

As a future extension to the existing visualization system, the software will be ported to virtual environments. For instance, an immersive workbench, such as ImmersaDesk™ or Responsive Workbench, can be used to enable users to investigate and navigate the specimen in a three-dimensional, stereoscopic display environment [17]. Such a virtual environment would facilitate the simulation of computer-aided diagnoses similar to those obtained in real-world surgery environments.

Since recent studies [18] have shown that training and exercise in common game navigation modes are beneficial in the training of future surgeons, we are planning to conduct a user study to ascertain intuitive and realistic navigation modes for virtual exploration tasks of cardiovascular data. This formal study will evaluate different navigation modes and input devices for a comparison with traditional real-world endoscopic navigation and investigate if the integration of force feedback functions, such as the rumble capability of the gamepad, for collision detection further enhances the realistic feel of the virtual simulation environment, especially when a virtual fly-through of a vesseltree with simulated bloodflow is conducted.

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References

[1] S. M. Drucker, T. A. Galyean, and D. Zeltzer, "Cinema: a system for procedural camera movements," in *Proceedings of the 1992 symposium on Interactive 3D graphics*. ACM Press, 1992, pp. 67–70.

[2] M. Gleicher and A. Witkin, "Through-the-lens camera control," in *Computer Graphics (SIGGRAPH '92 Proceedings)*, E. E. Catmull, Ed., vol. 26, no. 2. ACM Press, July 1992, pp. 331–340.

[3] F. Brooks Jr., "Walkthrough - A dynamic graphics system for simulating virtual buildings," *Proceedings SIGGRAPH Workshop on Interactive 3D Graphics*, pp. 9–21, 1986.

[4] C. Ware and S. Osborne, "Exploration and virtual camera control in virtual three dimensional environments," *Computer Graphics*, vol. 24, no. 2, pp. 175–183, Mar. 1990.

[5] D. Nain, S. Haker, R. Kikinis, and W. E. L. Grimson, "An interactive virtual endoscopy tool," in *Proceedings of the IMIVA 2001 workshop of MICCAI*, Utrecht(NL), Sept. 2001.

[6] T. A. Galyean, "Guided navigation of virtual environments," in *Proceedings of the 1995 symposium on Interactive 3D graphics*, P. Hanrahan and J. Winget, Eds. ACM Press, Apr. 1995, pp. 103–104.

[7] L. Hong, S. Muraki, A. Kaufman, D. Bartz, and T. He, "Virtual voyage: Interactive navigation in the human colon," *Proceedings of SIGGRAPH'97*, pp. 27–34, Aug. 1997.

[8] W. E. Lorensen, F. A. Jolesz, and R. Kikinis, "The exploration of cross-sectional data with a virtual endoscope," *Interactive Technology and the New Health Paradigm*, pp. 221–230, 1995.

[9] M. Wan and F. D. A. Kaufman, "Distance-field based skeletons for virtual navigation," in *IEEE Visualization 2001*, T. Ertl, K. Joy, and A. Varshney, Eds., IEEE. San Diego, CA: IEEE Computer Society Press, Oct. 2001, pp. 239–245.

[10] A. Vilanova Bartrolí, A. König, and E. Gröller, "VirEn: A virtual endoscopy system," *Machine GRAPHICS & VISION*, vol. 8, no. 3, pp. 469–487, 1999.

[11] S. You, L. Hong, M. Wan, K. Junyaprasert, A. Kaufman, S. Muraki, Y. Zhou, M. Wax, and Z. Liang, "Interactive volume rendering for virtual colonoscopy," in *IEEE Visualization '97*, R. Yagel and H. Hagen, Eds., IEEE. Los Alamitos: IEEE Computer Society Press, Oct. 1997, pp. 433–436.

[12] D. Bartz, W. Straßer, M. Skalej, and D. Welte, "Interactive exploration of extra- and interacranial blood vessels," in *IEEE Visualization '99*, D. Ebert, M. Gross, and B. Hamann, Eds., IEEE. San Francisco: IEEE Computer Society Press, 1999, pp. 389–392. [Online]. Available: http://visinfo.zib.de/EVlib/Show?EVL-1999-326

[13] H. K. Hahn, B. Preim, D. Selle, and H. O. Peitgen, "Visualization and interaction techniques for the exploration of vascular structures," in *IEEE Visualization 2001*, IEEE. IEEE Computer Society Press, Oct. 2001, pp. 395–402.

[14] G. Abdoulaev, S. Cadeddu, G. Delussu, M. Donizelli, L. Formaggia, A. Giachetti, E. Gobbetti, A. Leone, C. Manzi, P. Pili, A. Scheinine, M. Tuveri, A. Varone, A. Veneziani, G. Zanetti, and A. Zorcolo, "ViVa: The virtual vascular project," *IEEE Transactions on Information Technology in Biomedicine*, vol. 22, no. 4, pp. 268–274, Dec. 1998.

[15] J. S. Sobel, A. S. Forsberg, D. H. Laidlaw, R. C. Zeleznik, D. F. Keefe, I. Pivkin, G. E. Karniadakis, and P. Richardson, "Particle flurries: a case study of synoptic 3d pulsatile flow visualization," *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 76–85, March/April 2004.

[16] S. Lobregt, P. Verbeek, and F. Groen, "Three-dimensional skeletonization: Principle and algorithm," *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)*, vol. 2, no. 1, pp. 75–77, January 1980.

[17] W. Krueger and B. Froehlich, "The responsive workbench," *IEEE Computer Graphics and Applications*, vol. 14, no. 3, pp. 12–15, May/June 1994.

[18] J. C. Rosser, P. J. Lynch, L. A. Haskamp, A. Yalif, D. A. Gentile, and L. Giammaria, "Are video game players better at laparoscopic surgery?" in *Medicine Meets Virtual Reality 12 - Building a Better You: The Next Tools for Medical Education, Diagnosis, and Care*, J. D. Westwood, R. S. Haluck, H. M. Hoffman, G. T. Mogel, R. Philips, and R. A. Robb, Eds. Amsterdam: IOS Press, Jan. 2004.