Visualizing Geothermal Simulation Data with Uncertainty

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Abstract

Simulations of geothermal reservoirs inherently contain uncertainty due to the fact that the underlying physical models are created from sparse data. Moreover, this uncertainty often cannot be completely expressed by simple key measures (e.g., mean and standard deviation), as the distribution of possible values is often not unimodal. Nevertheless, existing visualizations of these simulation data often completely neglect displaying the uncertainty, or are limited to a mean/variance representation. We present an approach to visualize geothermal simulation data that deals with both cases: scalar uncertainties as well as general ensembles of data sets. Users can interactively define two-dimensional transfer functions to visualize data and uncertainty values directly, or browse a 2D scatter plot representation to explore different possibilities in an ensemble.

Index Terms: I.6.6 [Computing Methodologies]: Simulation and Modeling—Simulation Output Analysis; J.2 [Computer Applications]: Physical Sciences and Engineering—Earth and Atmospheric Sciences

1 Introduction

A substantial challenge in the representation and simulation of geological phenomena is the inherent uncertainty in the underlying models. Data is usually available along boreholes, however, direct borehole measurements are expensive and therefore rare. Hence, to complete the model, data has to be estimated based on additional sources such as seismic measurements and projected subsurface structure, thus introducing further uncertainty. If a single general structure of the model can be assumed, this uncertainty can often be expressed in terms of a scalar value, e.g., the standard deviation around each mean value of some model property.

However, the spatial heterogenity for, e.g., rock properties in the examined region is not always known due to the lack of direct measurements. A distribution function for these, as well as certain spatial constraints can, nonetheless, often be assumed or estimated from existing data. Based on this, a common strategy is to use a Monte Carlo analysis approach, randomly generating an ensemble of stochastically equivalent realizations fulfilling this distribution (using algorithms such as SGSim [1]), and independently perform subsequent simulations on all instances of the ensemble [7].

Ensembles constructed in this way do not feature a consistent spatial layout with uncertainties for each value, but instead a series of different spatial incarnations that can differ significantly depending on the available data. Highly permeable regions could be found, e.g., on the western side in one incarnation and on the eastern side in another. Thus, the results gained from simulations on these ensembles probably also yield very different possible subsurface flow paths and connections, that can no longer be adequately represented by a single data and uncertainty value, but have to be evaluated separately or in characteristic groups.

A visualization application for these kinds of uncertain simulations has to accommodate both cases—scalar uncertainties and general ensembles—to be effective, and should also be able to handle large ensemble sizes. We chose direct volume rendering as the underlying visualization technique, supplemented with a tool which supports interactive and explorative 2D transfer function definition for cases with scalar uncertainties. To explore general ensembles, we propose a technique based on a 2D scatter plot representation constructed using similarity measures that can be used to interactively browse even through large ensembles with several hundreds of instances.

2 Visualization Design

We created a prototypical application that was used to visualize ensembles obtained from different simulations of the Soultz-sous-Forêts enhanced geothermal reservoir in France [3, 7], containing between 49 and 880 instances per ensemble. Each instance is a series of regular 3D scalar or vector fields describing different properties, such as permeability, temperature or Darcy velocity.

As principal visualization technique, our application is based on direct volume rendering realized using a GPU-based ray casting approach. It is complemented by other established visualization techniques in order to allow users to assume their familiar workflow and migrate from existing tools, and to be able to act as a standalone visualization application without the need for additional supporting tools. We therefore included the possibilities to visualize scalar fields—or scalar properties of vector fields, such as vector magnitude—by interactively inserting and modifying cut planes, inserting isosurfaces and interactively sliding them through the value range, and probe data along a line (such as a possible borehole), plotted in a line graph. Vector fields can be visualized using interactive particle tracing [4], or by computing streamlines.

The system is based on the platform independent virtual reality framework ViSTA, which enables the application to scale seamlessly from simple desktop computers to fully-immersive CAVE-like virtual environments. This enables users to benefit from the advantages of immersive display systems for visualization comprehension [5, 2] where available, without compromising the usage of the application on standard desktop workstations.

2.1 Interactive Transfer Function Selection

Whenever scalar uncertainties are directly available or a mean/variance representation is justified—for example, when a subset of instances sharing a common structure is examined—it is helpful to visualize these uncertainties.

In order to display a scalar data value as well as a scalar uncertainty using volume rendering, both values are mapped to color and opacity using a two-dimensional transfer function, where color is usually determined by the data and opacity by the uncertainty value. Additionally, users can restrict the displayed data range by defining

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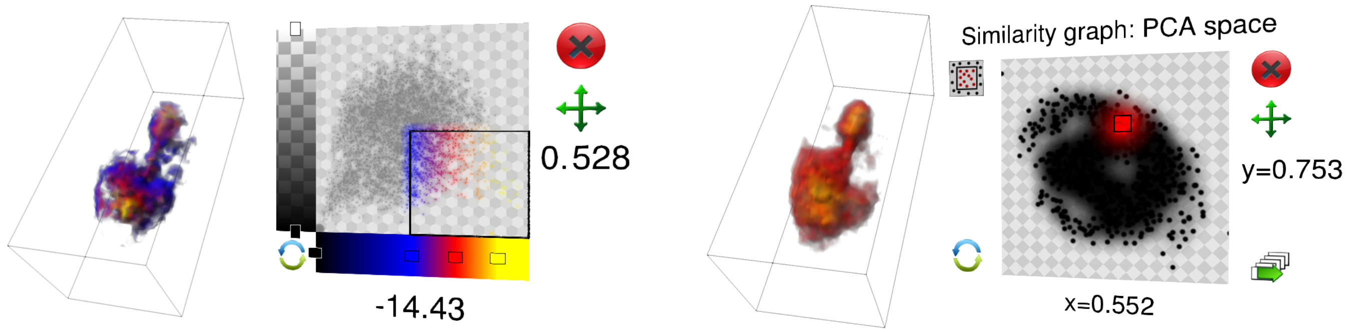

Figure 1: **Left:** Defining a 2D transfer function on a permeability field. The horizontal axis maps values to color, the vertical axis uncertainty to opacity. A scatter plot in the background shows the distribution of values; grayed-out values are entirely invisible. In this case, only highly permeable regions with low data uncertainty are selected as visible by the user. **Right:** The user selects a small subset of simulation instances from an ensemble whose rock permeabilities are combined into one mean/variance field and simultaneously displayed. Sliding the area along in different directions, a quick overview over the variations in overall permeability and the positioning of high-permeable regions becomes possible.

one or several rectangular regions in the domain of data and uncertainty values, outside of which the opacity value is set to zero. This is helpful, as a common use case is to look for data whose value is in a particular range and sufficiently certain. For example, when looking for possible subsurface fractures as candidates for effective fluid pathways, it is useful to select only highly permeable regions predicted with at least some minimum certainty.

The transfer function manipulation is done fully interactively in order to allow for an explorative examination of the data set, which means that all changes are visible in real time. Additionally, the specified selection windows can be slid over the data domain to develop an understanding of the distribution of data values. For example, sliding a region up and down along the vertical (uncertainty) axis quickly generates an overview where certain and uncertain regions are located. To simplify a meaningful selection, a scatter plot of existing value pairs is displayed in the background (see Figure 1, left). If the data are scalar—for example, when uncertainty information is not available—it is reduced to a histogram.

2.2 Interactive Ensemble Exploration

Getting an overview over hundreds or thousands of possible instances and possibilities in a large ensemble is a challenge. However, there are often structural similarities between different data fields in a simulation result. We therefore developed an interactive tool to browse through an ensemble based on a 2D scatter plot representation, where each ensemble instance corresponds to a point, and similarity between instances is expressed through spatial proximity between points (see Figure 1, right). A common method to create 2D scatter plot visualizations from higher-dimensional data is to apply a dimensionality reduction technique such as a principal component analysis (PCA) and interpret the coefficients of the two greatest principal components as 2D coordinates. This also yields useful representations here, as our data sets are usually aligned around fixed points where fact knowledge is available (e.g., borehole measurements), and there is also a certain local correlation, such that often a lot of variance is captured by the first few principal components.

However, particularly for data sets such as Darcy velocity vector fields (indicating subsurface flow paths), we expect that a semantic similarity measure, e.g., incorporating the number and configuration of connections between boreholes, will be more suitable. To be independent of the choice of similarity measure, we construct the scatter plot using a force-directed graph layout scheme, where nodes representing similar ensemble instances attract each other during the physical simulation. Currently, we use the negative Euclidean distance within a PCA subspace capturing at least 95% of the variance as similarity measure, which we empirically found to allow a rapid overview over the different major structural variations through fast browsing. However, we also allow to switch through other measures interactively (such as Euclidean distance).

3 Summary and Future Work

We have presented a visualization application that specifically helps geoscientists to interactively analyze simulation results of subsurface geothermal reservoirs and explore large and diverse ensembles. Although it already facilitates getting a good and quick overview over the different structures in an ensemble, we think that using similarity measures based on more domain-specific criteria will lead to an improved understanding of large simulation results, and may help to automatically classify results into human-comprehensible clusters. In this context, we are also investigating the use of further scatter plot layout techniques, such as multidimensional scaling or t-SNE [6]. To support domain experts in obtaining a comprehensive overview of available data, we further plan to integrate several data channels into the visualization (such as multiple data fields, seismic and borehole measurements, etc.).

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