Focus+Context Visualization of Features and Topological Structures

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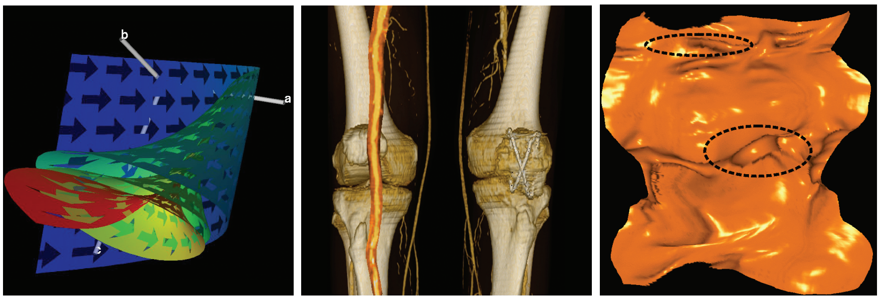


(a) (b) (c)

Fig. 1. Topology in focus+context visualization: (a) streamarrows cut the stream-surface of a dynamical system to enhance the visibility otherwise occluded parts [Löf98], (b) VesselGlyph metaphor for angiographic data [SvC*04], and (c) virtual colon unfolding for diagnosis [Vil01].

Focus+Context Visualization has been widely used in Information Visualization to emphasize important structures while at the same time providing an overview on the surrounding data. This principle can also be used in scientific visualization to illustrate small but important features or topological structures. In many visualizations topological structures are only displayed by themselves. They usually provide a rather sparse and highly abstract representation of the most important data characteristics. Focus+Context Visualization allows to also embed these sparse representations within the given original but dense data. How to avoid visual overload in this situation will be one topic of this paper. Our previous work in the area of focus+context visualization of features and topological structures will be shortly discussed. These approaches include: importance-driven volume rendering, multi-volume rendering, feature emphasis in direct volume illustration, the VesselGlyph as a Focus & Context Visualization in CT-Angiography, streamarrows, visualization of Poincaré Sections, real-time techniques for 3D flow visualization.

1 Introduction

Three-dimensional visualization is becoming an essential tool for the analysis of various scientific problems. One example is flow visualization for automotive industry design. Here the aerodynamics as well as engine combustion characteristics can be effectively researched through visual analysis. Recently developed interactive visual analysis techniques on this topic acknowledge the high potential of this application area [LCGJSH05, MJJ*05].

Visualization is also very useful for medical tasks such as diagnosis or operation planning. Starting with X-ray imaging, followed by two-dimensional inspection of computed tomography (CT) slices, three-dimensional visualization is increasingly used in the clinical routine. Diagnostic tasks include endoscopy and colonoscopy [Vil01], computer-assisted angiography [Kan04, SvC*04], mammography [CGB*05], lung nodules detection and visualization and many others. Expressive three-dimensional visualization turns out to be crucial for pre-operative surgical planning. Examples are neck dissection planning [KTH*05] or liver surgery training [TIP05].

Another important aspect of three-dimensional visualization is its high potential in education. This includes virtual autopsies, anatomical learning [SES05] or manipulation and interactive direct illustration of the complex underlying data [BG05].

A major challenge of current visualization research are the very large data sizes. For example the rapid development of high-precision medical imaging modalities causes the amount of data to steadily increase. Due to the increasing power of modern CPUs mathematical simulations of scientific phenomena deliver huge amounts of result data. Processing and visualization of time-varying data is becoming practicable in many applications. The added temporal dimension, however, furthermore raises the data sizes considerably.

Large data sizes entail two fundamental problems: The first is data manipulation with respect to data enhancement and processing in general. The second problem is the appropriate visual representation of the underlying data. The amount of relevant information is often relatively small as compared to the overall amount of acquired data. Therefore these small, interesting features have to be visually emphasized. Examples are singularities in flow visualization, or lesions inside the liver in medical visualization. In many of the cases visualization of the feature alone, does not clearly describe the inspected problem and thus does not satisfy the goal of an expressive visualization. The data surrounding the features includes more information and some of this information is necessary to communicate the visualized problem. Spatial position and vicinity to other structures can be very important for example. Hence, from a computer science point of view large data visualization is often a focus+context task.

In this paper we discuss appropriate visual representations and show the relevance of topology in focus+context visualizations. The paper is organized as follows: Section 2 shortly discusses the term topology. The following sections investigate the relevance of topology for visualization. Section 3 describes topology-based visual representations that significantly enhance visualization of dynamical systems. Section 4 focuses on high-level abstraction techniques that enhance expressivity by introduced topological changes of the underlying data. Finally we draw conclusions in Section 5.

2 Topology

Topology (Greek *topos*, place and *logos*, study) is a branch of mathematics concerned with the study of topological spaces. When the discipline was first introduced it was called *analysis situs* (Latin analysis of place).

Definition by *Wikipedia.org [wik05]*

Topology is a branch of mathematics which defines object characteristics such as connectivity information, genus (i.e., number of *holes* in the object), and other characteristics that are left unchanged through a continuous deformation. The genus classifies objects into categories, i.e., two object are *homotopic* (they have an identical genus) if one can be continuously deformed into another. In general topology provides abstract characteristics of a particular object or an abstract relation to other objects. A humorous definition of topology is the following:

Q: Who is a topologist?
A: Someone who cannot distinguish between a doughnut and a coffee cup [RD05].

Apart from pure mathematical studies, topology has been studied in the visual arts over the last centuries. One of the artists who exploited visual aesthetics of known topological structures was M.C. Escher [esc05, Hof79]. In Section 3 we depict how to efficiently use topologic characteristics for sparse and expressive visual representations in the field of scientific visualization.

3 Topology and Visual Abstraction

The relevance of features in an image is represented through their visual representations, i.e., levels of sparseness. Sparseness means the amount of visual representation in the final image, e.g., a sparse representation foe polygonal data is a wireframe representation, while a dense representation is a surface representation.

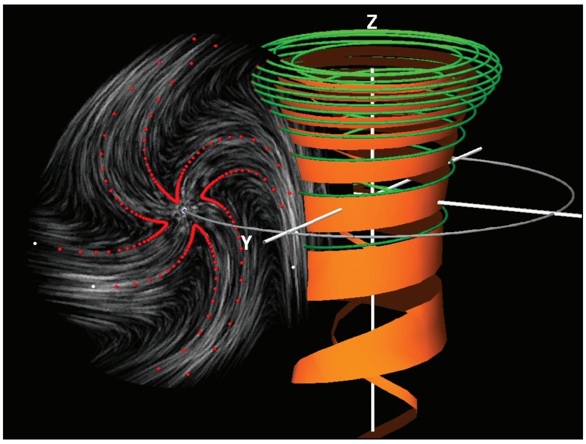


Fig. 2. Visualization of a complex dynamical system using Poincaré sections. Sparse high abstract information like the cycle is combined with denser low abstract information like spot noise flow streamlines and streamsurfaces [Löf98].

There are many ways to design appropriate visual representations. We will focus on those where emphasis on topology significantly increases the visual information content.

For a data set there is a wide spectrum of visual representations. The level of abstraction differentiates these representations. A direct representation does not use any abstraction and is easy to interpret. However for a large dataset or in higher dimensions it easily produces dense, cluttered images which are visually overloading. The other end of the spectrum are highly abstract (derived) data representations. They typically produce rather sparse images but can require quite some effort to understand. Showing MRI data of the brain as greyscale images is rather direct representation. Showing the same data through diffusion tensor imaging is a more abstract representation.

Topological information can be represented very sparsely, i.e., the visual representation may consist of just a few lines. Although this representation is very sparse, in many cases it represents the information in an effective way. There is no visual overload and image space is saved to display further information.

Topological visual representations are well known in flow visualization and in the visualization of dynamical systems. In some cases features are not clearly defined, i.e., there are no explicit boundaries among features. Interesting features might be vortex cores, fixed points (such as nodes, saddles, vortices), separatrices aso. For a clear visualization of particular phenomena, topological information of features of interest is crucial. Figure 2 visualizes a dynamical system by combining visual representation of greatly varying levels of abstraction. The topological information with high abstraction is given by a cycle around the z-axis. The flow is directly represented by spot noise [vW91] on the Poincaré cross section [Löf98]. A streamsurface in orange and a streamline in green provide further low abstract context information. The sparse topological information indicates the overall characteristics of the system. The dense and direct depiction of the flow is limited to just a small region of the data to avoid visual clutter. Further examples of topological visual representations can be found in referenced scientific publications [TWHS03, TGK*04, WTHS04, ZP04].

4 Visual Topological Changes

The previous section addressed visualizations where topological characteristics increase the visual information content despite the fact that this information is represented very sparsely. A visual representation can be reduced to just a few lines taking-up very little of image space. In this section we will focus on high-level visual abstractions also denoted as *smart visibility* techniques [VGB*05]. Such techniques deliberately change the topology of underlying data in order to uncover most of the relevant visual information. We discuss several techniques often used in traditional illustration: cut-away views (and ghosted views), exploded views, and unfolded views that have been recently proposed for expressive visualizations.

4.1 Cut-Away and Ghosted Views

Cut-away views and ghosted views are high-level visual abstractions that change the topology of the underlying data by *cutting away* part of the data (usually context information) to unveil relevant focus information. The context is subdivided into two parts: the occluding region that has been removed to enhance the focus information and the remaining context information. The difference between cut-away views and ghosted views is that cut-away views entirely remove the obstructed context information while ghosted views represent the occluded region very sparsely. In a ghosted view the focus is well visible but the occluding region also remains faintly recognizable (as a ghost of itself). In visualization we distinguish two types of cut-away views: In view-independent cut-away visualizations the shape and location of the cut is not influenced by the viewpoint information. The second category are view-dependent cut-away visualizations where the viewpoint information is considered to guarantee an unobstructed view on the most interesting structures.

An example of view-independent cut-away views are streamarrows proposed by Löffelmann et al. [Löf98] for the visualization of dynamical systems. They use arrows as a basic element for cutting away part of a stream surface. This allows to see through the surface and perceive other surfaces or structures behind. Moving streamarrows along the stream surface enables to see

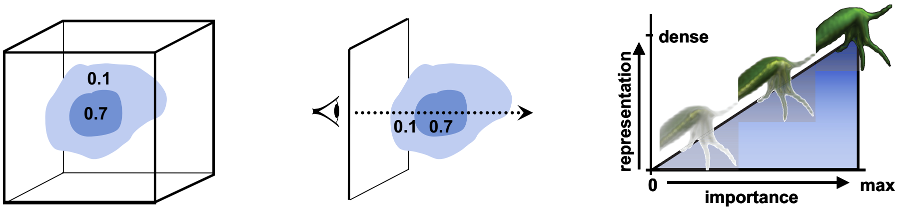


Fig. 3. Stages in the pipeline of importance-driven volume rendering: Volumetric features are assigned importance values (left image). The volume is traversed (center) in the importance compositing stage to estimate levels of sparseness (right). These levels are used to enhance or suppress particular parts of the volume. The resulting images then emphasize important features [VKG05].

beyond the front stream surfaces and perceive the flow direction. Streamarrows belong to the category of view-point independent cut-away techniques and are shown in Figure 1 (a).

The following examples employ viewpoint information in cut-away or ghosted visualizations. The first discussed technique is importance-driven feature enhancement [VKG05]. The traditional volume visualization pipeline assigns to features optical properties like color and opacity. With importance-driven feature enhancement we use another dimension which describes the importance of features. Importance encodes which features are the most interesting ones and have the highest priority to be clearly visible. Prior to the final image synthesis, the visibility of important features is estimated. If less important objects are occluding features that are more interesting, the less important ones are rendered more sparsely, e.g., more transparently. If the same object does not cause any unwanted occlusions in other regions of the image, it is rendered more densely, e.g., opaque, in order to see its features more clearly. This allows to see all interesting structures irrespective if they are occluded or not, and the less important parts are still visible as much as possible. Instead of using constant optical characteristics, which are independent from the viewpoint, we use several levels of sparseness for each feature. Levels of sparseness correspond to levels of abstraction, i.e., we do not assign a single optical characteristic, but several characteristics with smooth transitions in between. These multiple levels of sparseness allow the object to continuously change its visual appearance from a very dense representation to a very sparse one. Which level of sparseness will be chosen, is dependent on the importance of the particular object and the importance of objects in front and behind. The level of sparseness thus may continuously vary within a single feature. For different viewpoints the same part of a feature may be represented with different levels of sparseness. To determine the sparseness level for each object or parts thereof the rendering pipeline requires an additional step, which we call importance compositing. This step evaluates the occlusion according to the viewpoint settings, takes the importance factor of each feature into account and assigns to each feature a particular level of sparseness. The final synthesis results in images with maximal visual information with respect to the predefined object importance. The interrelationship between object importance, importance compositing, and levels of sparseness is depicted in Figure 3. The importance compositing traverses the whole volume to identify object occlusions and assigns the corresponding level of sparseness to each object. Object importance translates to object visibility in the result image. This causes different rendering settings for the context object (with importance *0.1*) in the area of the image which is covered by the focus object (importance *0.7*).

Figure 4 shows a cut-away view of multi-dimensional volumetric data of hurricane Isabel using importance-driven feature enhancement. The important feature was the hurricane eye selected through a cylindrical proxy geometry. Inside the cylinder the total precipitation mixing ratio is visualized. Thanks to the cut-away view it is possible to have a clear view at this property close to the eye of the hurricane. Outside the cylinder is the context area where the total cloud moisture is visualized.

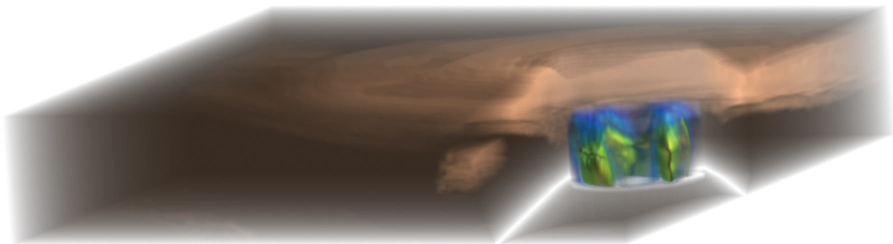
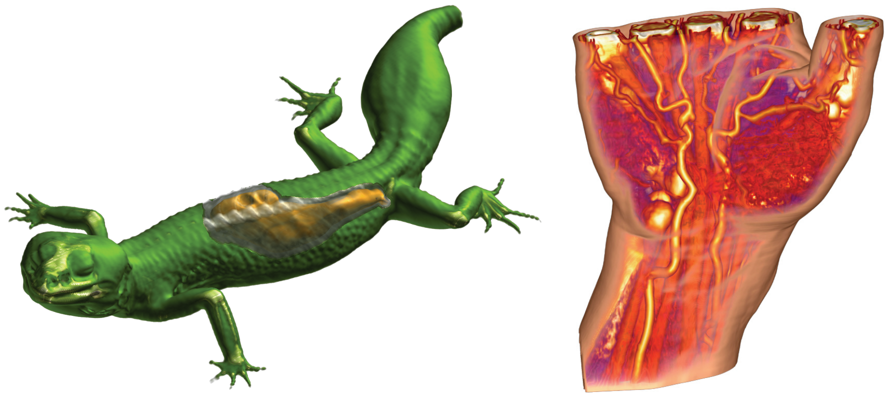


Fig. 4. Cut-away visualization of a multidimensional volumetric data of hurricane Isabel.

Figure 5 (a) illustrates a ghosted view of the scalar volumetric data of a Leopard gecko. The small internal structure (in yellow) of the Leopard gecko dataset is the most interesting information and has been pre-segmented. The body is considered as context information. In the area of occlusion the visual representation of the gecko body is reduced to contours to have a clear view on the interesting internal organ.

With the VesselGlyph Straka et al. [SvC*04] are introducing a cut-away technique for CT-angiography of peripheral arteries in human legs. The goal is to have a clear view on the vessels, which are partially segmented by their centerline. For a clear understanding of the spatial arrangement it is necessary to visualize also bones and skin contours. To have an unobstructed view on the vessel for each viewpoint it is necessary to perform a cut in the bone. Potential misinterpretations are avoided by clearly depicting the cut as an artificial and sharp change in the data. This is illustrated in Figure 1 (b).

An extension to direct volume rendering that focuses on increasing the visibility of features has been proposed by Bruckner et al. [BGKG05]. This technique is known as illustrative context-preserving volume rendering. The approach maps transparency to the strength of specular highlights. This allows to see *inside* the volume in the areas of highlights. The human perception can easily complete the shape of partially transparent parts and therefore additional information can be shown there. A further parameter tunes the ratio between specularity and transparency. A depth parameter determines how far one can look inside a volumetric object (fuzzy clipping). Certain data-value ranges can be excluded from the transparency modulation to allow a clear view on specific (inner) structures. The result in Figure 5 (b) has the flavor of a medical illustration and is achieved without any segmentation operation.



(*a*) (*b*)

Fig. 5. Cut-away visualizations: (a) importance-driven visualization of a Leopard gecko [VKG05] (b) context-preserving illustrative volume rendering of a human hand dataset [BGKG05].

An interactive tool for cut-away and ghosting visualizations has been recently implemented by Bruckner et al. [BG05, BVG05]. VolumeShop is an interactive system which features advanced manipulation techniques and illustrative rendering techniques to generate interactive illustrations directly from the volumetric data. The system is using latest-generation texture-mapping hardware to perform interactive rendering applying various kinds of rendering styles. It implements a multi-volume concept to enable individual manipulations of each volume part. The segmentation of the volumetric objects can be done directly via 3D painting. Apart from importance-driven visualization resulting into cut-away and ghosted views, VolumeShop features a label management to introduce basic descriptions for the visualized data. To focus at a particular feature, this feature can be moved from its original spatial position. To indicate its original spatial position it is possible to display a *ghost* there, or add additional markers such as fanning or arrows. Some ghosted visualizations generated using VolumeShop are shown in Figure 6.

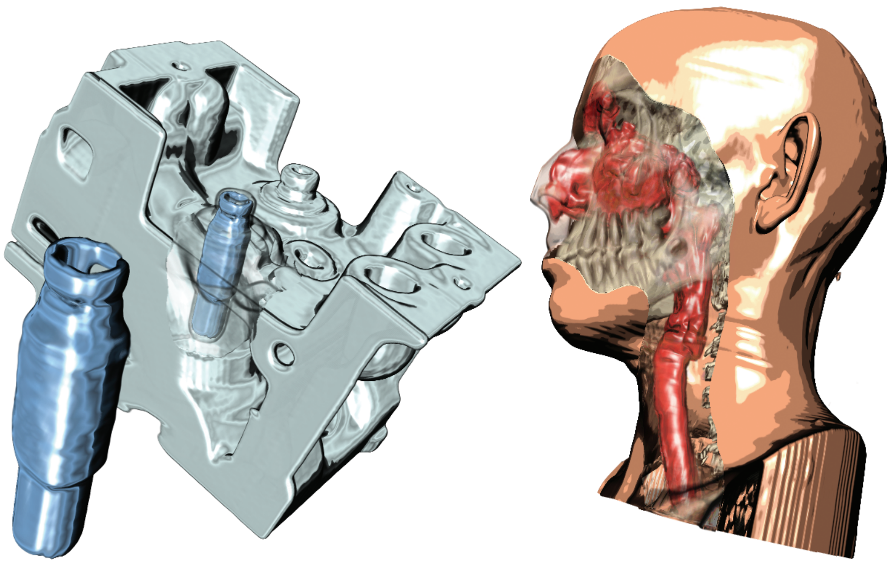


Fig. 6. Interactive ghosted visualizations of the engine block and human head datasets [BG05, BVG05].

4.2 Exploded Views

Exploded views modify the spatial arrangement of features to uncover the most prominent ones and thus change the topology of the underlying data. The previously discussed VolumeShop application allows to manipulate the data and displace parts from their original position. Thus it implements exploded views through manual interaction. Another multi-object visualization technique related to exploded views has been presented by Grimm et al. [GBKG04]. They present a data structure denoted as *V-Objects* for individual handling and manipulation of features within a volumetric dataset. Exploded views are handled in two domains: Exploding in the spatial domain displaces features from their original spatial location. The second exploding domain is temporal domain. This case handles time-varying datasets. Instead of traditional visualization as in an animation sequence, all time-steps are present in a single image enabling to see all time-steps at once. Examples of exploding in both domains is shown in Figure 7.

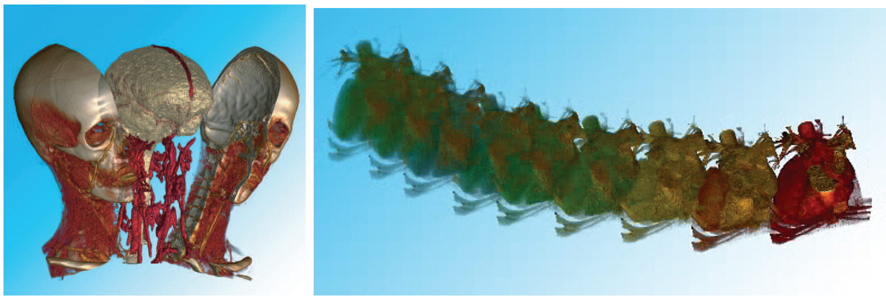


Fig. 7. V-Objects data structure for multi-volume visualization enabling exploded views in (a) spatial domain and (b) temporal domain [GBKG04].

4.3 Unfolding and Curved Planar Reformation

In this section we discuss two techniques from medical visualization. Although their correspondence to topology is different they have the same goal: both techniques resample the underlying data to a plane to clearly present every relevant information in a single image.

The first approach performs unfolding of a cylindrical structure to a plane, which is a topological change. This is applied to computed tomography data of the colon. The traditional way of colon inspection for polyps (early stage colon cancer) is using a real-world endoscope. Such an inspection process is very uncomfortable for the patient, therefore a virtual colonoscopy technique has been applied recently. The endoscope is replaced by a virtual endoscope traversing the tomographic data instead of the patient's body. This technique is much more comfortable, but the diagnosis is still time-consuming. Unfolding the tubular structure provides an instant ovaerview of the entire organ [Vil01]. In this case the topological change is important for a rapid diagnosis. An image of part of an unfolded colon is shown in Figure 1 (c).

Another approach exploiting easy readability of planar structures is known as curved planar reformation (CPR) and has been applied for CT angiography. Angiography inspection is used for peripheral vessels investigations. A typical pathologic change of peripheral vessels are stenoses (thinned lumen, i.e., reduced blood flow) caused by calcification of the vessel walls. To identify the calcifications in the vessels, the vessel interior has to be visible from all viewing angles. The basic idea of CPR is the alignment of a curved surface to the vessel centerline. The plane is perpendicular to the viewing direction. After resampling this cross section to a two-dimensional image, an unobstructed view on the vessel interior is present. The basic CPR visualizes the longitudal crossection of just one vessel without clearly showing the entire vessel tree and bifurcations. Multi-path CPR has been introduced [Kan04], where an individual surface is used for each vessel segment and results are fused to a single image. Although these visualizations effectively convey the information of the interior of the vessel, there are some viewing directions where a vessel is obstructing another one. To avoid occlusion and enable inspection of every part of the vessel tree for each viewing angle, untangled CPR [Kan04] deliberately moves vessels parts apart. This approach is shown in Figure 8 where the entire peripheral vessel tree of the low extremities is shown. This visualization technique changes the feature topology in order to show the relevant information. The connectivity of the vessels is preserved, although the connectivity of neighboring features provided as context information is neglected.

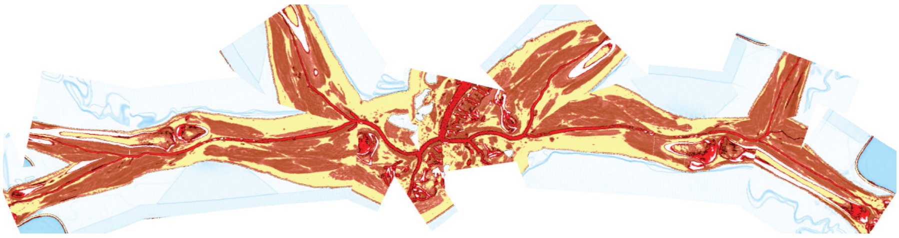


Fig. 8. Untangled CPR used for inspection of tomographic angiography data of lower extremities [Kan04].

5 Conclusions

In this paper we have discussed topology-driven techniques for visualization and feature definition. The sparse visual representation showing topological characteristics is very useful for flow and dynamical systems visualization. Higher level abstractions use topological changes to uncover more interesting structures and enhance information content of the resulting visualization. Topological changes are essential for various *smart visibility* techniques inspired by expressive illustrations such as cut-away views and exploded views. Furthermore the topological analysis can be used to define the importance of features and express their relevance in visualizations. Examples can be centerlines in a vessel tree, blobby characteristics of lung nodules, or tubes aligned to the hurricane eye.

The discussed examples of topological visual representations, smart visibility techniques, and topological analysis show the significance of topology for expressive focus+context visualizations.

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