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Uncertainty in medical visualization: Towards a taxonomy

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ABSTRACT

The medical visualization pipeline ranges from medical imaging processes over several data processing steps to the final rendering output. Each of these steps induces a certain amount of uncertainty based on errors or assumptions. The rendered images typically omit this information and allude to the fact that the shown information is the only possible truth. Medical doctors may base their diagnoses and treatments on these visual representations. However, many decisions made in the visualization pipeline are sensitive to small changes. To allow for a proper assessment of the data by the medical experts, the uncertainty that is inherent to the displayed information needs to be revealed. This is the task of uncertainty visualization. Recently, many approaches have been presented to tackle uncertainty visualization including a few techniques in the context of medical visualization, but they typically address one specific problem. At the moment, we lack a comprehensive understanding of what types of uncertainty exist in medical visualization and what their characteristics in terms of mathematical models are. In this paper, we work towards a taxonomy of uncertainty types in medical visualization. We categorize the types in an abstract form, describe them mathematically in a rigorous way, and discuss the visualization challenges of each type and the effectiveness of the existing techniques. Such a theoretical investigation allows for a better understanding of the visualization problems at hand, enables visualization researchers to relate other medical uncertainty visualization tasks to the taxonomy, and provides the foundation for novel, targeted visualization algorithms.

1. Introduction

Medical visualization is concerned with the visual representation and interactive visual analysis of medical data. As medical examinations and diagnoses need to be based on patient-specific data, medical imaging techniques are the typical starting point for medical visualization approaches. The imaging techniques provide the means to acquire images of the human body for clinical purposes or medical science. Different medical imaging techniques have been developed to capture different parts of the human body or their function. However, the imaging techniques are not free of artifacts such as noise, shadows, or bias fields, which introduce some error in the data.

Moreover, in many medical applications the generated images need to undergo a series of processing steps before they are presented for further investigation. Most interesting for us here are applications that require 3D visual representations to provide the desired information to the medical experts. Examples of such applications are the visualization of vessel-like structures, where 2D slices are of limited use, the visualization of neuro-imaging data, where the location of brain fibers are crucial for surgery planning, and the visualization for non-invasive therapy planning, where access paths need to be found in 3D renderings. These visualizations require the application of a pipeline of processing steps before the actual rendering step. Such processing steps include morphological image processing steps, registration, segmentation tasks, feature extraction algorithms, and reconstruction of continuous volumetric fields. Each of these processing steps is based on certain assumptions that affect the data and influence the results of the processing step and consequently of the entire processing pipeline.

In the end, however, the medical expert is provided with a visual representation of a rendering that alludes to the fact that the presented information is the only possible interpretation. Due to the errors in the data and the assumptions made in the processing pipeline, this assumption is far from being correct. Admittedly, the presented information typically represents the most likely interpretation, but other interpretations are also valid and their likelihoods are typically far from being negligible. Lundström et al. [1] reported that a falsely detected stenosis coming from a misleading transfer function in the direct volume rendering of a computed tomography (CT) scan led to an unnecessary surgical intervention.

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They showed that a slight modification of the transfer function would have delivered a visualization depicting the proper interpretation. It is the task of uncertainty visualization to detect uncertain areas, quantify the respective uncertainties, and convey the information visually to the user. Uncertain areas in this context refer to areas where slight modifications in the assumptions made or in the estimated error model can lead to a significant deviation from the most likely case.

Visual representation of such uncertainties is a crucial task in many medical visualization domains. For example, in the field of neurosurgery, a slight mistake in the fiber tracking approach may lead to wrong decisions in surgery planning tasks, which as a result may damage the healthy brain regions including the most crucial ones such as the visual apparatus or motor function. Similarly, in radio-frequency ablation, under- and over-estimation of a tumor needs to be avoided to not miss parts of the tumor and, at the same time, reduces the amount of affected healthy tissue to a minimum. To allow for a proper assessment of the data by the experts, the uncertainty that is inherent to the displayed information needs to be revealed.

Uncertainty visualization has for a long time been a common standard in statistical graphics in form of the visualization of standard deviations, variances, or similar statistical measures. Potter et al. [2] developed a hybrid summary plot to incorporate higher-order descriptive statistics to concisely present data with uncertainty information. In the field of volume visualization, uncertainty visualization only recently has gained major attention. Many approaches have emerged within the last years and a few of them relate the issue to medical problems. However, most of the presented approaches tackle a specific problem either focusing on a certain application or addressing a general uncertainty visualization task from an abstract perspective. Already in 2003, Johnson and Sanderson [3] recognized the “need to create a formal, theoretical error and uncertainty visualization framework and to investigate and explore new visual representations for characterizing error and uncertainty.” However, so far we are still missing a comprehensive understanding of the types of uncertainties that we encounter and a proper description of the uncertainty quantities in the form of a mathematical model.

It is the goal of this paper to thoroughly analyze the types of uncertainties in medical applications, investigate how the uncertainties can be estimated, and describe each type in a mathematically sound fashion that allows us to abstract from the underlying source and application. The abstraction step shall lead to a taxonomy for uncertainty types in medical applications. We want to derive those by starting from the identified sources of uncertainty and developing categories. The specific goals of this paper can be summarized as follows:

- Identifying relevant sources of uncertainty in the medical visualization pipeline and in medical visualization applications.
- Describing how the respective uncertainty quantities that stem from each of the identified sources can be quantified.
- Developing an abstract representation of the types of uncertainty leading to a mathematical description.
- Categorizing the uncertainty types with respect to the characteristics of their abstract mathematical description.
- Investigating existing state-of-the-art visualization approaches for each uncertainty category and discussing their limitations.
- Identifying open uncertainty visualization challenges.

At this point, we would like to point out that our goal is to work towards a taxonomy. We do not claim to be comprehensive with respect to the existing medical visualization problems. We identify common sources of uncertainty and follow through with those examples. Specific medical applications will certainly provide further examples, but we believe that those can then also be related to our taxonomy to enhance it with further examples or maybe even add another type of uncertainty. We see our work as a first step, where the proposed taxonomy shall be enhanced over the coming years. Also, we want to point out that we do not claim to provide a complete survey of the literature. We provide examples of uncertainty visualization techniques and analyze their effectiveness and limitations in light of the visualization challenges faced.

The impact of our work can be manifold: it will impact the visualization community, since researchers can start from our taxonomy, investigate the problems, and develop methods for underrepresented uncertainty types, i.e., addressing the identified open uncertainty visualization challenges. The theoretical foundation of the different uncertainty categories will enable a better understanding of all the different types of uncertainty data. On the other hand, one may also start investigating from the application point of view. Starting from an application at hand, our taxonomy shows what visualization methods exist. If the application is not listed in the taxonomy, one may abstract from the application to come to a mathematical description of the uncertainty visualization problem, which then may be looked up in the taxonomy table.

2. Related work

Recently, Brodlie et al. [4] and Potter et al. [5] presented two papers on categorizing uncertainty visualization approaches. Both typologies partition the work done in the area of uncertainty visualization based on the dimensionality of the data domain (1D–ND) and the dimensionality of the data range (Scalar, Vector, Tensor, Multifield). Following this categorization, a great effort has been made in discussing existing methods falling in each of the categories as well as in identifying areas, where the existing work is scarce, as possible future research directions. Similar to these papers, our work also considers the dimensionality of the data as one of the identifying categories. However, in contrast to these papers, our work focuses on building a taxonomy of the uncertainty type and, consequently, of the uncertainty visualization problem. We discuss those types that can be identified in the context of medical visualization and define each category type with a mathematical description. We also identify the type of uncertainty events rather than taking the range of the uncertainty data as an identifying trait. Moreover, we distinguish the spatial locations at which the uncertainty is defined as being either discrete or continuous. In summary, Brodlie et al. [4] and Potter et al. [5] categorize uncertainty visualization approaches according to the underlying data type, while we categorize uncertainty types leading to different visualization challenges. Depending on the application goal, the uncertainty type and the respective visualization problem can be quite different for one and the same data type.

A recent work by Dasgupta et al. [6] approaches the problem for categorization of uncertainty data, where they recognize and highlight the need for analyzing visual uncertainty in order to design more effective visual representations. They developed a taxonomy to categorize the various forms of uncertainty in the visual representation in the context of line-based and cluster-based parallel coordinates. They identified different sources of uncertainty and related them to different effects upon the user. Although the work is providing a taxonomy for uncertainty visualization, it is limited to one specific visual encoding (parallel coordinates) of one specific data type (multidimensional data). Earlier, Thomson et al. [7] and the extension by MacEachren et al. [8] had provided a more general categorization for the types of uncertainty present in geospatially referenced information along with a specification of the typology describing the specific uncertainties faced by intelligence analysts when tasked with creating an analytic product.