Visualizing highly multidimensional time varying Microseismic Events

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Abstract

Making decisions about improving an oil and gas reservoir model based upon microseismic data is a difficult challenge for reservoir engineers and analysts. These difficulties arise because the available data contains inaccuracies, has high-dimensionality and has a high degree of uncertainty. Currently these difficulties are intensified by the lack of computational tools to support interactive visual interpretation and integration of geophysical data leading to robust structural models of the reservoir and its parameters. To address these difficulties domain experts are demanding better and more detailed visualization tools to help them as they explore their data. In this paper, we present a tool that contains a set of interactive visualizations that combines, merges and extends existing visualization techniques. We describe the iterative design process we undertook to develop the tool, relying on insight from domain specialists. Our tool supports 3D spatial analysis and exploration of the data with a set of manipulations designed to provide domain experts with insights into their highly complex microseismic data. Our microseismic visual-analysis tool also provides an extended parallel coordinates implementation to: (1) support interactive filtering and selection through combined filter and shadow boxes that can remove the uninteresting events from further analysis, (2) correlate between the data attributes by axes reordering and outlier discovery, and (3) visually correlate the data events rendering through additional visual elements such as color maps. Our multiple coordinated views link the insights gained from one view with other views instantaneously. We conclude with a discussion of the feedback provided to us by the domain experts.

1 Introduction

The increasing demand and importance of energy in our lives motivates the oil industry to make better and smarter decisions about such factors as oil well placement. This in turn is driving the need for better analysis and visualization tools to help with these decisions. However, the increasingly complex oil/gas datasets pose challenges for developing intuitive visualization tools. These challenges affect the decision making process related to the development of the oil and gas reservoirs.

Microseismic monitoring is an important surveillance tool for reservoir development management. Microseismic data is comprised of events that each represent an extremely small earthquakes [1] [18]. They are the result of fractures created and/or activated to allow oil and gas trapped in rock pores to flow more easily. The raw data are preprocessed resulting in an event catalog comprised of tabular information with many attributes per event. The data inherits high abstraction and uncertainty from the measurements and the preprocessing. One of the major challenges that faces microseismic visualization is the modeling and visualization of sparseness, inaccuracies and uncertainty that exist in the large multidimensional microseismic datasets. Our fundamental goal in this project is to map and visualize the data to achieve 3D spatial analysis, flexible filtering & uncertainty reduction, and attributes correlation.

Microseismic data are analyzed by several people such as - geologists, geophysicists, and reservoir engineers with different interests. The analysis consists of several tasks they might need to know the locations of the events in relation to the well in the reservoir, or be able to filter out noisy events and perform correlations between various attributes. Some important tasks performed by the experts include: understanding hydraulic fracture geometry, estimating stimulated reservoir volume (SRV), and optimizing long-term field development [18]. For such critical decision-making related operations, it is important to have a visualization tool that converts the data into efficient and effective visual representations. Such a tool should be designed to be better able to reflect and express the available information, the level of uncertainty and other pertinent data details from different stages of oil/gas exploration and production. The ultimate goal is to support the domain experts with interactive methods that let them explore, understand, analyze, and comprehend their information from these complex datasets.

We present a tool with set of visualizations to enable exploration and analysis of microseismic events. Many of the techniques used in this tool are inspired from ideas explored in the field of information visualization. Our tool combines and extends existing and visualization techniques for helping the experts explore their data and make informed decisions. A major contribution of this work is in presenting a flexible interactive filtering and correlating views through our enhanced parallel coordinates implementation. These views allow the domain experts to (1) easily focus their analysis/visualization over subset of the data and discard any uninteresting events from further analysis/visualization and (2) discover the main trends in the data attributes and quickly detect any outliers. We developed our tool iteratively with feedback and consultations from domain experts. In presenting these discussions our paper provides detailed insight from reservoir engineering domain experts regarding the validity of our approach, its strengths and limitations, and directions for future improvements.

2 Microseismic Background

Microseismic data has been used for decades for various applications including engineering, mineral mining, and water storage. However, the use of microseismic monitoring for oil and gas is a recent field that began around ten years ago. The importance of this new method is increasing because of the industry focus on improving reservoir production [17].

Fracturing is one way to create a reservoir as it allows oil and gas trapped in rock pores to flow more easily [18]. The (hydraulic) frac-

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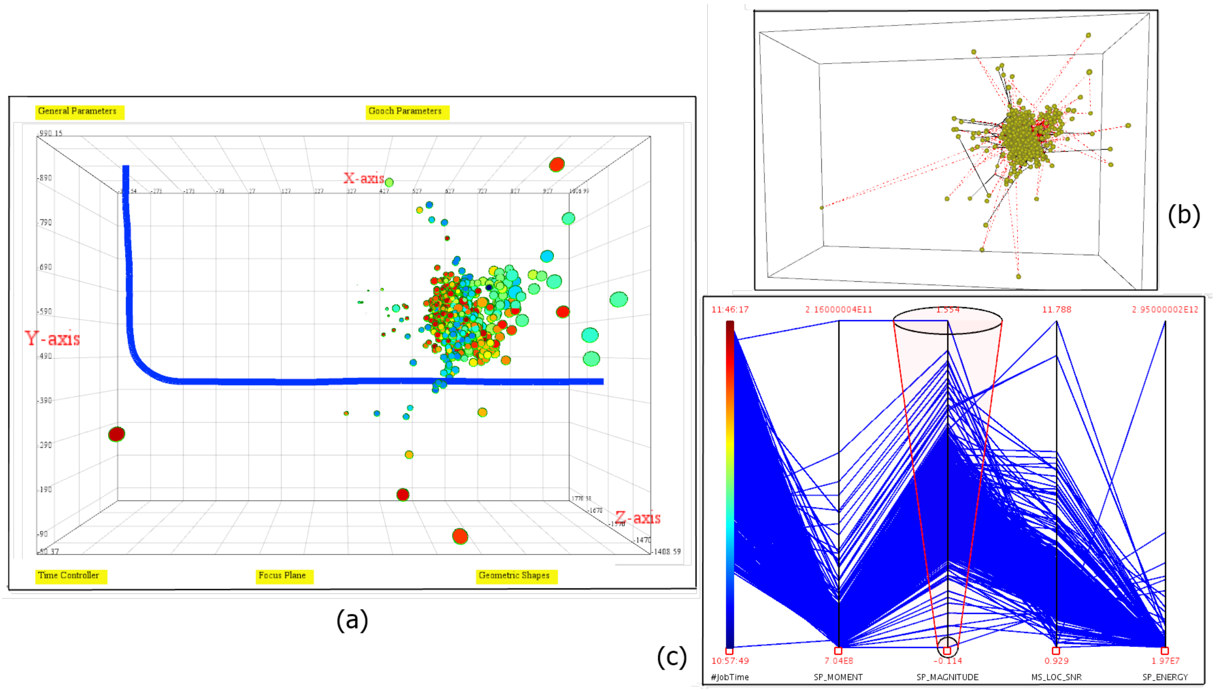

Figure 1: Synchronization of the parallel coordinates view (c) with other data visualization components: (a) 3D point cloud and (b) the point cloud topology (Geometric representations View).

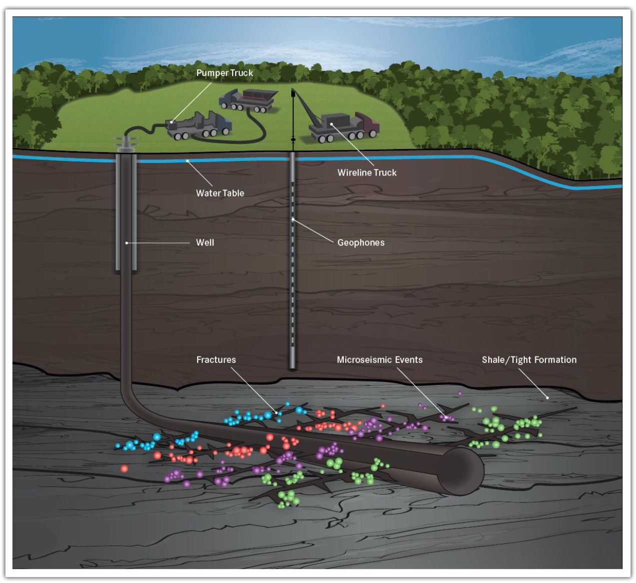

Figure 2: Hydraulic fracture schematic overview [1] .

ture is created by injecting water or other chemical fluids into the rock formation with high pressure causing the formation to crack or fracture. Sometimes multi-stage hydraulic fracturing techniques are designed to expose a larger amount of drainage area to the wellbore as compared to a single fracture. Micro-earthquakes (also called microseismic events) associated with either the creation of new fractures or activations of pre-existing fractures are used to image the hydraulic fracture growth. These images can be used to optimize the fracture process and the resulting production from the well. Receiver systems (i.e. geophones) can be placed in specific locations near the (fracturing) process to detect the energy generated by the microseisms and then to provide geometric and behavioral information about the process.

Microseismic events locations are calculated using a velocity model [6]. The velocity model typically considers the movement of the energy waves generated by the fractures. Specifically, the speed of these waves and/or the arrival times between the fractures initial locations and the receiver systems. Combined with minimal information (i.e. limited acquisition geometry), the uncertainty is inherit in this model causing uncertainty in the calculated locations of the microseismic events. In addition recorded microseismic events typically have noise associated with them, and this may come from many noise sources including even a truck moving on the surface. Thus the microseismic data events, in addition to its ambiguity, contain noise and inaccuracies that make it highly uncertain.

3 RELATED WORK

Many visual analytics systems & visualization techniques have been developed through the recent years [26]. These systems provided different forms of visualizations to support data analysis and exploration. Although these tools assist users in their decision making process, there is still lack of visual analytics systems of geophysical data in microseismic domain. In this section, we review some of the most related works in the context of visualization (especially for multidimensional data visualization) as well as the context of microseismic monitoring and visualization.

3.1 Visual Analytics

Information visualization research includes many known techniques for visualizing multidimensional data as well as using multiple (coordinated) views and focus & context techniques. In this section, we summarize some of the key related works that represent the basis of our implementation.

Multi-dimensional scaling MDS [29] is one popular method for reducing dimensionality for the purpose of finding the points similarity through the different dimensions. Elmqvist et al. proposed a starplot-like system; DataMeadow [8] which is a visual canvas for analysis of large-scale multivariate data with flexible visual queries. Although these techniques condense the data into few dimensions, we decided to base our visualization of the multidimensional data on parallel coordinates [12] which is a well-known technique for visualizing highly dimensional data by representing every dimension as vertical axis parallel to other dimensions on a 2D plane. Our extended parallel coordinates implementation supports correlation and filtering. Parallel coordinates have been applied in many different visual analytics systems. Feng et al. [9] presented a visualization tool for magnetic resonance data with high emphasize on parallel coordinates. Steed et al. [26] presented a system for weather analysis data using an enhanced parallel coordinates implementation. Parallel coordinates brushing is an operation to select subset of the data and reduce cluttering. Martin et al. [16] discussed high dimensional brushing for exploring multivariate data with focus on parallel coordinates. These brushing methods have been integrated in XmdvTool [28]; a system that integrates many multivariate visualization methods, proposed by Ward [28]. Besides that, some research has been done for evaluating the usability of parallel coordinates and how the current implementations are following the community guidelines [25]; they expressed that the people who performed the tasks on parallel coordinates found it more effective than those who used some other traditional methods.

Multiple coordinated views approach is considered a technique used in many visualization systems. Roberts provided a discussion of the state of art on using coordinated multiple views [22], and he also discussed many systems that support this technique. Bowman et al. [5] presented an example of a system for analyzing MRI repositories using multiple coordinated views. Wang-Baldonado et al. [27] provided a set of guidelines for using multiple views in information visualization while Andrienko et al. [2] provided a critical view for using multiple coordinated views.

In our implementation of parallel coordinates view and the hybrid visualization, we support filtering similar to the idea of Sigma Lenses [21]; a technique for improving the transition between focus and context, and the blurring of the context through semantic depth of field [14].Our implementation allowed this transition through the use of transparency and different color shading. Also our filter boxes (lenses) for brushing the parallel coordinates have some similarities with Magic Lenses [4].

3.2 Microseismic Monitoring & Visualization

Majority of the work in the domain of microseismic engineering and geosciences has been in the area of developing mathematical methods for microseismic monitoring [18] [6]. Unfortunately, not much research has been done in the area of microseismic visualization and many of the microseismic scientific papers use Matlab or commercial tools for their visualization needs [13].

Multidimensional transfer functions for volume rendering and glyphs proposed by Marbach et al [15] are used as tools for improving seismic interpretations. Rugis et al. [23] used a 3D reservoir visualization tool for modeling reservoir structures including visualization of microseismic events and their impact on the fracturing process.

Most of the microseismic technology available today is from industry commercial packages such as Schlumberger Microseismic Evaluation that provides many features, tools and plots for working with pumping data, microseismic events, and features extraction.

4 DESIGN DECISIONS

The multidimensional microseismic data is highly abstract and inherits high uncertainty making its visualization difficult.

Estimating the stimulated reservoir volume (SRV) is one of the common tasks in microseismic engineering. Early consultations with domain experts suggested that flexible filtering of the events is a key operation while analyzing the data events prior to calculating the SRV. In this task, the expert needs to focus and select freely from the subset of the events that s/he considers to be the important ones for estimating the SRV and the fracture growth. The ability to filter the data and base decisions about considering some event is greatly affected by understanding the data, and any relations between its attributes. Considering the uncertainty and abstraction of the data along with the requirements of this task, we analyzed the data, the different possible visual representations & techniques in our design process. Our goal was to provide a tool that supports microseismic visualization and analysis with emphasize on supporting flexible filtering and correlation.

In this section, we describe the design process as the following: First, we will overview the dataset, then the visual mapping, and finally some possible visualization techniques. The latter could be used for visualizing this type of data, and aiding in such a common task.

4.1 The Data

The data available for this project was provided by the Microseismic Industry Consortium, which is a geophysical research initiative at the Department of Geoscience, University of Calgary and University of Alberta, focused on technological innovations in microseismic methods and their applications for resource development.

The microseismic data is highly multidimensional time varying point cloud dataset. The dataset poses many attributes per event (36 attributes) along with more than 5000 events. It has high uncertainty because of the noise associated with it that mainly resulted from inaccurate measurements. The data may provide different interpretations making it quite abstract. The dataset consists of several microseismic (hydraulic) stages, and each stage has its own microseismic events. We only considered the first stage while developing this tool, but we are considering integrating more stages as future work.

One microseismic event has several different attributes. Following is an overview of some of the important attributes:

1. **Time**: hour, minute and second;
2. **Spatial location of a microseismic event**: (x,y,z);
3. **Distance from the event hypocenter to the sensor**;
4. **Signal-to-Noise Ratio**: which measures how a signal has been corrupted by noise;
5. **Ratio between P-wave and S-wave amplitudes**;
6. **Radius**: determines the size of ruptured area by the event;
7. **Moment**: the seismic moment, M0, has dimensions of energy (N-m or dyn-cm) and is the scalar measure of an earthquake rupture size related to the action of force across the area the fault;
8. **Magnitude**: a log scale similar to the well-known Richter scale for earthquakes;
9. **Energy**: calculated by considering the history of a particle as it responds to a transient seismic wave field.

Although the analyst can choose and consider any subset of the attributes, we designed the tool with a focus on emphasizing the most important attributes [24]. The decision about the choice of these attributes was a result of discussions and consultations with the domain specialists.

4.2 Visual Mapping & Design Decisions

It is important for any successful visualization to carefully choose a visual mapping model that better reflects intuitive and correct representation of the raw data. A seminal inspiration for this part is Bertin [3], who analyzes diagrams and maps as a semiotic system of marks, encodings, and spatial properties. He also introduced the concept of visual variables within the context of cartography, which we apply for creating visual representations.

Some visualizations can misinform people because of weakly designed representations, so we carefully used mapping of visual variables as discussed below to insure that the data is being represented as visual elements that clearly emphasize the importance of certain data attributes [24].

We chose to represent every microseismic event as sphere whose center is the 3D spatial location of the event. We also decided to consider the spheres radius to be proportional to any of the events attributes. We initially chose magnitude value since it is one of the most important attributes. The choice of mapping the radius of each event sphere with the magnitude of the event was acknowledged by our domain specialists. They considered this mapping as natural to them and comparable to many existing commercial tools.

Two customizable coloring models for shading the spheres surface are supported. The first color model is based on Gooch shading [10] which provides a consistent coloring for all the spheres. We expanded its implementation to support depth perception in addition to its classical color temperature. The second model shades the spheres according to a jet color map (that goes continuously from dark-red to dark blue). The color of each sphere is defined by relating one of the events attributes to the color map. This method of coloring the spheres surfaces allows the viewer to expect a reading order from color (color correlation). Specifically, the jet color map allows people to quickly identify/relate at least three categories, low (dark red), medium (green) and high (dark blue). In our implementation, we chose correlating the color of the events with respect to the time-stamps attribute since it is widely used for correlation with other attributes. The choice of careful mapping through multiple visual variables is powerful as it can provide the user with much information at once. For example, when the user sees some large spheres colored in red, s/he would know immediately that their distribution represents the 3D location of the high magnitude areas. Their color would give a quick idea about their time-stamp values. Our choice of these visual encodings has been accepted in a later discussion with the domain specialists.

4.3 Visualization Techniques

Many techniques can be used to visualize multidimensional data allowing easier interpretations and analysis. We will present overview about some of the techniques that we have investigated before starting our implementation, and then we will explain our choices.

One possible method for dimensionality reduction is Multidimensional scaling or (MDS) [29]. However, MDSs main focus is in studying points similarity. Scatterplot matrix [7] is also a famous technique to visually represent multidimensional data by creating a matrix of N2 scatterplots arranged in N rows and N columns. Scatterplot is a graphical plot of two variables aiming at visually analyzing them. However, the resolution of each scatterplot in the scatterplot matrix is limited when the data poses high dimensionality. Another widely used technique is Parallel coordinates [12] that visualize high dimensional data by representing each dimension with vertical axis parallel to other dimensions. Parallel coordinates is known to suffer from cluttering. However some strategies exist, such as brushing [16] and axis ordering [20] to alleviate these problems.

We considered different parameters for choosing which technique to use. First, we guide our design by one of the common tasks, and we choose the method that is deemed more relevant to our task. In this case, we wanted to provide visualization and correlation of the data attributes with filtering support. Second, parallel coordinates is widely used and supports scalability. For example, it can be combined with scatterplots as in [30]. Third, the study performed by [25] revealed that the people who performed their tasks through parallel coordinates found it more effective than those who used some other traditional methods. Finally, the experts of the microseismic domain are mostly familiar with plots from scientific tools such as Matlab, so by providing them with simple 2D plot in our case enhanced parallel coordinates may make more sense to them.

5 Approach

We present a tool that contains a set of interactive visualizations that combines and extends existing and visualization techniques (Fig. 2). Our tool supports 3D spatial analysis and exploration of the data with interactive mechanisms allowing the domain experts to gain insights into this highly complex microseismic data. The tool also presents an extended parallel coordinates implementation allowing interactive filtering and correlation.

5.1 Multiple Visualizations

Our implementation follows the multiple coordinated views approach. The system supports three views (Fig. 2), each presenting the data in a different way, allowing people to link and relate the meanings gained from one view with the others. The viewer can also use one view to control the data visualization and the other views will be updated automatically (synchronized or coordinated) to reflect these changes.

The main 3D view allows exploration and visual-analysis of the microseismic events in the reservoir space with well integration. The second, parallel coordinates, view allows correlation and interactive filtering. This view directly affects the steps prior to the calculation of the SRV leading to better estimation. The third view aims at reducing cluttering inside the main view. In the following subsections, we will provide a detailed description of each view.

5.1.1 3D Spatial Visualization

The main goal of this visualization is to represent the data in its spatial distribution, providing basic insights about its geometry. The 3D visualization component/view displays every event point as a sphere in the 3D view, where the spheres color and radius each encode an attribute value. In the example shown (Fig. 2 (a)), the radius is relative to the events magnitude, and the surface-color is relative to the events time-stamp value. Depicting data spatially show data points in relationship to each other to aid exploration, 3D correlation, analysis and understanding of the data.

We support rendering the point events in this view in many ways. One of them is through depth-based Gooch shading (Fig. 3). In our customizable implementations, the events are being rendered with their colors being modified according to the distance from the camera eye, and this is to simulate depth perception. This view also gives the user the option to keep partial context while focusing on subset of the data events. S/he can decide to render the filtered-out events with transparency instead of removing them completely. Furthermore, color map (jet) has been implemented and the rendering of point events in this view can follow this color map allowing a time-based reading order from the color value immediately (Fig. 2). Our interface also allows the user to control whether the rendered event spheres will have a variable radius, according to their magnitude or not.

5.1.2 Parallel coordinates Visualization

Parallel Coordinates technique can be used to better visualize and understand the main trends or relations between the data attributes.

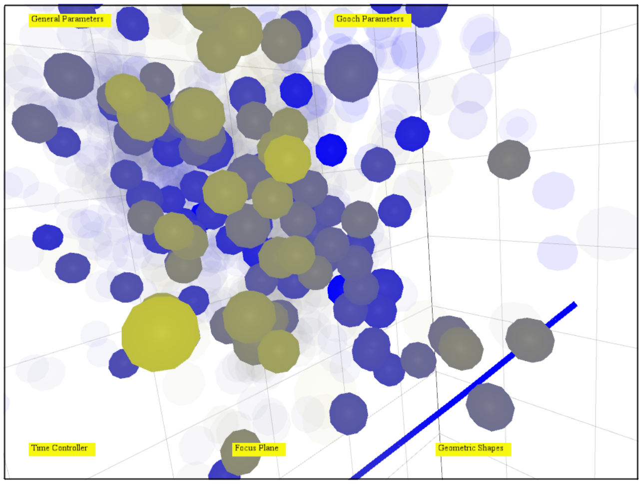

Figure 3: 3D visualization view showing the events being rendered using extended Gooch shading. The filtered out events are rendered transparent to keep the context.

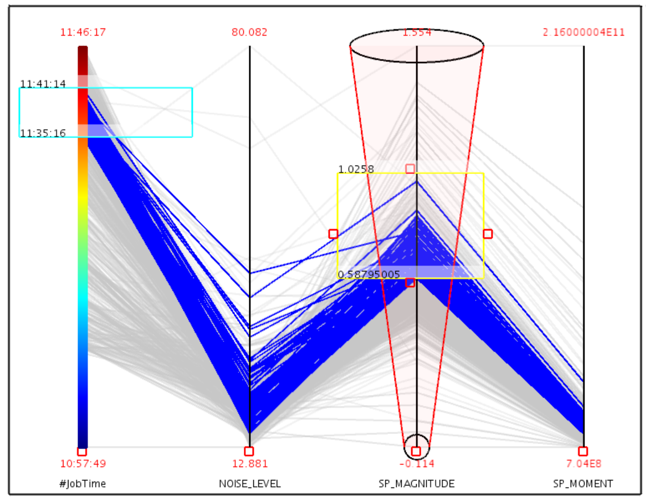

Figure 4: Parallel coordinates with filter boxes, jet color map and the blended size-mapping graphical legend.

It is considered a robust way to visualize high-dimensional geometry and to support analyzing multivariate data. The standard implementation of parallel coordinates is a 2D projection of the multidimensional data attributes by representing every attribute/dimension as vertical axis or column. We extend parallel coordinates implementation (Fig. 4) by adding the concept of filter (rectangular) boxes (similar to lenses) over the 2D view, supporting interacting and filtering of the data attributes. The user can create many filter boxes to achieve complex filtering. This idea is similar to iterative brushing [8] which allows creating composite filters in order to focus on subset of the data. We also present graphical legends over some of the columns. For example, a continuous jet color map has been rendered over the time-stamp attribute showing coloring of the event spheres according to the color map range/scale. Another example is about a sizing visual element legend that has been placed over the magnitude column supporting quick connections between the events spheres size with the magnitude value; for instance, the higher the magnitude of an event, the bigger its sphere radius. In addition to that, the user can reorder the sequence of the attributes columns. This is important for analyzing attributes correlations, detecting trends and discovering outliers. The user may reorder the attributes by dragging any columns handle (red square at the bottom of every column) closer to any other attributes columns, and as a result, they will be swapped when the user stops the dragging.

The user can create new filter box by clicking and dragging over an empty area of this view. A preview box will be rendered while the user is dragging an axis to provide a guide that shows the current area the filter box will be occupying. When the user releases the mouse to end the dragging action, a filter box will be created. All the visible attributes columns that intersect the filter box will be filtered. For example, the filter box shown (in Fig. 4), over the #jobTime or time-stamp attribute, selects only the events that has time-stamp values between 11:35:16 and 11:41:14.

Observe that there are two filter-boxes (Fig. 4); one of them is colored in yellow which means it is being selected, and can be resized, using any of the four red corners, or moved/dragged as you move any desktop icon (just click inside and drag). Finally, you can remove any filter-box by clicking inside its bounding area with the right mouse button. If the user created any filter box, the lines representing all the data events inside this filter will be rendered in solid (shown in blue), while the filtered out events lines will be rendered in transparent gray to keep the context.

Shadow boxes (Fig. 5) are other novel visual elements or graphical legends that can be attached with filter boxes allowing (1) range/cluster navigation; by gradually fading all the point events before and after the current active filter box, and (2) partial contextualization. This feature is inspired by the work on [11], which presents a visualization showing the evolution of 3D flow with time. The number of shadow boxes as well as their properties can be controlled through a specialized Graphical User Interface (GUI) panel in the 3D view. For example, in Fig. 5, three shadow boxes have been attached to the filter box created over the time-stamp attribute. We can see that although we are strictly filtering the point events between 11:20:26 (light-green) and 11:25:28 (light-yellow), but the (synchronized) 3D view shows also some events colored in light-red and light-blue. Notice also that shadow boxes transparency increases gradually allowing clustered navigation with gradual partial context. Furthermore, the contour of all the completely visible events has been rendered to allow quick identification of the spheres strictly inside the filter box. This will allow quickly identifying them among the other clustered one by the shadow boxes. This idea is all about showing the immediate neighboring context of the current active filter box. All of the actions performed on this view are automatically coordinated the other visualization views. We think that combining the idea of shadow boxes with filter boxes can inspire more techniques. For example, imagine our filter boxes with shadow boxes as custom lenses over the parallel coordinates that allow custom transition between the focus points (inside the filter box) and the context (the points inside the shadow boxes) [14].

5.1.3 Additional visualizations

The user might also want to explore, in 3D, any geometric relations among some interesting point events. Therefore, s/he may need to see the points connectivity in representational structure, i.e., exploring a tree/graph structure that connects these point events together providing geometric analysis.

Our tool supports 3D Ball-Tree (Fig. 6 (b)) [19] that bounds a subset of events similar to the binary tree data structure. The ball-tree structure allows similarity-like analysis by creating a binary tree graph connecting all the interesting points defined by the user. For example, by showing ball-tree for any subset of the events, the user would be able to identify and trace all the similar events by starting from any single event. Another geometric structure that has been implemented is 3D Histogram Tree (Fig. 6 (a)). Histogram Tree bounds each group of point events that share the same time-stamp value in one (green) sphere, and connects them using solid lines. Each distinct group with different time-stamp is connected to the next/previous one using stylized lines.

The 3D view also provides the user with the ability to specify a region of interest (ROI) where further processing will only be applied to events inside that area (Fig. 7 (a)). The user can specify a ROI (light violet sphere) by selecting a focus point (black square) over a focus plan (light green), and defining the ROI area size and depth (through the GUI). Then s/he can enable some controls for generating different geometric structures such as ball-tree structure, or the histogram tree structure (Fig. 6) only for the events inside the virtual sphere (ROI). The ability of showing these 3D geometric relations for all the visible point events in the 3D scene, even if they are not inside the ROI, is also supported. The rendering of the geometric representations can be directed to another view, if needed, to prevent cluttering this view with many visualization aspects.

5.1.4 Tree View Visualization

The main purpose of Tree view (Fig. 7 (b)) or Geometric representations view is to act as additional view to show the 3D geometric connectivity (such as graphs/trees) between some point events. This would prevent cluttering the main 3D view with many visualization features. This view is coordinated automatically with the contents of the 3D main view.

5.2 Implementation

We implemented our visualization environment using Java and Processing library; a visualization framework/language based on OpenGL. Our project uses some external Processing-based libraries such as: XlsReader for reading the data files, PeasyCam for providing 3D Camera navigation and interaction, and finally G4P for providing components for building the GUI. The application is highly interactive with real-time performance; running on 60 FPS most of the time. The implemented tool represents an initial prototype for visualizing microseismic events, and many improvements and ideas are currently being investigated and integrated.

6 RESULTS & DISCUSSION

As we previously mentioned, we envisioned our implementation by one of the main tasks in microseismic analysis; estimating the SRV. Intuitive events filtering/selection and attributes correlation are key operations for satisfying this task. The following subsections will be organized according to the main tool themes: flexible events filtering, attributes correlations, and 3D spatial analysis.

We did three assessment sessions. Each session included one microseismic domain expert and visualization specialists. We asked them about our visualization tool and their feedback regarding it. In this section, we will discuss the details of these sessions including ideas for improvements, positive & negative feedback.

After having our first session, we received many feedback and suggestions so we updated the system. Then, we had our second session with the same group, because we wanted them to provide us with more accurate feedback and to validate/confirm if the new updates make more sense to them. Finally, we had the last session with different domain experts who provided (1) feedback similar to what weve received from the first two sessions, and (2) new feedback regarding different system aspects. Much earlier before having these assessment sessions, we had early consultation sessions with domain experts, where we discussed the main directions/requirements for the development of this tool.

6.1 Regarding Events Filtering & Selection

A key operation to the SRV estimation is the selection of subset of events, ideally, those which have minimal noise and uncertainty. We supported flexible interactive filtering and selection of events through our extended parallel coordinates implementation. In this section, we will discuss their feedback including weaknesses and strengths.

6.1.1 Filtering Feedback

Our tool initially implemented filter boxes by strictly showing only the point events inside them and completely removing all the other point events. During our first session, we got feedback that removing the filtered-out point events is not useful since the user loses the context. So we updated our filterings implementation to show those filtered-out data events using transparency (as showing in Fig. 3) so the context is not lost. During the second session, the same participant who initially gave us this feedback expressed that our implementation now is more useful.

Another participant, also during the first session, suggested an alternative way to keep the context while filtering the data inside the parallel coordinates view. S/he described the idea as a way to support clustering the points in certain ranges using gradual color/transparency values. S/he suggested the use of virtual boxes that could be attached to our filter boxes to maintain partial context. We implemented this idea as shadow boxes. Other participants, later, found that to be a good way of seeing the future/past virtual events around our currently active filter box. After we implemented this feature, and during later sessions, most of the participants expressed that the feature of shadow boxes is good for keeping the transparent context of the events of around the currently active subset.

We asked another participant if our events filtering method is easier or not in comparison to other similar tools. S/he specifically expressed that s/he is unsure if our filtering and correlation method is easier or not, but s/he thinks that it is different, intuitive and easy enough to use.

6.1.2 Ideas for improvements

Many of the participants during the sessions were excited about our system. We received many ideas and suggestion for improving out tool. Free-form sketch-based selection and filtering is an important suggestion to support an advanced filtering mechanism that could be guided by the user knowledge. One example stated by one of the participant was the idea of allowing the user to select all the point events around the well regardless of their attributes. Another participant suggested the idea of extending the filter boxes customization with extra parameters, so one filter box may inverse the visibility of all events inside it or even render them in a different way. S/he also suggested that it will be even more useful to allow the user to accurately define the bounds of any filter box. This can be done by a customization that gives the user the ability to directly specify the bounding limits (dimensions) of any filter box. We are considering this as part of our future work. Another suggested idea (which has been implemented) was about drawing the contour of all the visible point events inside the filter boxes, especially when we are fading some of the filtered-out events.

6.2 Regarding Attributes Correlation

One domain expert specifically expressed that the tool is good, especially the flexible interaction which is really nice. S/he specifically likes the parallel coordinates view. S/he expressed that correlating the attributes in this view can help in finding & detecting outliers. Furthermore, s/he expressed that the ability to reorder the attributes is intuitive idea for visually showing the trends and relations between successive attributes. While we were presenting the system, a domain expert discovered some weird values, and expressed that it is a good finding and needs more careful analysis/reviewing. Furthermore, when we were showing the feature of axes reordering, s/he specifically expressed that the sequence of numbers is interesting and s/he suggested the display of units with the option to convert them will be really helpful.

Most participants think that our improvements over the parallel coordinates attributes are good. Specifically the idea of placing the color-map and sizing-visual-element (graphical legends) over the time-stamp and magnitude attributes, respectively. Most of them suggested that extending this feature to allow placing these legends over any of the PCs attributes will be useful. Indeed, some participant stated that the only criticism is that we should make sure that the attributes units and numbers are written correctly.

6.3 Regarding 3D Spatial Analysis & Correlation

Analysis of events in 3D is the next logical operation to do after the filtering. Users would try to select some events and explore the analysis of their distribution (geometric analysis).

During one of the assessment session, one participant expressed that some of the implemented features are very important for her/his work. S/he expressed that the way we allowed ROI selection is more intuitive in comparison to some other (commercial) tools that s/he is using for doing this task. Finally, s/he expressed that the idea of listing more details about any (highlighted) event in the 3D view will be helpful. This idea is basically details-on-demand that can be supported through lenses, and we are considering it as part of our future work.

Most participants, on the other hand, were confused about our 3D geometric representations, and they preferred a simplified correlation in a 2D Scatter-plot like visualization than doing the correlation in 3D which they claim was not so expressive. One of them also expressed that we should minimize the GUI cluttering of having many windows/views visible at once most of the time. S/he expects that the main interface to only show the 3D visualization and the parallel coordinates visualization, with the ability to show the other views whenever needed.

7 Conclusion & Future Work

The analysis and visualization of microseismic events is important for optimizing many processes in the reservoir development. Microseismic data is multidimensional with high uncertainty and high abstraction. In this paper, we present a tool for exploratory analysis and visualization of the microseismic data events. The main goal of this tool is to allow 3D spatial data analysis, attributes correlation, and flexible filtering & selection. These are the key operations for having better estimation of the stimulated reservoir volume (SRV) leading to better oil/gas production. We combined information and scientific visualization techniques for supporting the users with integrated flexible highly interactive tool.

Our tool supports interactive multiple visualizations. It visualizes different aspects of the data in different coordinated views in order to link and relate insights gained from one view with the others. This can also facilitates and correlate the data aiming at uncertainty reduction. The developed tool also uses our enhanced parallel coordinates implementation to (1) allow correlating the data attributes with the flexibility to re-arrange them to find important trends as well as to discover any outliers, and to (2) allow flexible filtering of the microseismic events by creating a subset of the events that could be used to estimate the SRV of the reservoir.

Beyond the developed tool and visualizations, we present the results of the assessment sessions we had with domain experts. We discussed their feedback regarding validating our approach, its strengths & weaknesses, and the directions for improvements. Furthermore, we highlighted (from the discussion and their feedback) how insights could be gleaned through our tool.

Since it is an ongoing project, with preliminary prototype developed, there are many improvements to follow. As future work, integrating a sketch-based visualization technique will allow incorporating user free-hand manipulation of some point events leading to a better SRV estimation. Expanding the tool to visualize multiple microseismic stages and integrate actual geological models is also a future work. This would provide more contextualization and scalable correlation support.

Regarding improving our parallel coordinates implementation, we are looking forward to support attributes zooming by expanding and scaling the range of its values. We will also consider improving the idea of graphical legends (such as the sizing-visual-element and color map) placement over any attribute, in order to achieve better rendering of spheres and better visual correlation. Another idea is to improve our filter boxes implementation by expanding them with extra properties. This can be used for comparing subsets of the events through assigning each one of them different rendering properties and then analyze them. It can also be used for giving the user more flexibility to customize the exact boundary values of any filter box for more accurate filtering. Our ultimate goal is to create a complete visual-analytics solution for the microseismic experts by extending and integrating other visualization techniques.

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References

[1] ESG Solutions hydraulic fracture mapping. `https://www.esgsolutions.com/english/view.asp?x=741`. Accessed: 31/03/2012.

[2] G. Andrienko and N. Andrienko. Coordinated multiple views: a critical view. In *Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV '07. Fifth International Conference on*, pages 72 –74, july 2007.

[3] J. Bertin. *Semiology of graphics: diagrams, networks, maps*. University of Wisconsin. Press, 1983.

[4] E. A. Bier, M. C. Stone, K. Pier, W. Buxton, and T. D. DeRose. Toolglass and magic lenses: the see-through interface. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '93, pages 73–80, New York, NY, USA, 1993. ACM.

[5] I. Bowman, S. Joshi, and J. Van Horn. Query-based coordinated multiple views with feature similarity space for visual analysis of mri repositories. In *Visual Analytics Science and Technology (VAST), 2011 IEEE Conference on*, pages 267 –268, oct. 2011.

[6] B. Daku, J. Salt, and L. Sha. An algorithm for locating microseismic events. In *Electrical and Computer Engineering, 2004. Canadian Conference on*, volume 4, pages 2311 – 2314 Vol.4, may 2004.

[7] N. Elmqvist, P. Dragicevic, and J.-D. Fekete. Rolling the dice: Multidimensional visual exploration using scatterplot matrix navigation. *Visualization and Computer Graphics, IEEE Transactions on*, 14(6):1539 –1148, nov.-dec. 2008.

[8] N. Elmqvist, J. Stasko, and P. Tsigas. Datameadow: A visual canvas for analysis of large-scale multivariate data. In *Visual Analytics Science and Technology, 2007. VAST 2007. IEEE Symposium on*, pages 187 –194, 30 2007-nov. 1 2007.

[9] D. Feng, L. Kwock, Y. Lee, and R. M. Taylor II. Linked exploratory visualizations for uncertain mr spectroscopy data. *Visualization and data analysis*, 7530:1–12, 2010.

[10] A. Gooch, B. Gooch, P. Shirley, and E. Cohen. A non-photorealistic lighting model for automatic technical illustration. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '98, pages 447–452, New York, NY, USA, 1998. ACM.

[11] W.-H. Hsu, J. Mei, C. D. Correa, and K.-L. Ma. *Depicting Time Evolving Flow with Illustrative Visualization Techniques*, page 136. 2010.

[12] A. Inselberg and B. Dimsdale. Parallel coordinates: a tool for visualizing multi-dimensional geometry. In *Proceedings of the 1st conference on Visualization '90*, VIS '90, pages 361–378, Los Alamitos, CA, USA, 1990. IEEE Computer Society Press.

[13] L. B. A. E. M. C. J.H. Le Calvez, R.C. Klem and S. J.C. Palacio. Real-time microseismic monitoring of hydraulic fracture treatment: A tool to improve completion and reservoir management. pages 29–31, College Station, Texas USA, 2007. Society of Petroleum Engineers.

[14] R. Kosara, S. Miksch, and H. Hauser. Semantic depth of field. In *Proceedings of the IEEE Symposium on Information Visualization 2001 (INFOVIS'01)*, INFOVIS '01, pages 97–, Washington, DC, USA, 2001. IEEE Computer Society.

[15] J. Marbach, B. Kadlec, and J. Carlson. Multiattribute Visualization Using Multivariate Volume Rendering and Glyphs. In *Attributes: New Views on Seismic Imaging – Their Use in Exploration and Production: 31st Annual*, volume 31, pages 140–158. SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS, 2011.

[16] A. R. Martin and M. O. Ward. High dimensional brushing for interactive exploration of multivariate data. In *Proceedings of the 6th conference on Visualization '95*, VIS '95, pages 271–, Washington, DC, USA, 1995. IEEE Computer Society.

[17] S. Maxwell. Microseismic: Growth born from success. *The Leading Edge*, 29(3):338–343, 2010.

[18] P. Norm Warpinski. Microseismic monitoring: Inside and out. *Journal of Petroleum Technology*, 61(11):80–85, 2009.

[19] S. M. Omohundro. Five balltree construction algorithms. Technical report, 1989.

[20] W. Peng, M. O. Ward, and E. A. Rundensteiner. Clutter reduction in multi-dimensional data visualization using dimension reordering. In *Proceedings of the IEEE Symposium on Information Visualization*, INFOVIS '04, pages 89–96, Washington, DC, USA, 2004. IEEE Computer Society.

[21] E. Pietriga and C. Appert. Sigma lenses: focus-context transitions combining space, time and translucence. In M. Czerwinski, A. M. Lund, and D. S. Tan, editors, *CHI*, pages 1343–1352. ACM, 2008.

[22] J. Roberts. State of the art: Coordinated multiple views in exploratory visualization. In *Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV '07. Fifth International Conference on*, pages 61 –71, july 2007.

[23] J. Rugis and P. Leary. Towards crustal reservoir flow structure modeling through interactive 3d visualization of meq & mt field data. In *In Proc. 33rd New Zealand Geothermal Workshop*, November 2011.

[24] J. Shemeta and P. Anderson. It's a matter of size: Magnitude and moment estimates for microseismic data. *The Leading Edge*, 29(3):296–302, 2010.

[25] H. Siirtola and K.-J. Räihä. Discussion: Interacting with parallel coordinates. *Interact. Comput.*, 18(6):1278–1309, Dec. 2006.

[26] C. Steed, J. Swan, T. Jankun-Kelly, and P. Fitzpatrick. Guided analysis of hurricane trends using statistical processes integrated with interactive parallel coordinates. In *Visual Analytics Science and Technology, 2009. VAST 2009. IEEE Symposium on*, pages 19 –26, oct. 2009.

[27] M. Q. Wang Baldonado, A. Woodruff, and A. Kuchinsky. Guidelines for using multiple views in information visualization. In *Proceedings of the working conference on Advanced visual interfaces*, AVI '00, pages 110–119, New York, NY, USA, 2000. ACM.

[28] M. Ward. Xmdvtool: integrating multiple methods for visualizing multivariate data. In *Visualization, 1994., Visualization '94, Proceedings., IEEE Conference on*, pages 326 –333, oct 1994.

[29] M. Williams and T. Munzner. Steerable, progressive multidimensional scaling. In *Proceedings of the IEEE Symposium on Information Visualization*, INFOVIS '04, pages 57–64, Washington, DC, USA, 2004. IEEE Computer Society.

[30] X. Yuan, P. Guo, H. Xiao, H. Zhou, and H. Qu. Scattering points in parallel coordinates. *Visualization and Computer Graphics, IEEE Transactions on*, 15(6):1001 –1008, nov.-dec. 2009.

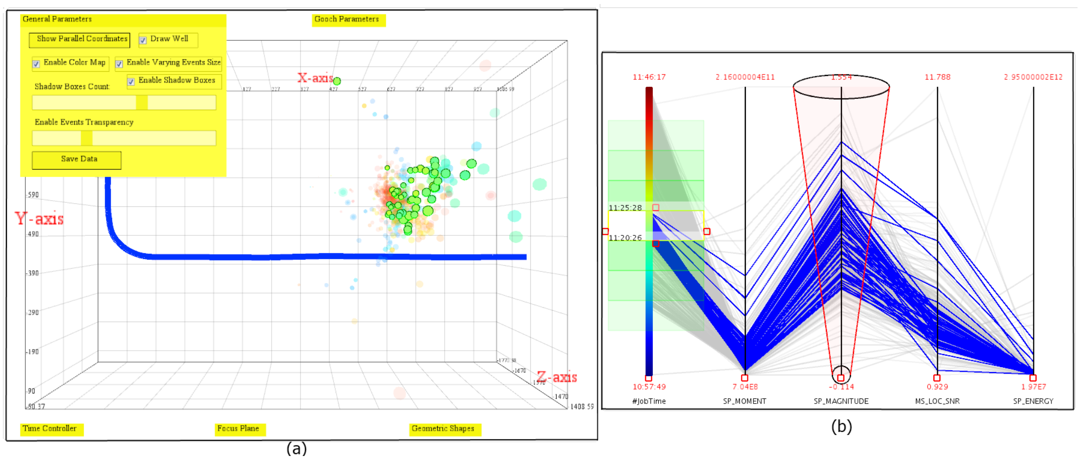

Figure 5: (a) Synchronization of the main 3D view with (b) three Shadow boxes (green transparent boxes) attached to a filter box.

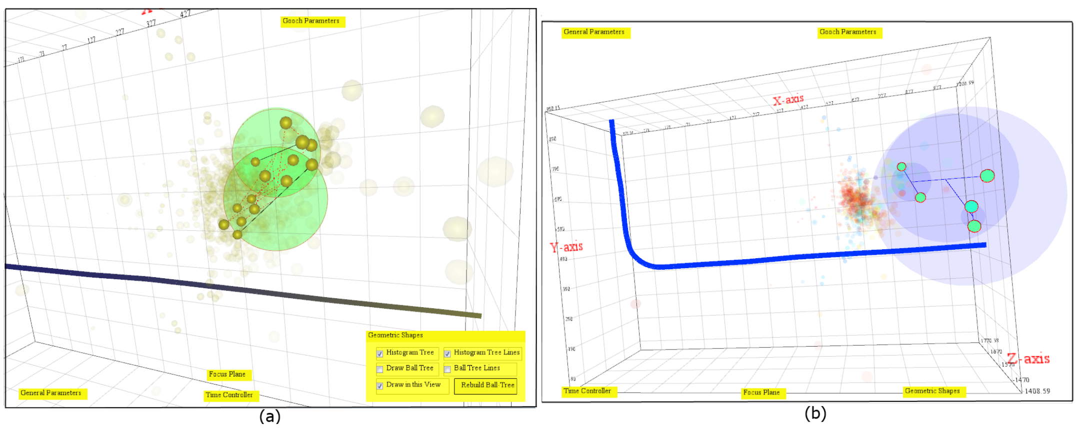

Figure 6: Supported geometric representations for some point events: (a) Histogram-Spheres (b) Ball-Tree.

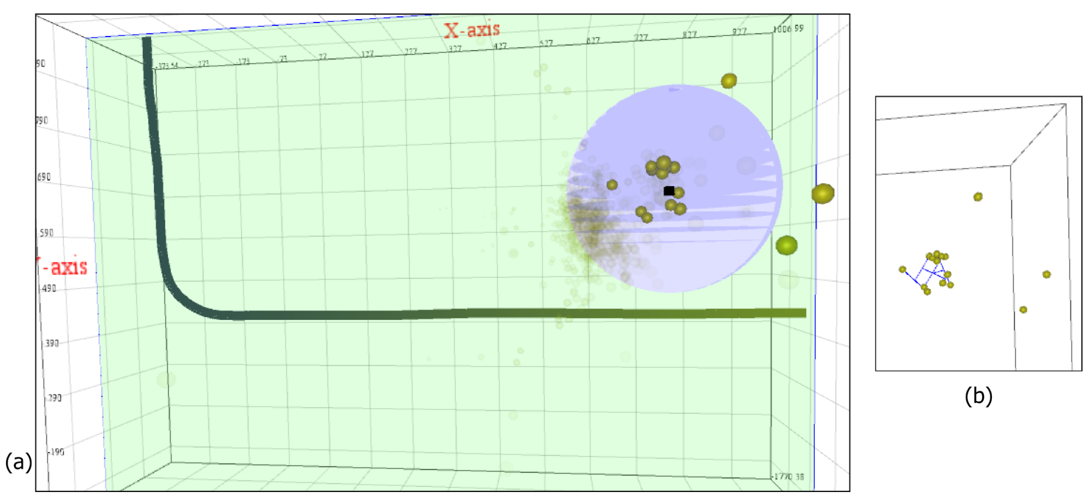

Figure 7: (a) Showing focus plane (green) with subset of events inside the ROI (violet) with (b) synchronization in the History View.