THE UNIVERSITY OF CALGARY

Exploring Tabletops as an Interaction Medium in the Context of Reservoir Engineering

by

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Abstract

Digital tabletops are powerful interaction mediums. As a virtual medium their computational capabilities allow the user to digitally explore, transform and embellish the input content to gain further insights about the pertinent information. On the other hand, as a physical medium, their form factor inherently supports collaboration and presents opportunities to place other physical objects atop to assist and enhance the exploration experience. In this thesis, we propose the use of tabletops as an interaction medium to explore reservoir post-processing flow simulation models using virtual content - visualizations and a physical agent - *Spidey*: a tabletop robotic assistant. We discuss results that emerged from evaluating each of the prototypes, presenting the potential of each of these concepts and their applicability to the domain of reservoir engineering. With the *Spidey* testbed we explored the notion of proxemics between a user and a robotic tabletop assistant and performed a user study in which participants interacted with *Spidey*. Thus in the results, we also discuss the proxemics results reflecting on the interaction between people and tabletop robots.

Publications

Some of the materials, ideas and figures in this thesis has previously appeared in the following:

- **N. Sultanum, S. Somanath, E. Sharlin and M. Costa Sousa. "Point it, split it, peel it, view it": techniques for interactive reservoir visualization on tabletops. Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS'11), November 2011, Kobe, Japan.**

The following paper was recently submitted and is currently under review:

- **S. Somanath, E. Sharlin and M. Costa Sousa. Exploring Proxemics in Interaction with a Tabletop Robot Assistant.**

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

A traditional table or a desk is defined as a furniture with a flat and satisfactory horizontal upper surface used to support objects of interest, for storage, show and/or manipulation. Horizontal digital tabletops that are similar in their form factor to traditional tables enhance such interactive environments with an additional computational layer. Digital tabletops are not so different from traditional tables in terms of the purpose they serve, but their strength to support objects of interest, virtually and physically, makes them interesting interaction mediums (Figure 1.1).

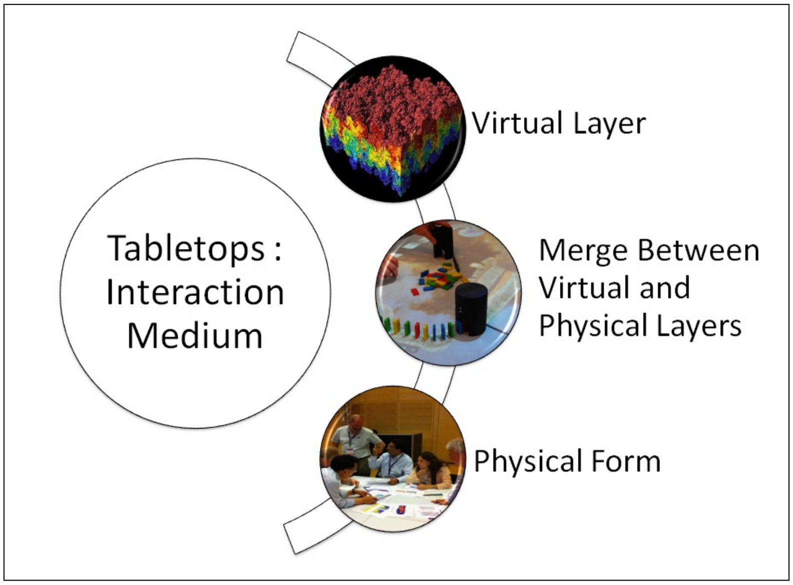


Figure 1.1: Tabletop: an interaction medium.

As a virtual medium, tabletops present an environment that allows digitalizing our objects of interest. It gives us an opportunity to transform data into something more meaningful and engrossing, an advantage that goes beyond traditional tables. The computational power of such technologies gives us the ability to reconstruct and represent our data in different ways, allowing us to gain further insights. Although the facility to digitalize data is not unique to tabletops, the large screen space, interaction modalities and fostering team work abilities of the tabletop in sum make it an interesting interaction medium [80].

The next stage in the spectrum of tabletops as an interaction medium is the merge between the virtual content and the physical world. Interactions on a tabletop presented a complete paradigm shift [63]. With the advances in the field of computer vision, the computational layer of the tabletops can recognise physical touch. Multiple touch points can be processed and gestures can be defined to map physical action's to represent manipulation of the digital content. We can manipulate and interact with our visual representations in a more natural fashion. Simple actions such as click of a mouse button or moving objects on the screen using a mouse can now be done with physical touch, perhaps fostering a more engaging work environment.

Moving along the spectrum, the physical form factor of the tabletop further extends the possibilities for merging the virtual and physical layers. The physical form of the table allows us to place other physical objects atop. Thus, the communication between the virtual content and physical world is not necessarily restricted to happen via direct touch only. The horizontal space of the tabletop gives us the ability to place tagged physical objects or tangibles atop to enhance interactions [40].

Tangible user interfaces (TUI's) have often accompanied interactions on a tabletop. Based on their functionality they can be can be classified to belong to two different categories: static and interactive. Static TUI's are often used to define modalities or a change in state for the virtual content [83]. Interactive TUI's on the other hand help advance communication further [14]. Their feedback can help to communicate other details in a more subtle or obvious ways. This physicality of the TUI's is helpful for enhancing interactions.

Going a step beyond physical touch and tangible user interfaces, is the possibility of merging the virtual and physical layers via the introduction of robots on the tabletops. Robots can move, communicate via body language and can be programmed to represent behaviours. Their nature to influence people socially and come 'alive' in the minds of the humans interacting with them presents them as potentially strong collaborators on the tabletop and might help to enable a richer exploration experience.

Adding to the theme of collaboration, tabletop interfaces are known to be inherently supportive of collaboration [63]. Unlike stand-alone single user desktop systems, digital tabletops allow people to gather around them to discuss and learn from their explorations of the data. Groups of individuals can sit around the tabletops to exchange ideas and discuss their opinions. The digital content can now be manipulated either in a "turn-by-turn" manner while the others observe or everyone can take part simultaneously and involve in working together [26, 66]. Either way, the physical form factor of the table helps to improve team work and promotes collaboration.

In this thesis, we take advantage of the tabletop as a virtual and physical medium of interaction, and explore ways that can benefit the process of investigating reservoir flow simulation, post-processing models. We selected this particular engineering domain, wherein the experts need to explore 3D models with a number of static and dynamic, and time varying parameters, since the interactive requirements for this class of application typically requires engineers to explore, search and filter different regions of the model and its parameter values in a collaborative environment to facilitate further decision making. We believe and previously observed [73], that tabletops can promote a richer learning experience and facilitate awareness in exploration of such data. We present our efforts in this direction, through our exploratory visualizations and tabletop robotic assistant prototype. We also present insights we gathered through three formal user evaluations we conducted. The remainder of this chapter presents an overview of the domain of reservoir engineering. This is followed by the goals, approach and contributions of this thesis. We finally conclude with an overview of other elements of this thesis.

1.1 Reservoir Engineering and Interactive Exploration

Oil and gas exploration and production (E&P) involve economically valuable but complex tasks. They comprise workflows with pipelined processes depending on a multitude of variables, with datasets coming from inter-related disciplines (geophysics, geology, reservoir engineering and others) throughout the E&P life cycle (Figure 1.2). During the field development on the E&P cycle, 3D reservoir models are built embodying our understanding of the reservoir descriptions (static and dynamic) and its processes to obtain predictions of how the field will perform. Static descriptions are modelled by geophysicist and geologists, and include the overall geometry and topology of the geological structures and attributes. Dynamic descriptions are modelled by reservoir engineers and include values of properties such as fluid pressure and saturation that change through time. Reservoir engineers also focus on optimizing production by working towards achieving good well placements, improving production rates and developing enhanced oil recovery methods in the most economical manner [23]. These tasks are typically performed in teams, accessing and reviewing models and information, working in collaboration towards time-critical decision-making.

One important challenge is this process is the rapid growth in the complexity and scale of reservoir engineering models and datasets. This has brought increased attention to the costs of interacting and navigating through such large quantities of data in search of relevant and/or critical information. The reservoir engineer has to have access to all the required and available information and have a good

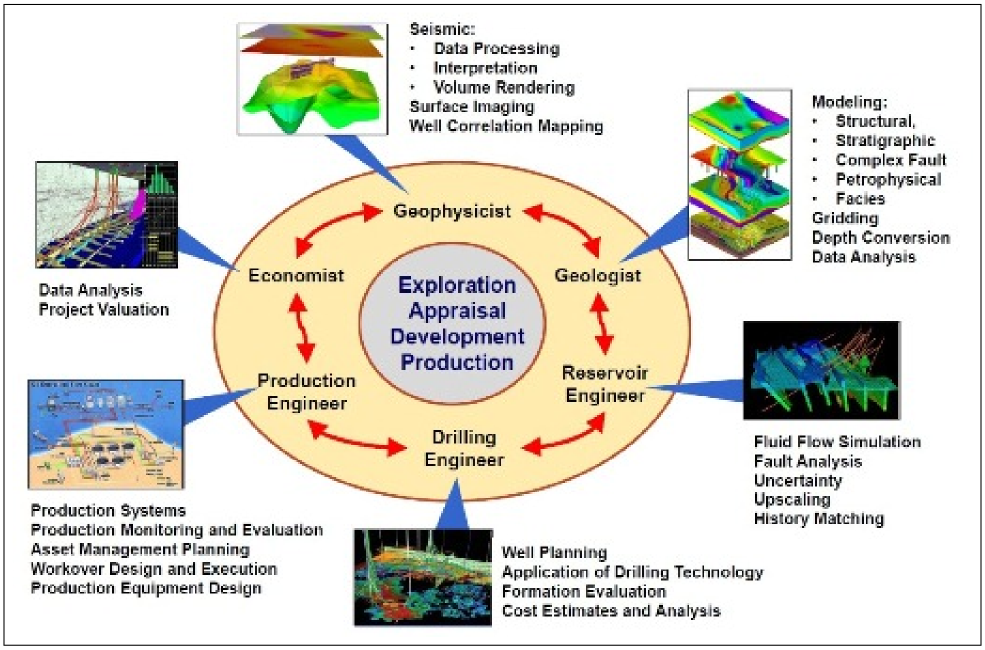


Figure 1.2: Oil and Gas exploration and production cycle and the corresponding key disciplines.

understanding of the various attributes associated with the reservoir. The nature of the reservoir engineer's work demands meticulous details to support exploration of the reservoir models, following which visualizations and analysis methods are developed for assisting explorations. Thus, the aspect that is important to this domain is the need for exploration.

Beyond the high-level need for exploration, there are specifics involved in the oil and gas E&P process. Although automated tools can give direct results to an engineer, interpretation and decisions taken are end results of human involvement in the process of investigation. This human involvement in the analysis and decision making process can be supported via interactive exploration techniques, thereby giving researchers opportunities to investigate and experiment different ways the 3D reservoir model can be explored. The multi-dimensionality of the dataset is also another reason for the need for interactive explorations. Due to the several parameters associated to each task being performed on the reservoir model, several solutions exist for a single problem. For example, history matching [22] is the process of adjusting the parameters of a reservoir model till it can closely reproduce the past behaviour of the real reservoir. This is an optimization problem with several solutions. Experts need to intervene to select solutions based on their experience and this would be cumbersome to perform without interactivity in application. Following the need for decision making and expert involvement, it is important to address aspects of interactivity in exploration.

In this thesis, keeping in mind the threads associated with the domain of oil and gas and the benefits of tabletops as interaction mediums, we investigated ways to benefit from using tabletops for the exploration of 3D reservoir post-processing flow simulation models interactively.

1.2 Goals

The main goal of this thesis is to investigate and engage in the design, implementation and evaluation of new exploration paradigms using tabletops to gain further insights about reservoir flow simulation models. To explore the affordances of tabletops as a virtual and physical interaction medium, we navigated through concepts in visualizations, human-computer interaction (HCI) and human-robot interaction (HRI) with the domain of reservoir engineering serving as the core context to conceptualize our ideas.

1.3 Methodology

To address our research goals, we designed and implemented four prototypes and evaluated three prototypes in formal user studies:

- A set of visualization variations to explore uncertainty in 3D reservoir post-processing flow simulation models;
- A focus and context technique to visualize well trajectories in reservoir models.
- Three prototypes for sketching simple configurations of well trajectories.
- *Spidey*, a tabletop robotic assistant, who can collaborate with the tabletop user and assist her in a valid set of tabletop reservoir exploration tasks.

To investigate our research objectives we implemented each of these prototypes for Microsoft Surface 1 and used post-processing reservoir datasets provided by CMG Ltd. [2] . The datasets are end results of a simulation program and consists of four types of information: (a) structural information, (b) time steps, (c) cell specific information (geological properties - both static and dynamic) and (d) well trajectory specific information (type of well, length of well, perforation blocks etc.). The structure of the 3D reservoir model consists of thousands of corner point cells [58] with irregular geometry but arranged regularly along three dimensions (i,j, k). The arrangement of the cells represents both spatial continuity as well as discontinuities to accommodate geological structures such as faults. The model encompasses fluid flows and represents other interesting events occurring below the surface of the earth.

Three of our prototypes were evaluated in a series of formal qualitative studies involving domain experts. All three of our studies invited both reservoir engineers and computer science experts to evaluate our prototypes. One of our study (Chapter 3) also involved participants from other specializations. Evaluations such as these helped us gain insights about the usefulness, applicability and potential strengths and weakness of our approach. For the well creation prototypes we present a design critique.

1.4 Contributions

On a higher level the main contribution of our thesis can be considered to be the exploration paradigms we investigated for gaining insights about 3D reservoir post-processing flow simulation models using tabletops. This main contribution can be broken down into smaller components belonging to the following two categories: - virtual explorations and physical explorations. The former address visualization concepts for investigating reservoir models and the latter deals with introducing a physical entity such as robotic assistant into the interaction environment. The smaller building blocks that form portions of our main contribution are as follows:

Virtual exploration

1. A set of user evaluations reflecting on the user's insights about the validity and usefulness of a set of visualizations for exploring reservoir models.
2. Novel interactive 3D visualizations for reservoir post-processing flow simulation models, using tabletop environment.
3. Other exploratory prototypes for investigating ways for creating simple 3D well trajectories.

Physical exploration

1. User investigations reflecting on the potential of introducing a tabletop robotic assistant in a tabletop interactive environment. This study also reflects on the concept of proxemics in interaction with a tabletop robot.
2. A tabletop robotic assistant prototype for assisting in a set of valid tabletop reservoir exploration tasks. To the best of our knowledge, this is the first attempt to prototype a tabletop robotic assistant to perform a set of valid engineering tasks.

1.5 Thesis Overview

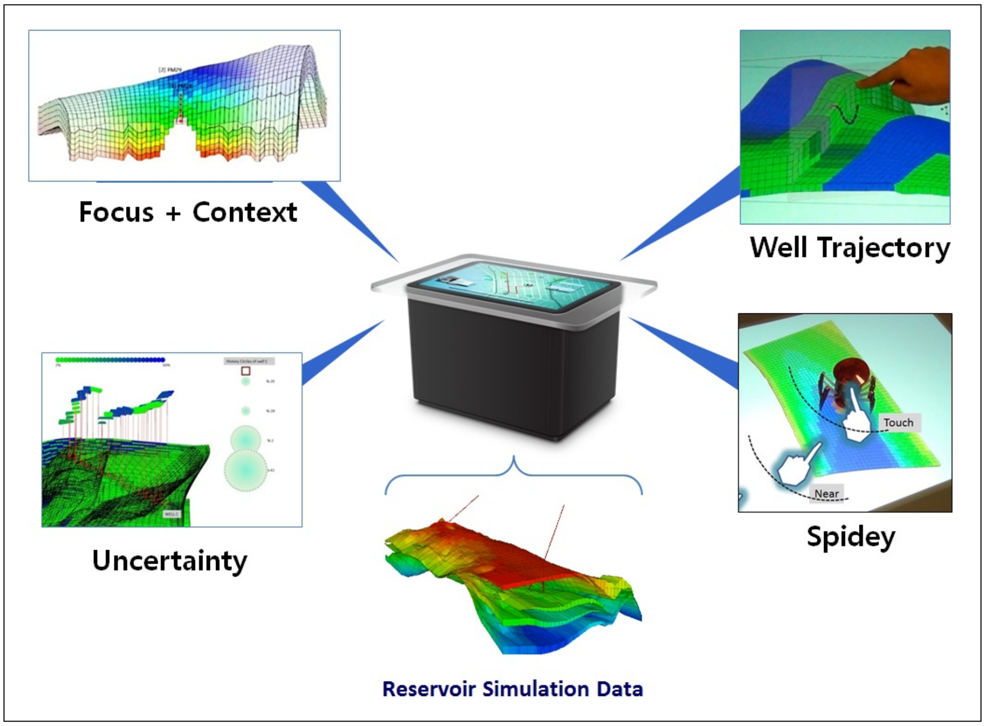


Figure 1.3: Threads constituting the thesis.

The remaining of this thesis is organised as follows:

- In *Chapter Two*, we provide a background to the core elements of this thesis. We discuss a few relevant past efforts in mostly in the realm of visualizations, sketching ,human-robot interaction and proxemics in interaction.

- In *Chapters Three and Four*, we present the design, implementation and evaluations of four visualizations for exploring reservoir flow simulation models.

- In *Chapter Five*, we present a set of exploratory prototypes for creating new well trajectories in the reservoir model.

- In *Chapter Six*, we detail the design, implementation of *Spidey* and summarise our findings from the perspective of both the robot and the proxemics in interaction with our *Spidey*.

- In *Chapter Seven*, we present a set of discussion points that emerged during our exploration of the tabletop as an interaction medium.
- In *Chapter Eight*, we conclude and present some perspectives for future work.

Chapter 2

Background

This thesis revolves around themes borrowed from visualization, human-computer interaction (HCI) and human-robot interaction (HRI), applied to reservoir engineering as seen in Figure 1.3. In this chapter we present the context for our work by discussing prior art that relate to the different components of our work. While tabletop and reservoir models stitch different pieces of our thesis together, the elements constituting the thesis learn from various other fields. Following the order of the thesis chapters, this chapter is organised as follows:

1. A short introduction to the domain of reservoir engineering;
2. A discussion of related work mostly in the realm of visualizations to give background to our research presented in Chapter 3 and 4;
3. Sketching in 3D, detailing the research that influenced our well trajectory creation prototypes (Chapter 5);
4. Background to assitive robots and tabletop robots to provide a broad overview of state-of-the-art researches under these two categories of HRI (Chapter 6);
5. Brief background for proxemics in interaction, to provide a broad overview to the theory of proxemics and its influence on the domain of HCI and HRI (Chapter 6).

2.1 Reservoir Engineering

Oil and gas reservoirs are subsurface pools of hydrocarbons encompassing rock formations and fluid flow (Figure 2.1). The ultimate goal of studying reservoirs is to explore them and find optimal ways to extract oil and gas in the most economical and environmental friendly manner. To achieve this goal, the E&P cycle consists of different phases and is a multidisciplinary effort. In this section we attempt to present a broad overview of the various aspects related to this domain.

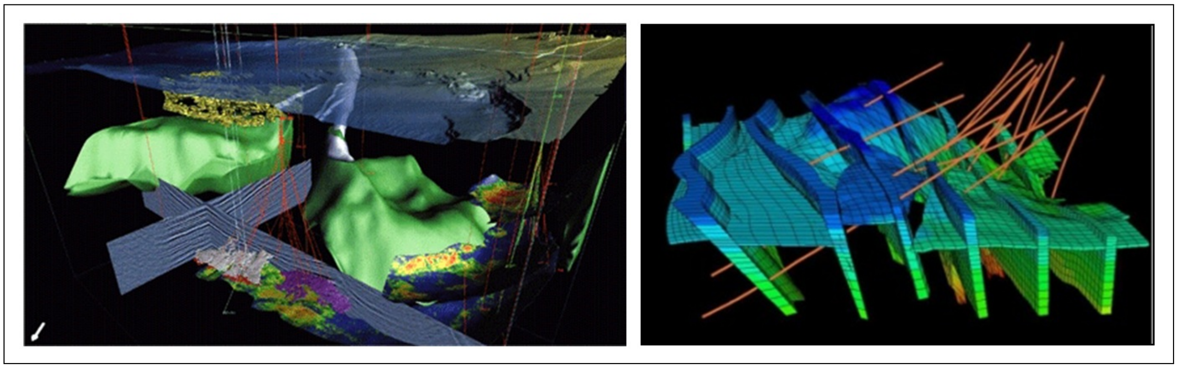


Figure 2.1: Examples of 3D reservoir models with geophysics, geological and flow simulation descriptions.

2.1.1 Oil and Gas Exploration and Production Cycle

Oil and gas industry consists of two main sectors - upstream and downstream, where the former deals with the exploration and production phases of the E&P cycle and the latter work with processing of crude oil and gas products and marketing of the products [5]. The operations performed by these sectors comprise of four main phases [1]:

1 **Exploration**: The first stage of the E&P cycle consists of surveying the hydrocarbon containing rock formations using techniques such as gravity survey, magnetic survey and seismic survey. Areas of interest, often called "leads"

undergo further seismic survey to gain further insights about the sub-surface structures. When a promising location is identified an oil well is drilled in that area. However, this is a cost intensive task, since the estimated amount of oil may not be found.

2 **Appraisal**: The next phase consists of determining if the reservoir is feasible for development. More wells are drilled into the reservoir to reduce the uncertainty of the potential field. If the results of these exploratory wells promise the presence of suitable amount of hydrocarbons, further seismic surveys are performed and the results are used to estimate the production capacity of the reservoir.

3 **Development**: If the results of appraisal phase indicated that the production will be profitable, then the development phase is started. In this phase, engineers begin to decide on strategies that help to discover the hydrocarbons in the most economic manner.

4 **Production**: This phase consists of producing the oil and gas. The important aspects of this phase consist of activities such as well planning, maintaining rate of production and maximising the production.

2.1.2 Reservoir Models

To explore the reservoir, engineers often depend on constructing virtual models of the underground reservoir.The conventional steps taken to construct a model are as follows (Figure 2.2)[42]:

1 In the first step, the reservoir model is defined by surfaces defining the top and bottom bounds. These surfaces are results of seismic data interpretation (Figure 2.2 - A).

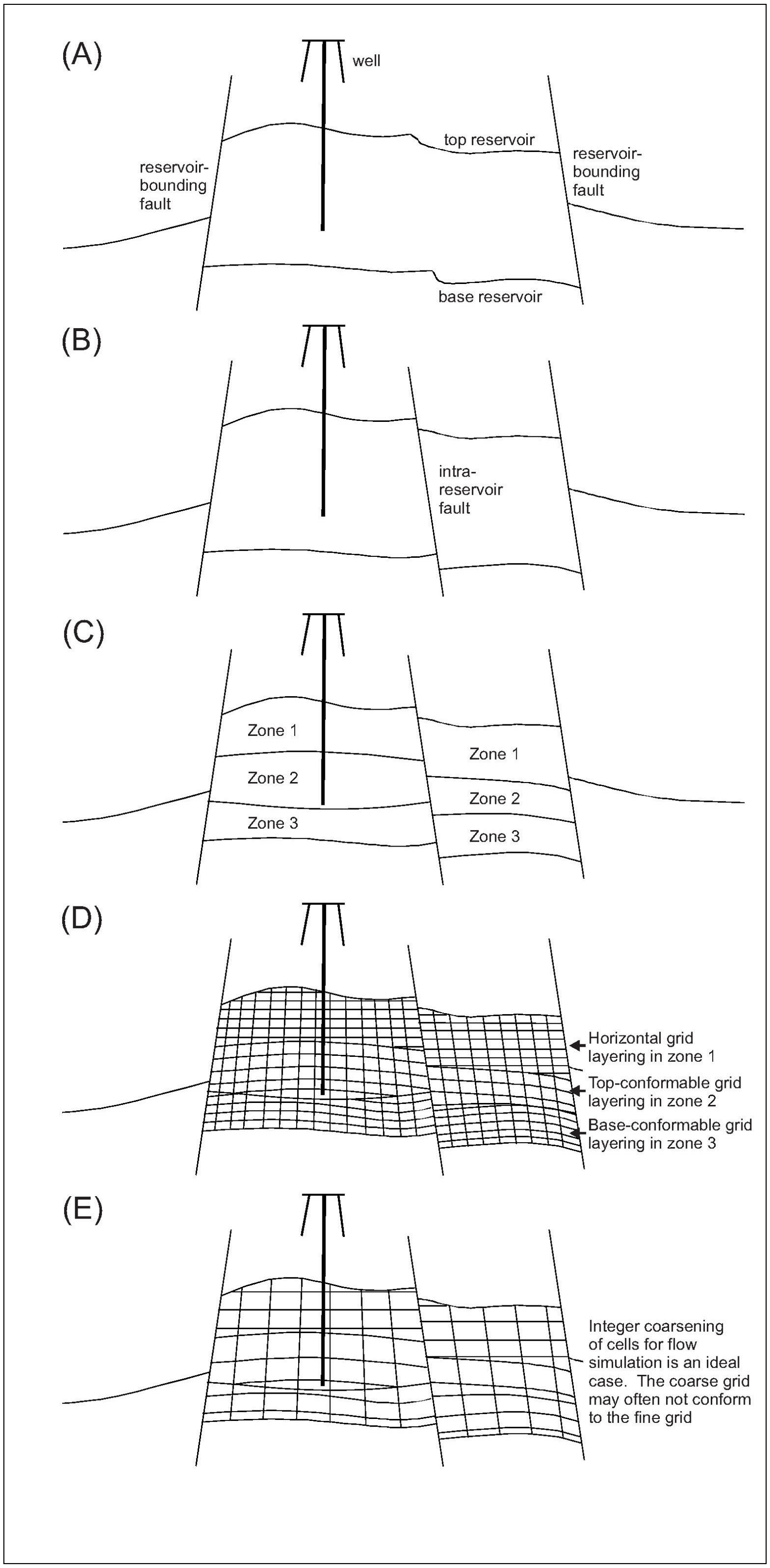


Figure 2.2: Key stages during reservoir modeling [42]: (a,b,c) defining the main geological surfaces, (d) discretization of the model resulting in a geo-cellular grid and (e) upscaling the grid for simulating fluid flow.

2 Each fault is also represented by a surface placed between the top and bottom bound (Figure 2.2 - B).

3 The reservoir model is then divided into various geological zones, each indicated by one or more surfaces. These surfaces are results of seismic interpretation or correlations between wells (Figure 2.2 - C).

4 Next a grid is defined within each of the zones. The gridding spanning the X and Y axis is uniform, but the layering along Z may vary (Figure 2.2 - D).

5 Each grid cell is then assigned porosity and permeability values using geostatistical methods.

6 Finally the grid is upscaled for flow simulation (Figure 2.2 - E).

At the end of the simulation process, the resulting models are associated with the following information and more: time varying geological properties per each cell, information of existing well trajectories and fault locations. These post-processing flow simulation models are then visualized to allow engineers to gain further insights about the reservoir. A reservoir engineer is interested in exploring the model using analytical and empirical methods to learn how production can be optimized.

2.2 Interfaces Explored by the Domain

At the post-processing stage, the reservoir models are visualized as end results of the simulation program and analysed to gain further insights. However, due to the complexity of the tasks involved and the need for collaboration the domain of oil and gas has explored different interfaces for exploring their datasets other then the traditional desktop WIMP applications [2, 6, 3]. In the following section we present an overview of the different interface solutions investigated by the domain under the following two broad categories - tabletop solutions investigated by the domain, which is most relevant to our work and then we present a collection of other solutions explored by the domain.

2.2.1 Tabletops in the Domain

Tabletops have been explored for visualizing and monitoring reservoir production. Tateosian *et al.* [79] presented a tangible geospatial modeling visualization system that allows manipulation of a terrain directly through a miniature clay surface (Figure 2.10a).

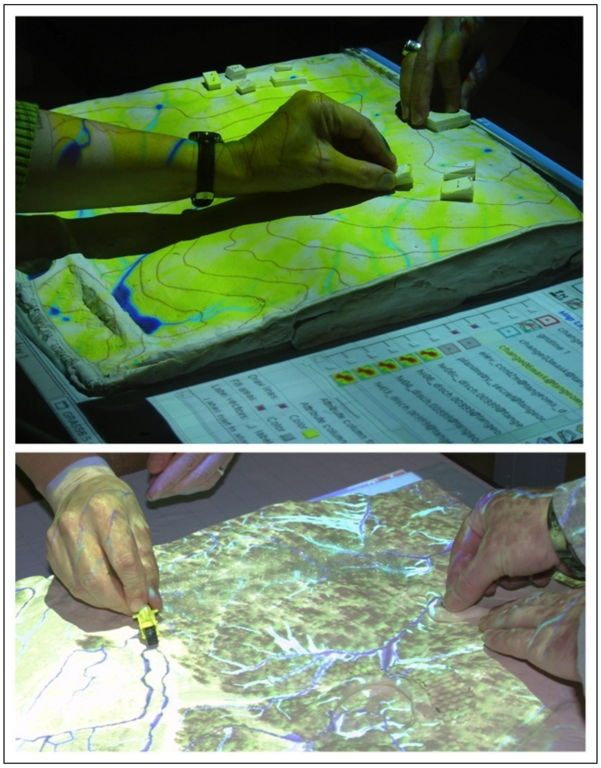


Figure 2.3: TanGeoMS [79]: an interface for physically interacting with 3D terrain data.

Another system based on TUI's was developed by Couture *et al.* [24] designed a tangible user interface for geophysicists for the analysis of 3D seismic volume. They tried to recreate an environment with tangibles (one-puck prop, two-puck prop, ruler prop and the button box) wherein the geophysicist could work with their data in a way they are commonly used to (using pen/paper/ruler) (Figure 2.10b).

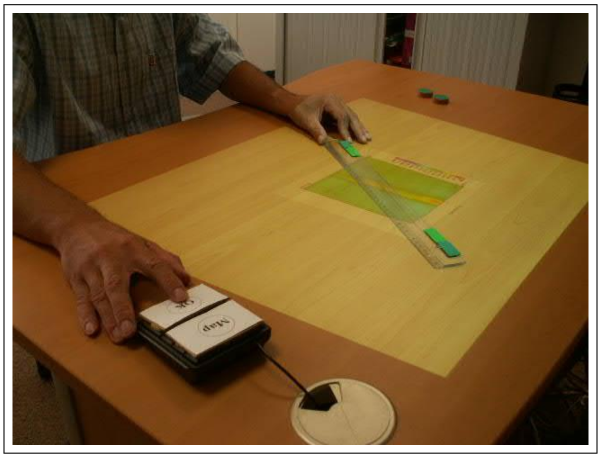


Figure 2.4: GeoTUI [24]: tangible user interface for defining cutting planes on a geographical map.

The commercial solution Petrotrek [4] offers a tabletop version for the Microsoft Surface for complementing oil production monitoring with the ability to geographically locate and monitor oil production plans in an interactive multi-touch map (Figure 2.10c).

Figure 2.5: Petrotrek [4]: Microsoft Surface solution for oilfield data visualization.

For post-processing visualizations in specific, Sultanum *et al.* [73] is the most related instance of research. They developed a tabletop interface for exploring 3D reservoir models by mapping known techniques such as probing and splitting to be performed by direct touch. The use of physical touch allowed to explore different ways for performing such tasks more intuitively (Figure 2.10d). Based on the potential of tabletops for exploring reservoir post-processing models in the work of Sultanum *et al.* [73], we further investigated tabletops from the perspective of an interaction medium. We developed a set of of prototypes for exploring reservoir models virtually and with the assistance of a physical entity - a tabletop robot. To the best of our knowledge, these prototypes present new concepts of explorations not seen in the domain of oil and gas.

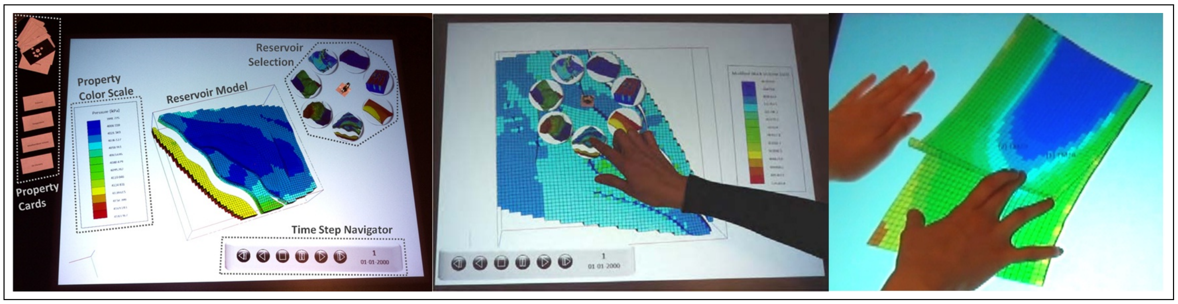


Figure 2.6: Tabletop reservoir visualization system developed by Sultanum *et al.* [73].

The domain of oil and gas has always been in a constant pursue for investigating different types of technologies to support exploration of the reservoir models. In the next section we discuss the other technologies that have been investigated by the domain of oil and gas for the exploration tasks.

2.2.2 Other Interfaces

The most dominant interface used by the domain for visualizing 3D reservoir flow simulation models are the desktop computers with mouse as the interacting device. Several commercial desktop applications are available for visualizing reservoirs in 2D and 3D (eg. CMG Results[2], Petrel[6] and AssetView ^{TM}[3]). However,the WIMP interface of these applications require users to navigate through several menus and procedural steps to perform a task, making the process cumbersome (Figure 2.7).

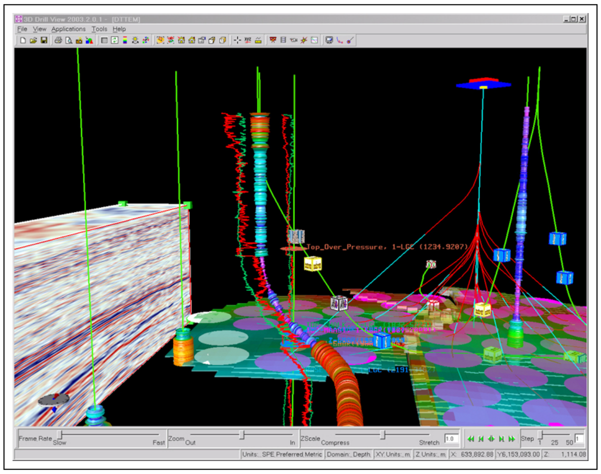


Figure 2.7: AssetView software [3].

Other technologies have also been investigated to support analysis and exploration of reservoir models. Visualization rooms [13, 92] consisting of large displays were used to visualize and study reservoir models in a group environment. Haptic devices [92] and virtual reality environments [50] were explored to support exploration of 3D environments in a collaborative setting (Figure 2.8). Recent work by Harris *et al.* [37] introduced a tangible user interface [37] called *Snakey* (Figure 2.9) for manipulating and interacting with 3D well trajectories in the reservoir model[37], investigating intuitive and more direct ways for well trajectory manipulation.

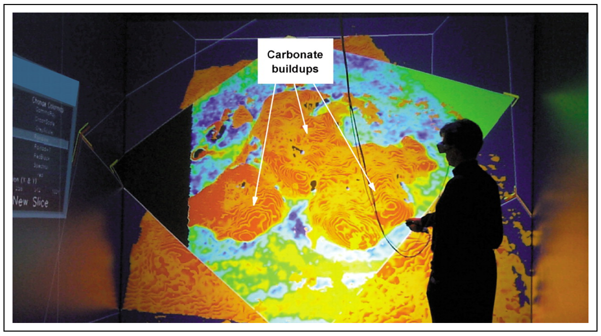


Figure 2.8: Visualization rooms.

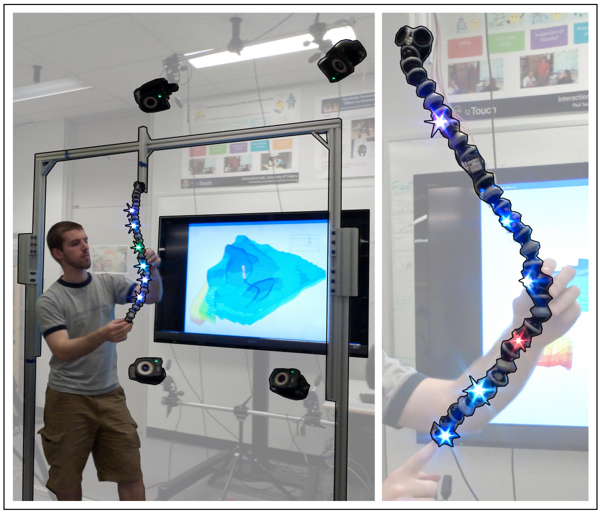


Figure 2.9: *Snakey* [37].

Moving beyond the technologies used for the exploration process in the next few sections we discuss related research that helps to facilitate the explorations - techniques that help to visualize the reservoir models for the engineers to gain further insights.

2.3 Visualization

Visualizations are essential to reservoir engineers since the virtual 3D models are the closest representation they have of the actual reservoirs. In the work of Sultanum *et al.* [73], we saw a set of interactive visualization tools for the exploration of reservoir flow simulation models. However, with so many parameters to explore and the number of tasks involved in this multi-disciplinary domain, there are other open questions and a wide scope for investigating other visualization techniques for assisting the engineers in gaining insights about the reservoir. In this thesis we present four different visualizations for exploring reservoir models (Chapter 3 and 4). The following subsections present a brief discussion on the different aspects involved in our visualizations with related instances of research.

2.3.1 Uncertainty Visualization

Interpretation or making a decision is often clouded by uncertainty. Should a reservoir engineer chose an area at the top of the reservoir or at the bottom? Such choices or interpretations or doubts if called uncertainty can perhaps be visualized in some manner to help in the process of clarification. Thus in this section we present related work from two perspectives: (a) how uncertainty can be visualized and (b) once visualized how can we explore such a model - techniques applied for revealing obscured or hidden data.

In the domain

Majority of the work in the domain of reservoir engineering and geosciences has been in the area of developing mathematical methods for quantifying uncertainty [28, 49, 52]. The quantification here refers to the method of comparing various simulation run values to determine the effect of change. Our definition of uncertainty however is different (Chapter 3). In this section we discuss the few instances of research that discussed visualizing uncertainty in the reservoir model. A few examples of researches which detailed techniques for visualizing uncertainty include the following: early research by Srivastava *et al.* [71] described the use of presenting dynamic visuals of the plausible outcome of simulations in every frame differing only slightly from the previous (Figure 2.10) to visualize spatial uncertainty. However, such a technique cannot be applied at the post processing stage where the data used to construct and visualize the reservoir models is not changed by the simulator dynamically.

In the field of geosciences we see examples of visualizing uncertainty in the works of Sambridge *et al.* [61] and Zehner *et al.* [93]. Sambridge *et al.* [61] discussed a set of examples for characterising and representing uncertainty. Some suggested techniques for visualizing uncertainty included the use of color schemes based on hue-saturation-

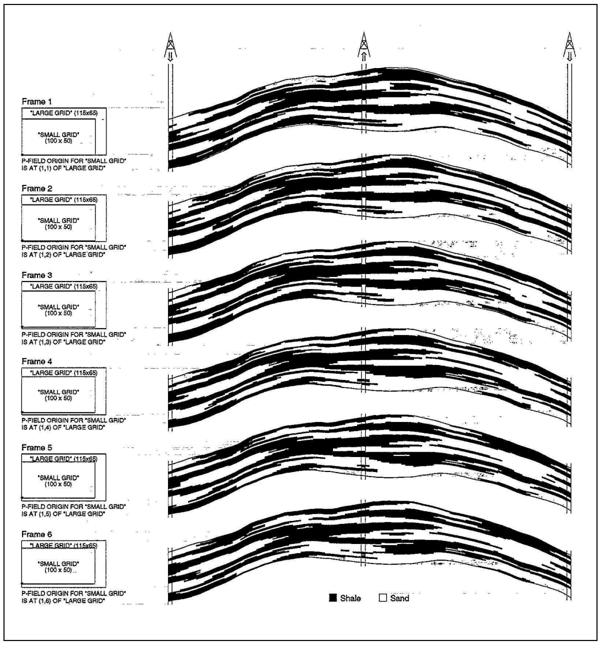


Figure 2.10: Spatial uncertainty visualization [71].

brightness (HSB) values, blurring, error bar graphs and visualizing data misfit values (Figure 2.11).

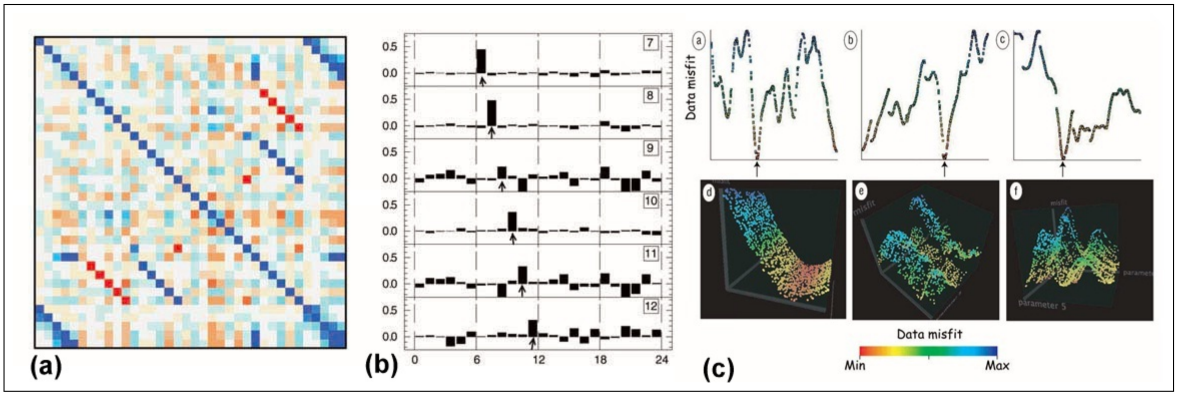


Figure 2.11: Examples of visualizations that can be adopted for visualizing uncertainty: (a)Visualizing covarience values using color and blurring, (b) error bar graphs and (c) visualizing data misfit values

Zehner *et al.* [93] describes the use of a color scheme coupled with isosurfaces to represent uncertainty in gridded scalar data (Figure 2.12). The isosurfaces coupled with the color schemes helps the viewer identify regions of low and high uncertainty.

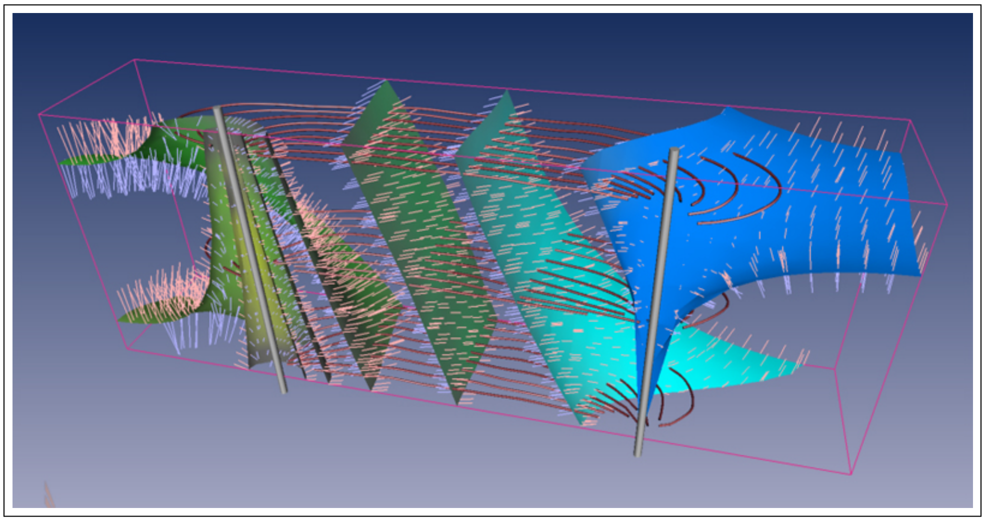


Figure 2.12: Uncertainty visualization techniques as applied by Zehner *et al.* [93]

Other fields

Alternative to color schemes, blurring and error bar visualization solutions presented by the domain, there are other ways to visualize uncertainty as explained by Wittenbrink *et al.* [89]. Wittenbrink *et al.* [89] presented the use of glyph shape to represent uncertainty in winds and ocean currents. Uncertainty was represented by the mean direction and magnitude of the glyph (Figure 2.13).

Zuk *et al.* [94] in their research explored uncertainty visualization with three data sets - archaeological data, geophysical data and medical data. For the archaeological data, their approach included the use of various visual cues (transparency, color change, blur etc.) to represent temporal uncertainty within an interactive time window animation sequence (Figure 2.14(a)). The approach adopted to visualize uncertainty in seismic data, was to use static glyphs and a flow based representation to visualize the uncertainties in flow (Figure 2.14(b)). And lastly, for the medical data set, a visualization system consisting of a decision tree and other windows to support diagnostic reasoning was used (Figure 2.14(c)) to understand uncertainty.

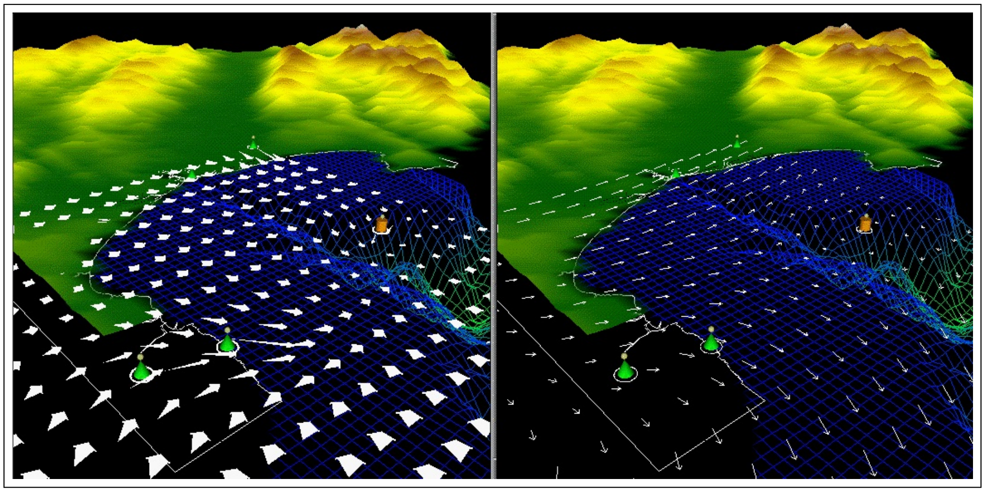


Figure 2.13: Use of glyph's to represent uncertainty. [89]

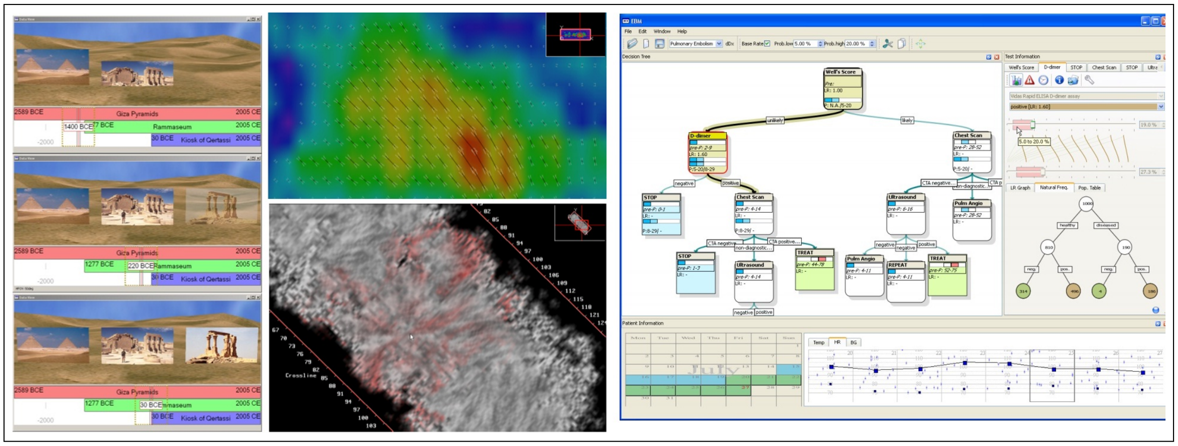


Figure 2.14: Zuk *et al.* uncertainty visualization techniques [94] (a) Animation sequence for presenting temporal uncertainty in archaeological data, (b)uncertainty visualization using static glyphs and flow based representation and (c)Visualization system to support exploration of uncertainty in medical data sets.

Our uncertainty visualizations uses color to present an overview of the uncertainty in the model. However, since occlusion of internal layers is a major concern with 3D models, approaches such as color, transparency, blur etc. cannot suffice to present the information. Hence, in addition to using color to represent an overview of the uncertainty, we also use concepts borrowed from cartography and attempt to make use of visual variables [11] to learn about the uncertainty in the well trajectories and individual cells of the reservoir model.

2.3.2 Offsets: Displaced Aspects of Context

Offsets are an old cartographic technique of displacing a portion of the map to magnify it or highlight particular data aspects. This concept influenced us to investigate ways that could help us to overcome the occlusion problems in 3D structures and at the same time, not compromise the context.

Recent techniques such as DragMag by Ware and Lewis. [88] (Figure 2.15) borrow from the offset idea but visually connect the magnified region to the context at all times with vertical lines. Our technique of candy visualization (Chapter 3) is influenced by this work in that we displace portions of the data. However it differs in that we do not use magnification of the original data for extraction. Rather, we simply displace the original 3D well blocks. In other words, we bring them out of the 3D reservoir model for clear viewing. These pulled out blocks are clones of the original blocks same size, same shape and same color as the original blocks. We connect the original and the clone blocks using vertical lines, like those seen in the DragMag [88], for retaining the connection between the focus and the context. Another similar concept was presented by Taerum *et al.* [77]. In their research they explored the idea of contextual close up for viewing the area under focus (Figure 2.16). Methods such as these can be said to belong to the category of “focus-out-of-context” since they pull out the pertinent portions of the visualizations and present them to the viewer for clearer understanding.

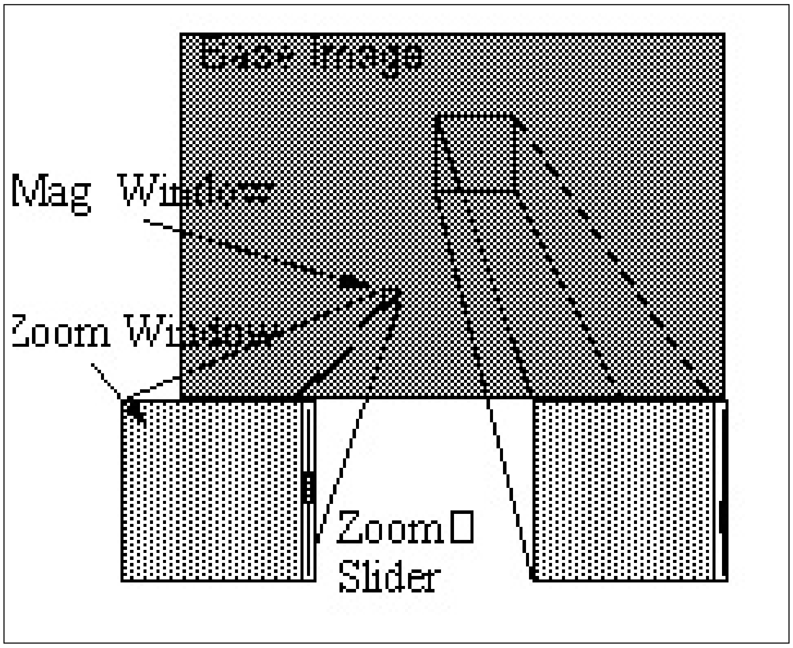


Figure 2.15: DragMag: image magnifier [88].

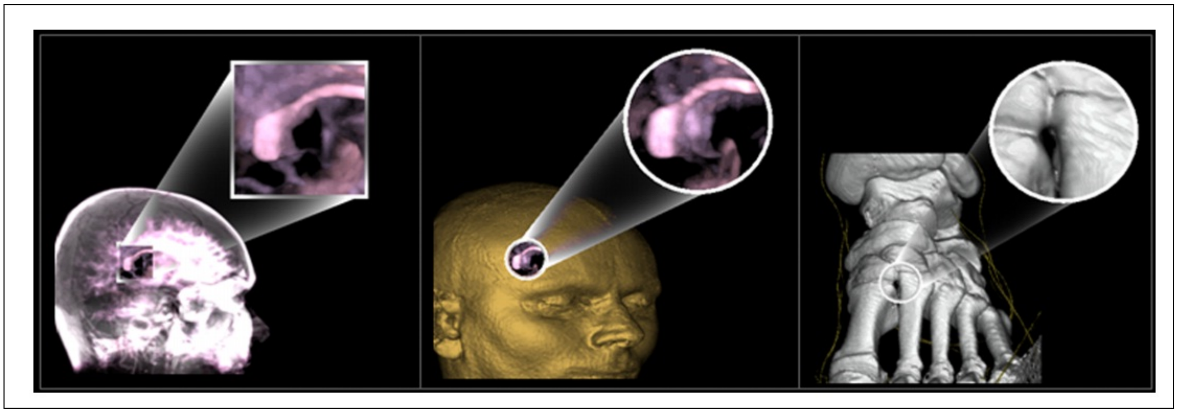
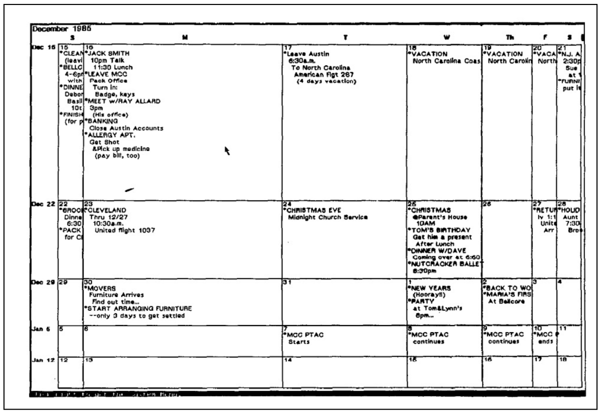


Figure 2.16: Contextual close-up: technique for visualizing internal anatomical features [77].

2.3.3 Focus and Context Techniques

Focus and context are a group of techniques that highlight areas of importance in a particular structure (e.g. human body, architectural building designs) while retaining the context in a subtle fashion for a complete view. Influenced by this style of presentation for our visualizations (Chapter 3 and 4), in this section we discuss some state-of-the-art research to present an overview of the various ways in which this technique has been applied.

A variety of focus and context techniques provided options for 2D data [30] (Figure 2.17) using the concept of "fisheye views" - a visualization technique imitating wide angle lenses that show nearby areas in great detail and surrounding areas with less detail (Figure 2.18). Subsequently a united framework [18] was developed to include different techniques such as distortion, magnification and detail-in-context in a single interface (Figure 2.19). The concept of detail-in-context was extended into 3D data through use of animated, temporary displacement of context by Carpendale *et al.* [17] (Figure 2.20).



December 1985

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Dec 15	15 *CLEAN (leavi *BELLC 4-6pr with *DINNE Debor Basil 10t *FINISH (for p	16 *JACK SMITH 10pm Talk 11:30 Lunch *LEAVE MCC Pack Office Turn in: Badge, keys *MEET w/RAY ALLARD 3pm (His office) *BANKING Close Austin Accounts *ALLERGY APT. Get Shot &Pick up medicine (pay bill, too)	17 *Leave Austin 6:30a.m. To North Carolina American Flgt 267 (4 days vacation)	18 *VACATION North Carolina Coas	19 *VACATION North Carolin	20 *VACA North	21 *NJ. A 2:30p Sue at *FURNI put i
Dec 22	22 *BROOK Dinne 6:30 *PACK for C	23 *CLEVELAND Thru 12/27 10:30a.m. United flight 1037	24 *CHRISTMAS EVE Midnight Church Service	25 *CHRISTMAS @Parent's House 10AM *TOM'S BIRTHDAY Get him a present After Lunch *DINNER W/DAVE Coming over at 6:60 *NUTCRACKER BALLET 8:30pm	26	27 *RETUR lv 1:1 Unite Arr	28 *HOLID Aunt 7:30 Bro
Dec 29	29	30 *MOVERS Furniture Arrives Find out time... *START ARRANGING FURNITURE --only 3 days to get settled	31	1 *NEW YEARS (Hooray!!) *PARTY at Tom&Lynn's 8pm...	2 *BACK TO WO *MARIA'S FIRS At Bellcore	3	4
Jan 5	5	6	7 *MCC PTAC Starts	8 *MCC PTAC continues	9 *MCC PTAC continues	10 *MCC ends	11
Jan 12	12	13	14	15	16	17	18

Figure 2.17: Fisheye calendar [30].

In the realm of focus and context for volumetric data Viola *et al.* [84] described the use of assigning importance levels to the data to highlight the object of focus (Figure 2.21). Bruckner *et al.* [16] presented ways to implement focus and context using computer generated illustrative rendering methods for volumetric data (Figure 2.22).

However, from these examples of focus and context techniques we observe that

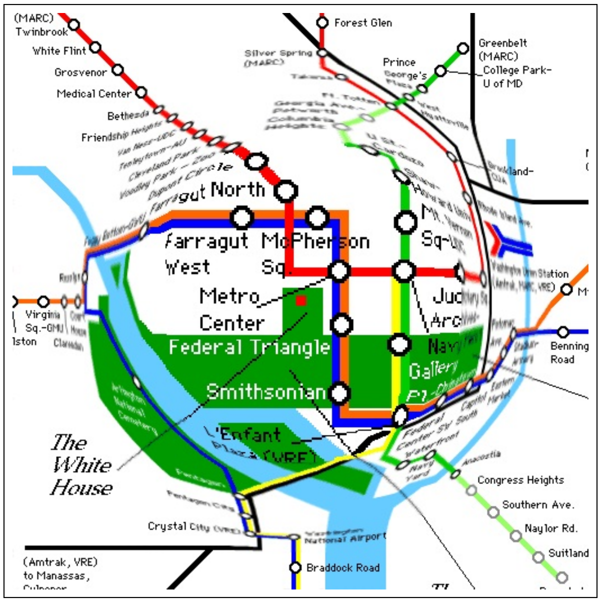


Figure 2.18: Fisheye view of a map.

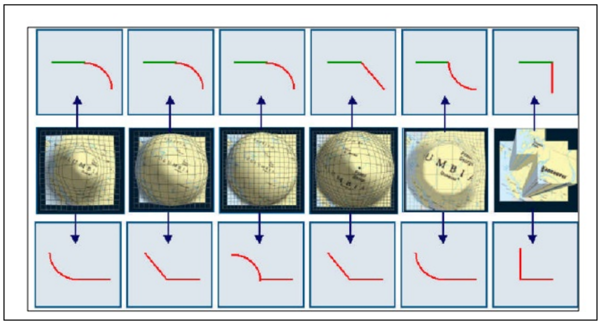


Figure 2.19: Different types of lenses available in the framework [18].

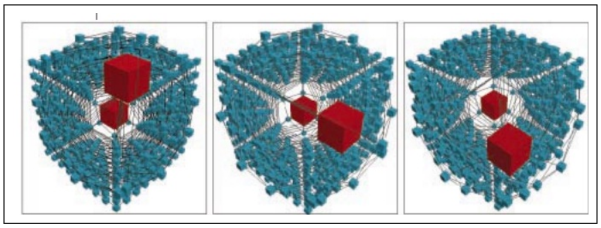


Figure 2.20: Snapshot of detail-in-context techniques applied to 3D data [17]

Figure 2.21: Importance driven visualization [84].

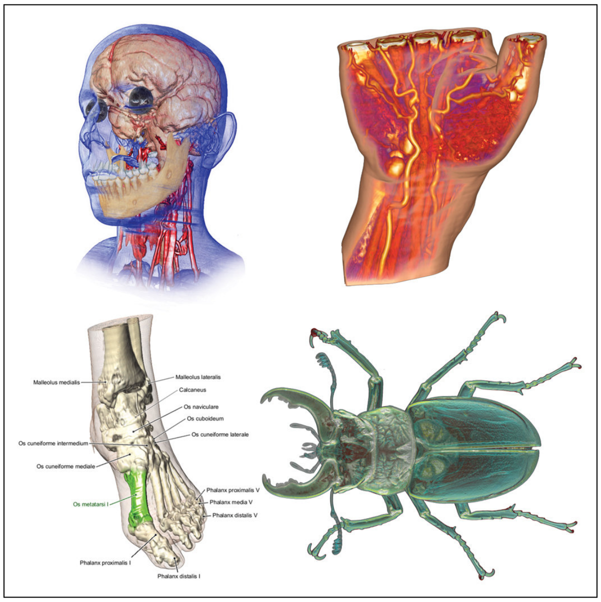


Figure 2.22: Illustrative volume visualization [16].

the context is usually compromised (transparency, distortion etc.) to make the entity in focus visible. This context compromise was stated as a drawback by our domain expert participants during the study of our focus and context approach for visualizing wells (Chapter 4). One of the main attempts of our visualization techniques presented in Chapter 3 was to overcome this problem of context compromise.

2.3.4 Visualizations for Correlation

In multi-dimensional datasets, apart from the need for focus and context techniques, correlation between different attributes of the focus is equally important. In this section we present a few approaches that have been adopted to support correlation.

Lampe *et al.* [45] in his work presented two visualization techniques for visualizing well configurations (Figure 2.23). The visualization presents a deformed view of the volume surrounding the well to be compared with an inside out projection (2D projections with no perspective distortion in the horizontal direction) of the same volume to gain further insights.

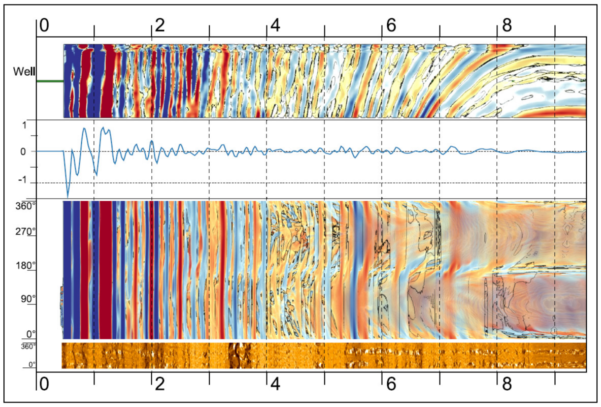


Figure 2.23: Curve-centric volume reformation [45].

Gasteiger *et al.* [31] described a technique for correlating between different focus-and-context attributes using lenses for exploring blood flow in cerebral aneurysms. The lens allows for correlation between two or more properties of the element in focus by showing the object of focus in one property outside the lens and another property inside the lens (Figure 2.24).

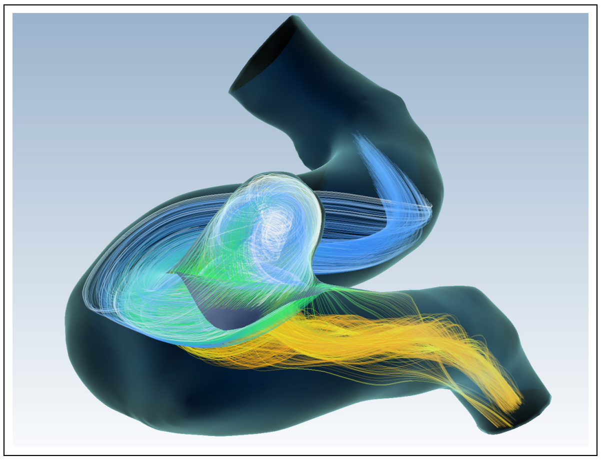


Figure 2.24: FlowLens [31].

Castani *et al.* [19] in his work VolumeExplorer developed a visualization system for interactive oil and gas explorations (Figure 2.24). The system also makes use of painted isosurfaces to understand the relation between horizons and faults as well gain knowledge of the structural model for well planning tasks.

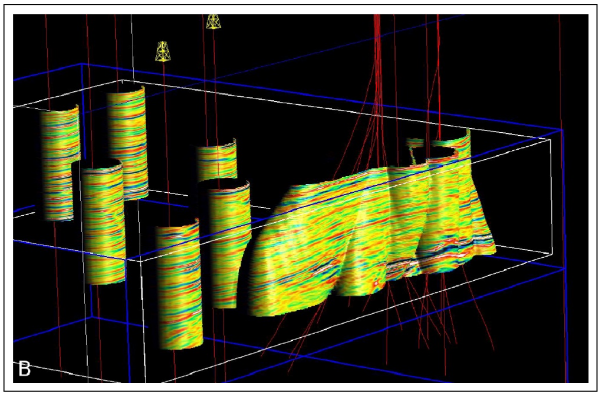


Figure 2.25: VolumeExplorer [19].

In our visualization the aspect of correlation was not explicitly addressed. However, we present visuals that allow comparisons between entities and between an entity and the context. In the next section we discuss background relating to Chapter 5.

2.4 Sketching in 3D Space

Chapter 5 presents three prototypes for creating simple well configurations via sketching. The main challenge to attempt this task is how the 3D space can be explored. Sketching in 3D is a challenging task. One of the main problems of sketching in 3D arises from the limitation of the interface being used to create the sketches. Using a 2D screen such as a desktop, or a tabletop, it is difficult to determine at what depth value a user wants to place a point. It is challenging to approximate the depth values between the near and far plane based on the user's intention. Another challenge that is a result of the depth identification problem is the need to change the view multiple times in order to find points on previously sketched lines or surfaces.

Several examples of applications developed to support 3D sketching exists. Teddy [39] is a sketching interface that allows user's to quickly model 3D structures using 2D strokes (Figure 2.28). The 2D stroke is then inflated to create the 3D polygonal structure.

Figure 2.26: Teddy: A Sketching Interface for 3D Freeform Design[39]

Cohen *et al.* [21] presented an approach to create 3D curves from a single view point. The shape of the 3D curve is determined using the projection of the user drawn 2D curve to a shadow from a virtual light source. ILoveSketch [9] is yet another recent interface for sketching 3D curves with new features such as automatic view rotation and easy sketch surface selection.

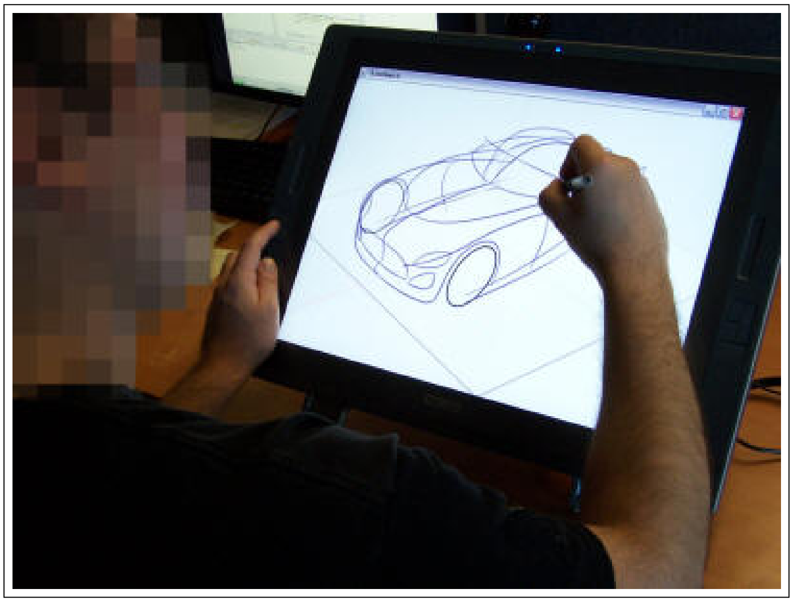


Figure 2.27: ILoveSketch[39]

Sketching in 3D was approached using other technologies as well. HoloSketch [25] is a virtual-reality based tool used for creating and manipulating 3D geometry. The user wears a head-tracked stereo shutter glasses and can create or manipulate 3D virtual models using a hand-held six-axis 3D mouse or wand. 3D Tractus [46] is a system consisting of a tablet placed on a surface whose height can be altered. Sensors measuring the height of the table allows to map from the physical space to the virtual space by providing the third dimension. Harris *et al.* [37] introduced a tangible user interface [37] called *Snakey* (Figure 2.9) for manipulating and interacting with 3D well trajectories in the reservoir model [37], investigating intuitive and more direct ways for well trajectory manipulation.

In all these instances of research, the purpose was to create 3D objects. A well

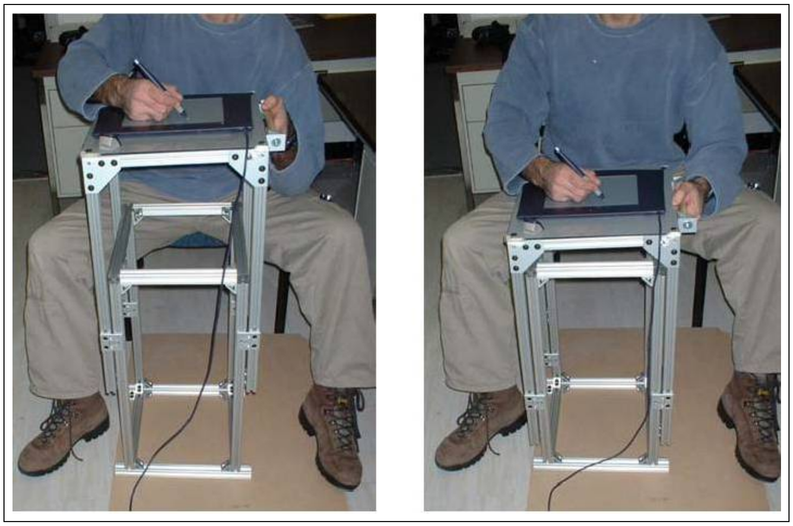


Figure 2.28: 3D Tractus: A Three-Dimensional Drawing Board[46]

however in its simplest representation is just a line in 3D space. The 3D curve representing a well can have different configurations, such as horizontal, vertical and multilateral.

This point onwards we move from the visualization phase to the physical exploration phase. In the following sections we present related work for our *Spidey* prototype both in terms of assitive and tabletop robots and proxemics in interactions.

2.5 Robots

In this section we present a broad overview of the assitive robots and tabletop robots in the domain of HRI followed by robots in the domain.

2.5.1 Assistive Robots and Tabletop Robots

This section briefly covers the state-of-the-art in tabletop robots and the HRI subdomain of assistive robots. *Spidey*, a tabletop robotic assistant (presented in Chapter 5) is strongly influenced by both these domains, but as an assistive tabletop robot

Spidey is, as far as we know, unique in combining the two domains.

Assitive robotic interfaces are often attempting to help disabled users. For example, Guide Cane [7] is a robotic cane designed to help visually impaired users. Hillman *et al.* work [38] and NavChair [48] are examples of assistive robotic wheelchairs (Figure 2.29). Other efforts proposed robotic assistants that play a more complex rehabilitative role, arguably becoming a sort of a mentor: Plaisant *et al.* [57] developed a story telling robot that could be used for pediatric rehabilitation (Figure 2.30) while Wada *et al.* [86] used Paro, a seal robot, in animal assisted therapy for the elderly (Figure 2.31).

Figure 2.29: Assistive robotic wheelchair [48].

Interactive tabletop robots have been introduced in the past: RoboTable [44] and IncreTable [47] are two tabletop robots used in interactive mixed reality frameworks in a game application (Figure 2.32).

Figure 2.30: Story telling robot for pediatric rehabilitation [57].

Figure 2.31: Paro: therapeutic robot [86].

Figure 2.32: RoboTable [44] .

Guo *et al.* [35] created a tabletop interface for interacting with a group of remote robots, either by physical touch or using toy tangibles (Figure 2.33). Tangible Bots [56] are active motorized tangibles with haptic feedback, which can be used for performing fine-grained manipulations on tabletop surfaces (Figure 2.34).

Spidey as a robot is quite simple, but is unique in its design to become an assistant in a valid tabletop engineering application. *Spidey* can perform specific domain-related tasks in the context of the reservoir post processing application in which its assisting. *Spidey* can have sliding assistive roles within its task: it could be viewed as a tool, for example, searching for a particular attribute value in the reservoir or it could be a mediator or a mentor, for example by playing back to a novice user a sequence of past explorations done by an expert, or cutting open the 3D reservoir model to reveal information that was otherwise hidden to the viewer. However, the

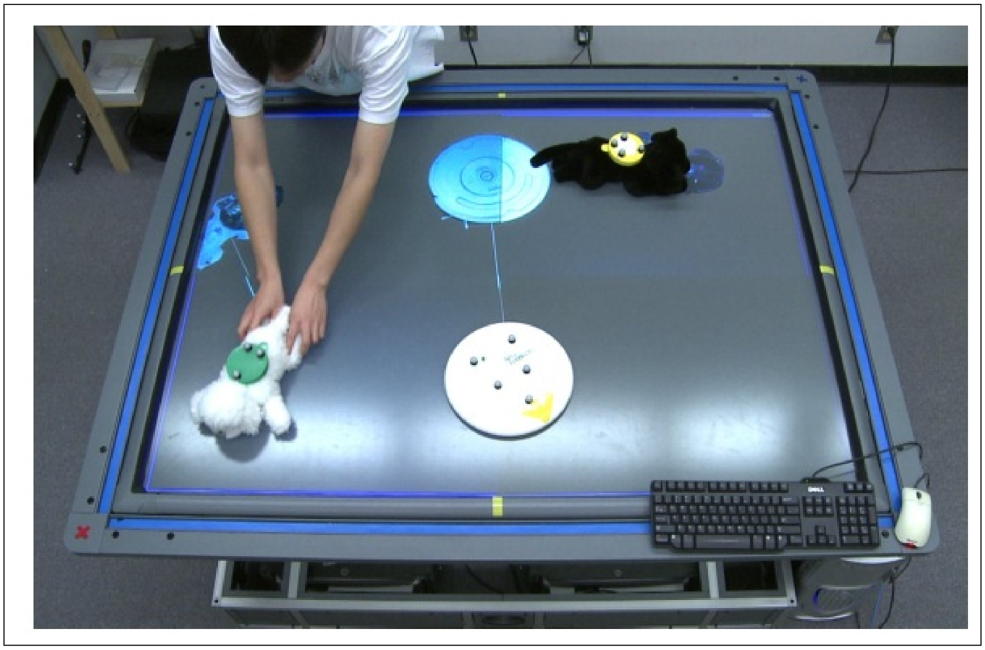


Figure 2.33: Touch and Toys interface [35].

Figure 2.34: TangibleBots [56].

roles played by such assitive agents depends on the perception and the interaction style of the people interacting with the robot. To study the behaviour reaction of people towards the robot we explore the theories of proxemics.

2.5.2 Robots in the Domain

In 1971, L. A. Rupp [59] described the role of manned underwater vehicles and remote-controlled robots in deep water oil exploration. He explained the challenges of robots used in 1962 - Mobot and Unumo, used for underwater oil exploration. L. A. Rupp noted that the cost and performance of these robots were the main reasons for their limited use in the process of oil and gas exploration. Latter in 1984, H. L. Shatto [68] described the use of a remotely operated vehicle (ROV) for providing drilling. Sagatun and Fossen [60] developed an advanced supervisor computer controlled underwater robot manipulator for inspecting welds underwater. Recently Pretlove *et al.* [41] described the challenges of offshore operations and the advantages of employing robots for remote operations. They also describe early results from testing a robot in both a laboratory setting and in the field.

The research in the domain of oil and gas involving robots as can be observed from the related work shows that robots in the domain have mostly been used for field operations. *Spidey* on the other hand is a robot that comes into the workspace of an engineer. It attempts to assist engineers in their day to day operations by collaborating with them at their workspaces on a tabletop.

2.6 Proxemics in Interaction

Digital tabletops have been established as useful interaction mediums [80]. In the Chapters 3, 4 and 5 we present our efforts exploration efforts via visualizations involving physical touch and tangibles for enhancing the interaction. However, moving beyond these two forms of interactions, we explored how interactive physical objects could influence interactions using our simple tabletop robot. To understand and learn about the interactions between a interactive physical agent on the tabletop and a tabletop user we explored the concept of proxemics. In this chapter we broadly discuss instances of research that utilized theories of proxemics to influence interaction in the realm of HCI and HRI.

In 1966 Hall defined proxemics as “the interrelated observations and theories of mans use of space as a specialized elaboration of culture” [36]. He suggested a set of “reaction bubbles”, observed zones, into which people tend to divide the personal space around them ranging from the intimate, personal, and social to the public. The process of dividing our surrounding space is dynamic [36], for example, when two friends are communicating with each other the distance maintained between each other is very different from that maintained between two strangers. Hall also theorized the concept of territoriality, describing how animals and humans lay claim and “defend” an area surrounding them [36]. Over the last decade Halls theories of proxemics were found to influence the way we interact with technology, and to inform the design of new interfaces[34, 53, 64, 65, 78, 85, 87].

The application of the concept of proxemics and territoriality to HCI has been investigated in different scenarios. Scott *et al.* [64, 65] explored proxemics between individuals in a tabletop collaborative environment (Figure 2.35). They found that individuals tend to divide the table space into three main territories personal, group and storage, according to the way an individual and a group of people performed tasks.

Vogel and Balakrishnan [85] developed design principles and an interaction framework for tuning public ambient displays to react to changing implicit (body orientation

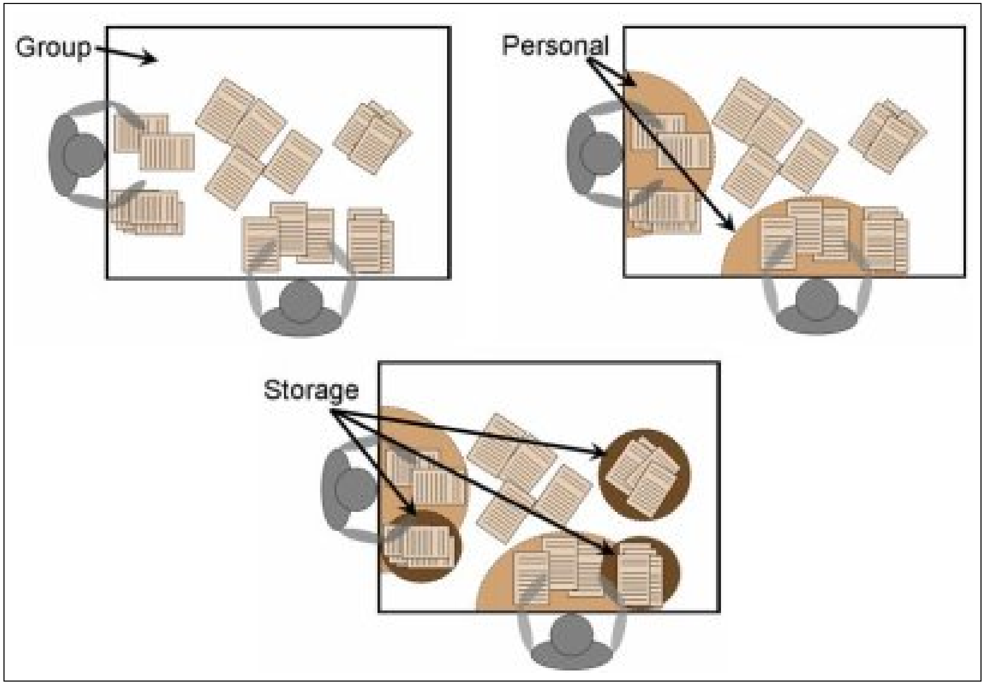


Figure 2.35: Territories in a tabletop collaborative environment [64]

and position cues) and explicit interactions (hand gestures and touch input) of people (Figure 2.36).

Greenberg *et al.* [34] further explored this concept in terms of how technology in an ubicomp setting can be made to be responsive not just to the presence of individuals but also other devices in the environment (Figure 2.37). They tested a proxemics toolkit they developed in various scenarios around a large display interactive environment and highlighted three main challenges for studying proxemics in such settings: designing under the assumption of a set of "rules of behavior", developing a robust system that can overcome the limitations of current sensors devices, and finally, a way that can help to accurately identify the expectations of individuals from a proxemics-based system.

The notion of proxemics in human-robot interaction can be quite different from proxemics between people and displays. Robots physicality and movement, especially

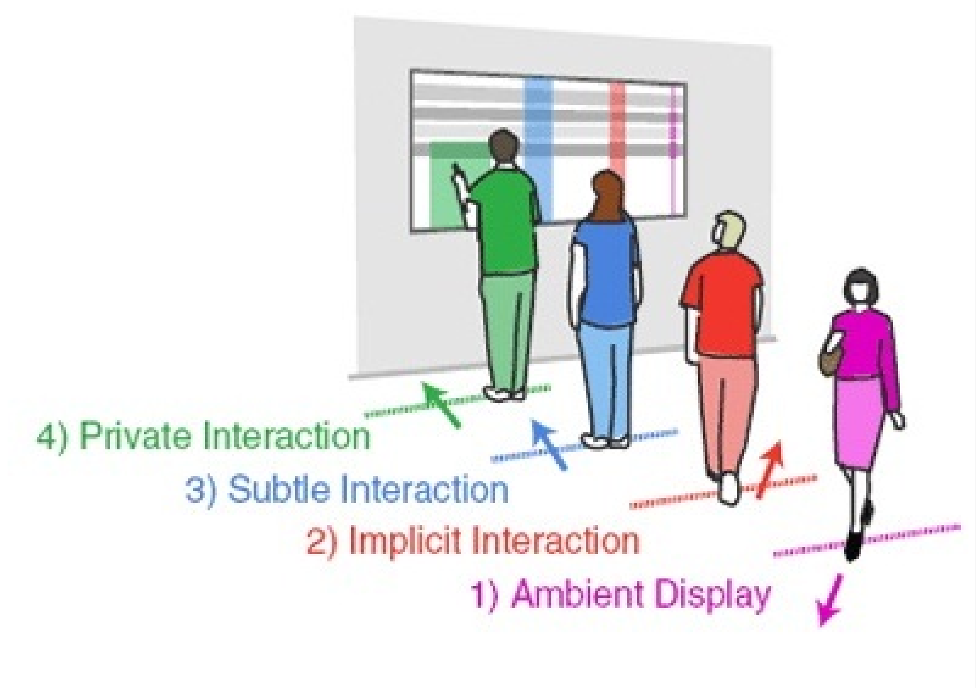


Figure 2.36: Implicit and explicit interactions with a public ambient display [85].

Figure 2.37: Proxemics in a Ubicomp setting [34].

in collocated interaction, affects people in ways that often resemble interaction with animals or with other people. Takayama and Pantofaru [78] investigated the influences of proxemics in human robot interaction with a large humanoid robot (Figure 2.38). They observed three main characteristics that influence the proxemics-related interaction - previous personal experiences with pets or robots, physical characteristics (i.e. orientation of robot head) and personality traits of the human users (i.e. agreeableness, negative attitude).

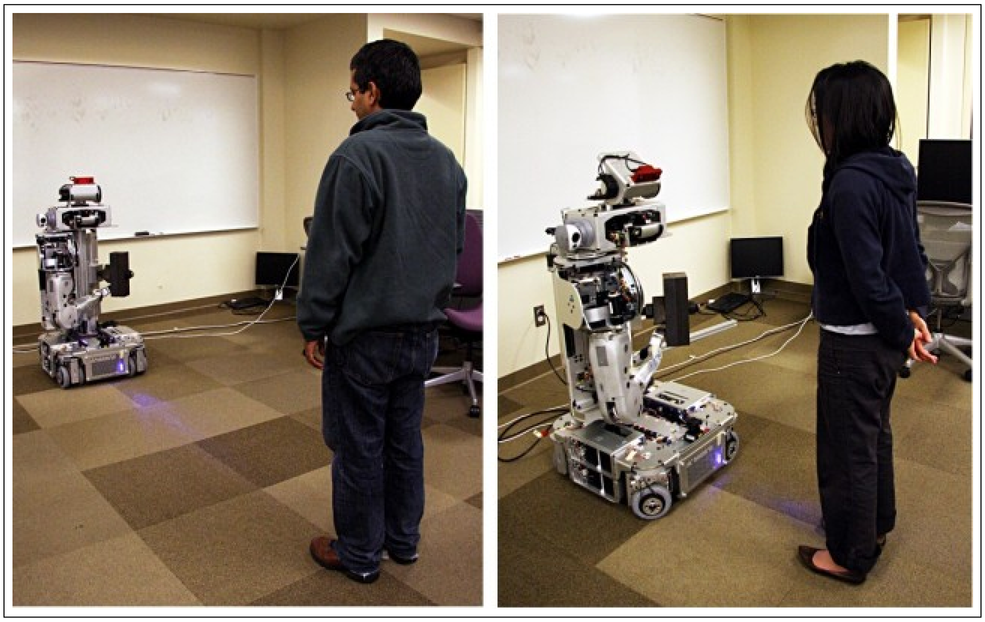


Figure 2.38: Interaction between a human user and a humanoid [78].

Walters *et al.* [87] proposed an empirical framework which can inform how proxemics, and more explicitly interpersonal distances between humans and robots can be used by the robot to affect human robotic interactions. Bethel and Murphy. [12] present a survey of the effect of appearance-constrained robots in proximate interactions and found that distances of 3m or less effect interactions, a behavior commonly observed in social humans interactions. Mumm and Mutlu. [53] conducted a study using a Wakamaru robot (Figure 2.39) to understand how the concept of proxemics can explain the variation in physical and psychological distancing in a human robot interaction. They used likeability and gaze behavior of the robot to study the reactions of the participants and observed that the physical and psychological distances would increase if the participant disliked the robot and if the gaze of the robot increased.

Figure 2.39: Wakamaru robot.

We see tabletop robot proxemics as a unique challenge that combines threads relating directly to both human-robot interaction proxemics [53, 78, 87] as well as tabletop proxemics [64, 65]. As far as we know proxemics between a user and a tabletop robot is still unexplored.

2.7 Summary

This chapter discussed the background for this thesis by reviewing the domain, technology and related work that inspired our four prototypes. In the following chapter, we present three visualization variations used to learn about the uncertainty values in the reservoir model.

Chapter 3

Interpretive Analysis for 3D Reservoir Flow Simulation Models

3.1 Overview

Reservoirs are entities hidden several thousands feet below the surface of the earth. The only initial information that the reservoir engineer has about the reservoir comes through indirect means such as rock samples or the output from multiple sensors. Using this limited information and additional interpretations by reservoir engineering experts a virtual 3D reservoir model is constructed [23]. Investigating the virtual 3D reservoir model is the closest analysis that an engineer can perform in regards to gaining further insights about the actual reservoir.

At the post-processing stage or the visualization phase, a reservoir engineer solely depends on the virtual 3D representation of the actual reservoir to gain insights and make important decisions. However, due to the limitations on the kind of information that can be provided by a visualization application, interpretation and decision making becomes a difficult and challenging task. Consider the task of identifying optimal locations for drilling a well. This is a task of high importance to a reservoir engineer, since drilling an oil well is a cost intensive activity. To perform such a task, an engineer would like to learn about the relation between two or more geological properties, the variation of such combined properties for existing well locations and so on. However, performing such a task in the current commercial visualization packages [2, 6] is not straight forward and intuitive. Usually such problems are approached by creating two or more instances of the same reservoir model and mapping them to different geological properties to facilitate comparison and decision making. However, comparing two models is difficult to perform and make the task of gaining insight cumbersome.

Using these concerns as design rationales, in this chapter we present the design, implementation and evaluation of a proof-of-concept prototype which maps two geological properties to a reservoir model simultaneously using some logical reasoning and presents three visualization variations - *candy visualization, history circles and indicator* for exploring and interpreting the discrete numerical values of individual cells of the 3D reservoir model in the context of both existing well trajectories and/or the reservoir itself. The main motivation is to allow the engineer to concentrate on gaining insights and interpret the important information using our simple visuals and single mapping rather then having to deal with the visualization application constraints.

Information clarification is one of the major goals of visualizations in general. However, the pertinent information could either be portions of the actual context itself (raw data) or it could be correlations resulting from the analysis of the raw data. Generally, solutions which present portions of the context in a manner that indicates that they are the current data aspect of interest can be classified under the broad category of focus and context techniques, whereas visualizations of data correlations are more often presented as augmentations and overlays. In most cases of focus and context solutions, the context is compromised in some manner to allow presentation of the area under focus. However, in underground datasets like reservoirs, where the primary purpose of the visualization application is to present the hidden context itself, compromising the context to gain further insights may not be a reasonable trade-off. Using this as a motivation the three visualization techniques were developed to explore and interpret the reservoir models without compromising the reservoir context by blending concepts of scientific visualization and information visualization.

In summary, in this chapter we present a way to map the reservoir model to two geological properties simultaneously using logical reasoning. To explore the model we present three visualization variations which borrow from concepts in scientific and information visualization, to explore the 3D post-processing reservoir model. The chapter is divided as follows: We first present details about the mapping formulation followed by the design and implementation of the three visualization variations. Latter in the chapter we discuss the results and evaluations of the three visualization variations.

3.2 Mapping formulation

As discussed in the introduction, in this prototype, we attempt to create a formulation that combines two geological properties to create a new map of that can be applied to the 3D reservoir model. For prototyping reasons we perform a simple calculation involving the values of two geological properties - oil pressure (dynamic) and porosity (static) for calculating the new combined property value for each cell. The rationale behind selecting oil pressure and porosity is that the well is usually drilled in regions where the pressure is high and the rock is porous, to facilitate the flowing of oil and gas. To formalize a term for regions of low pressure and low porosity, we call them regions of high uncertainty, corresponding to the engineer interpreting them to be unfitting for placement of well trajectories. Similarly, regions of high pressure and high porosity correspond to regions of low uncertainty. However, it is important to note that there are possibly many ways to calculate such combination values based on different correlation equations and ratios as per the experts discretion.

3.2.1 Implementation

To calculate the new mapping values for each cell of the reservoir model, the following steps are followed: (a) first the reservoir model is divided into a number of smaller partitions. To create these partitions, we begin with the cell with index i=1,j=1 and k=1. We group every 50 (experimental value) set of cells to belong to one partition. The last partition may have lesser number of cells. This is accounted for in the ratio calculation. (b) Next, every cell is marked to be a uncertain cell if its pressure and porosity value is within a minimum range [minimum,maximum/1.4], identified by trial and error. We keep a count of these uncertain cells per partition. (c) Finally the following equation is applied to calculate the uncertainty percentage of every partition:

$$uncertainty\ percentage = \frac{number\ of\ uncertain\ cells\ per\ partition}{total\ number\ of\ cells\ per\ partition} * 100$$

The uncertainty percentage of every partition is assigned to be the uncertainty percentage of every cell in that partition. For example, if a partition has 5.0% uncertainty than every cell in that partition will have an uncertainty percentage of 5.0%. As mentioned previously, it is important to note that the above mentioned measurements are only a proof of concept to what can be done and the reservoir engineer may provide better insights about the kind of calculations that can be applied.

3.2.2 Visualization

To present an overview of these uncertainty values, we map the values using a color scale defined to vary from green to blue (Figure 3.1). Green indicates low uncertainty, and blue represents the highest uncertainty. In other words the green areas consist of cells which have high pressure and high porosity, indicating better locations to drill a well compared to areas in blue, which represent cells with low pressure and low porosity. For this particular model (Figure 3.1) with 33000 cells, the uncertainty was found to vary from 2% to 60%. The red lines seen in the Figure 3.1 are three individual well trajectories. In order to make the wells visible, only the reservoir shell was rendered with some added transparency. Meaning, the cells inside of the reservoir cannot be seen in this image. As can be observed from Figure 3.1, our calculation involving two geological properties resulted in a somewhat checkerboard like pattern. This could be modified to some extend by changing the partition algorithm. However, it also depends on the geological property values we obtain from the simulation result.

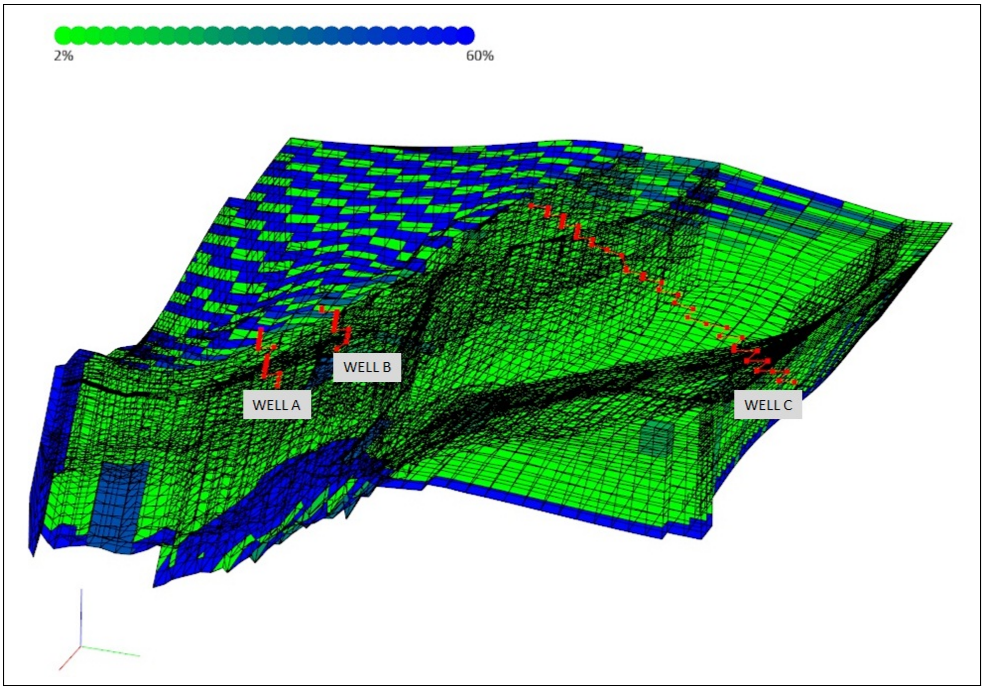


Figure 3.1: Overview of the uncertainty present in a reservoir model.

3.3 Our Techniques - Candy, History and Indicator

This section discusses the three visualization variations we implemented to explore and interpret the information mapped to the reservoir models.

1. *Candy Visualization* - is a modification of the concept of “focus and context”.

This visualization is useful for visualizing and exploring uncertainty in wells hidden in the reservoir model.

2. *History Circles*- makes use of visual variables [11] and encodes statistical information about the well uncertainty ranges using shape and size.

3. *Indicator*- is a technique which supports free form exploration of uncertainty in the 3D reservoir models.

3.3.1 Candy Visualization

Occlusion is one of the main problems with 3D visualizations. How do we visualize and read the associated information for a well trajectory hidden below and behind several layers of rock, without compromising on the context? This is the question that formed the basis for this visualization.

In our previous work [75] focus and context for wells was a technique used for visualizing well trajectories (Chapter 4). The visualization would create a 'V' shaped opening by removing all the occluding blocks in order to make the well visible from the current view point. However, creation of such an opening meant a compromise on the context, and such a compromise was mentioned to be not much of an acceptable trade-off by some of our participants from the domain [75]. In order to address such a problem, we developed candy visualization. It is a way to pull out the pertinent portions of the reservoir model out of the context to be viewed more easily.

Figure 3.2 shows the candy visualization for well C in the reservoir model. The metaphor of candy is being used because of the visualization's appearance. The candies look like lollipops with red sticks and 3D well block attached to them (Figure 3.3). The blocks attached to the red lines are clones of the actual 3D well blocks hidden below. They have the same size, shape and color as the actual well blocks.

The red lines show the connection between the original block and its corresponding clone.

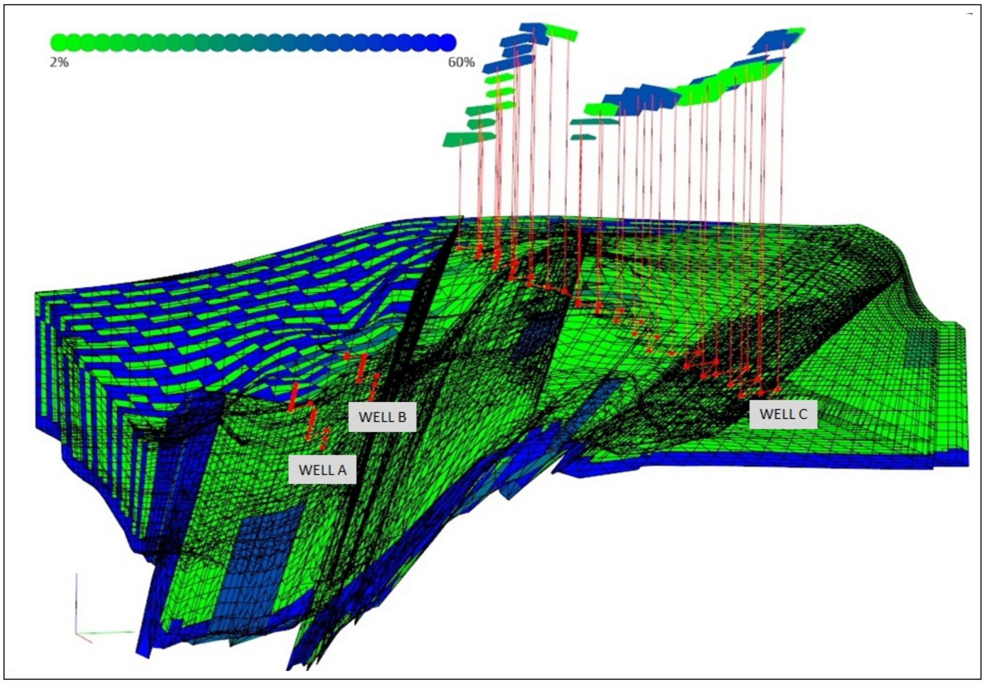


Figure 3.2: Candy visualization of well C.

In the current prototype the height of the candy lines depicts the depth of the well trajectory at that point relative to its immediate neighbours. In other words, if a point A of the well trajectory belongs to depth layer 2 and point B belongs to depth layer 5 (depth layers arranged in ascending order), than the candy line of B will be taller than that of A. However, it is important to note that the layer to which a well point belongs may not be obvious from the 3D model structure. The shape of a layer is not necessarily vertical as seen in Figure 3.4.

The advantages of our visualization according to us are as follows: (1) we could maintain the entire context, while we explored hidden entities; (2) using this visual we could have a quick glance of the uncertainty distribution in the well blocks and (3) we could gain insight about the shape of the well. Later on in our study we used

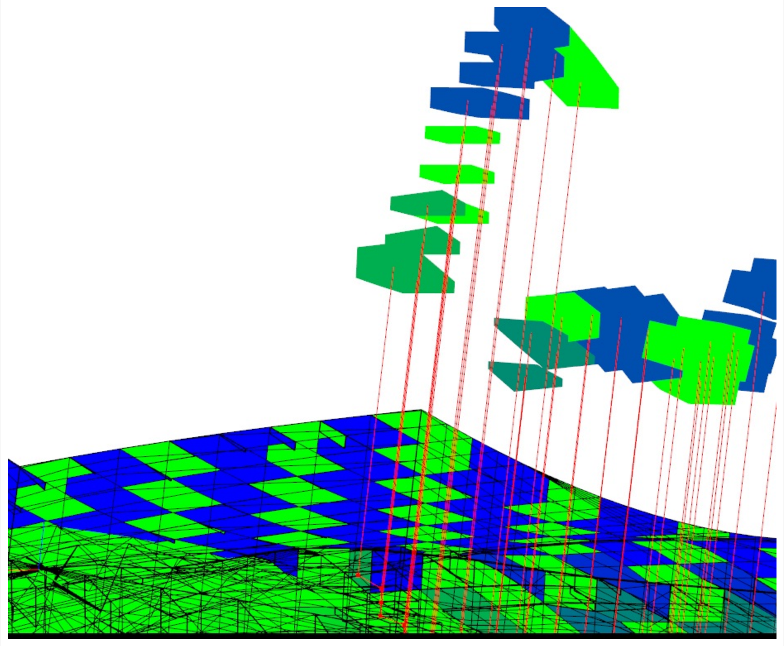


Figure 3.3: A closer look at the candies.

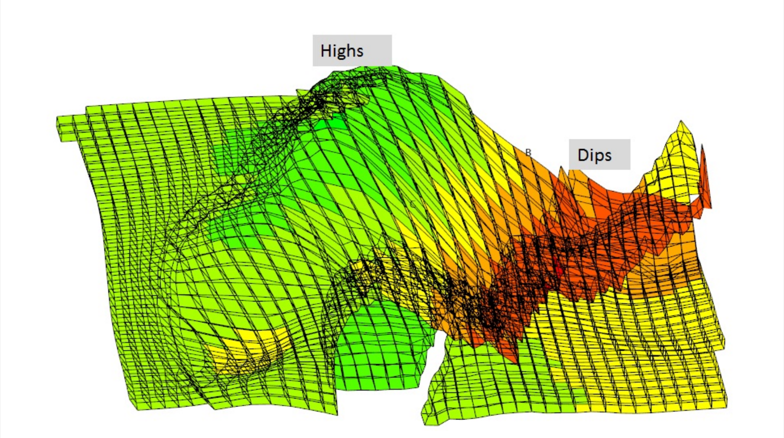


Figure 3.4: Depth layer 8 of the reservoir model.

these three points as the guiding elements to evaluate if our assumptions about this visualization were true.

As can be seen in Figure 3.2, well C is more spread out and long in comparison to the other two well trajectories, which are compact and almost vertical. The resulting candies were clear and spread out for well C. To understand how the candy visualization would work for wells which had a slightly more compact shape, we devised a simple mechanism which would allow users to select a particular well and see its corresponding candy visualization. Figure 3.5 shows the candy visualization for well A. The wire frame triangles seen in the figure are button like elements. The user can simply tap inside the wire framed triangles to select a particular well and bring up the corresponding candies.

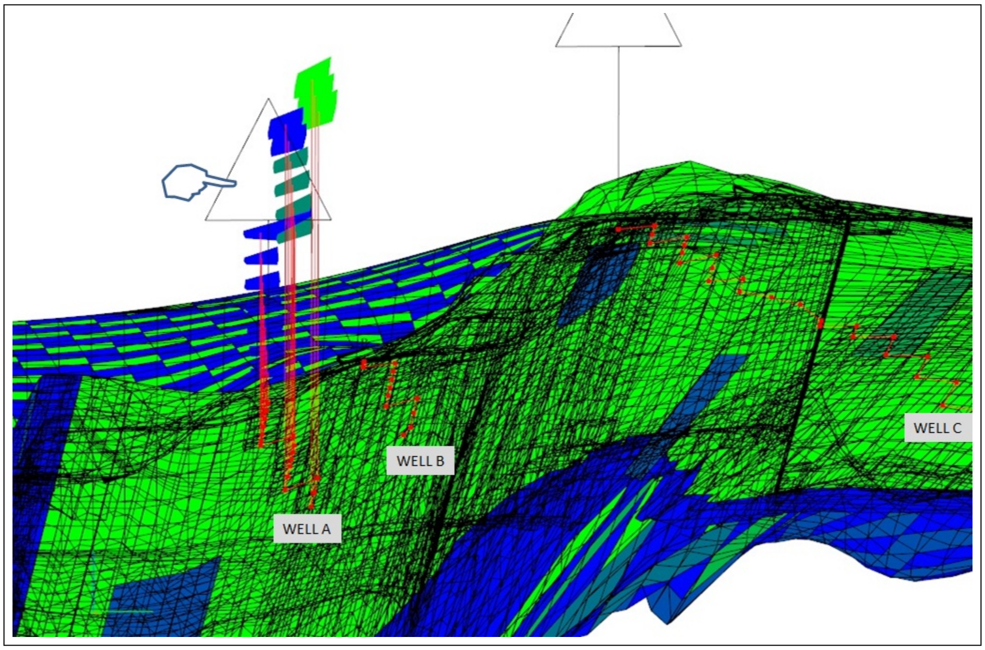


Figure 3.5: Candy visualization of well A.

While we explored the possible uses for candy visualization, we considered a scenario where candies and the reservoir model can be mapped to different properties. Figure 3.6 shows a reservoir color mapped to represent oil pressure and the candies mapped to represent uncertainty. Essentially, this allows engineers to study the reservoir and the well trajectories in different contexts and combinations of geological properties.

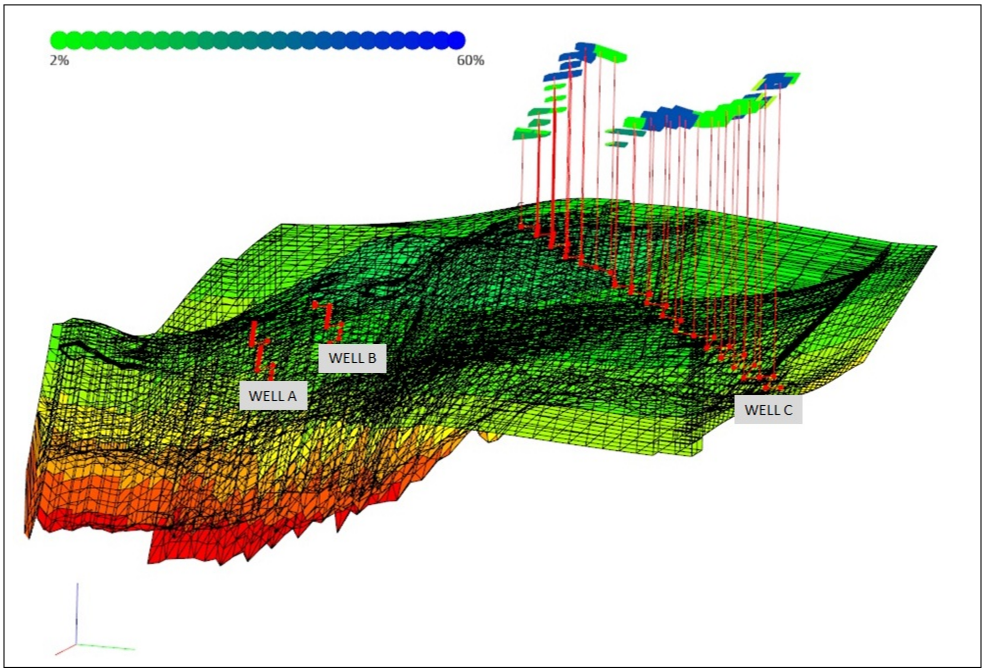


Figure 3.6: Candy visualization representing uncertainty in the context of a pressure mapped reservoir.

3.3.2 History Circles

History circles relate to the concept of maintaining the past history or information about either existing well trajectories or newly created trajectories. History of a well could consist of information such as the location of a well, the length of a well and geological property values of the individual perforated blocks. Using this rationale we designed and implemented a visualization that would allow to gain knowledge about the uncertainty values present in the individual well blocks.

From candy visualization an engineer can tell the approximate range of uncertainty associated with a particular well, because of color scale issues or dense overlapping of cells. However, the meticulous nature of a reservoir engineer's work may require that she need more information about the exact distribution of uncertainty associated with a particular well trajectory. To address this, we developed our second technique history circles.

History circles for a single well

Figure 3.7 shows the history circles in blue. The history circle appears at the position of the tag that defines the modality of uncertainty visualization. Associating the position of the history circles to the tag position allows us to easily reposition the history circles on the tabletop surface.

The history circles encode two things: (a) the unique uncertainty percentages associated with the well blocks (which are represented by a text to the side of the circle) and (b) the number of blocks in the well trajectory which have that uncertainty percentage (represented by the area of the circle). The circles are ordered according to the area of the circle.

From the Figure 3.7 it can be seen that the history circle shows that for the well trajectory C, the well blocks belong to four unique uncertainty percentage values: 20%, 28%, 2% and 42%. The area of the circle corresponding to 42% uncertainty indicates that majority of the perforated blocks for well C have 42% uncertainty, while few blocks have 20% and 28% uncertainty, indicated by smaller circles.

Alternative to history circles, we could have used well known techniques such as histograms or bar charts to show this distribution. However the main goal of history circles was to have a visual that would enable an engineer to see a quick overview of the requested information and present details only on demand. One of the main disadvantages of this visualization is the number of circles that would result if the range of uncertainty is wide. However, generally a well trajectory would be drilled

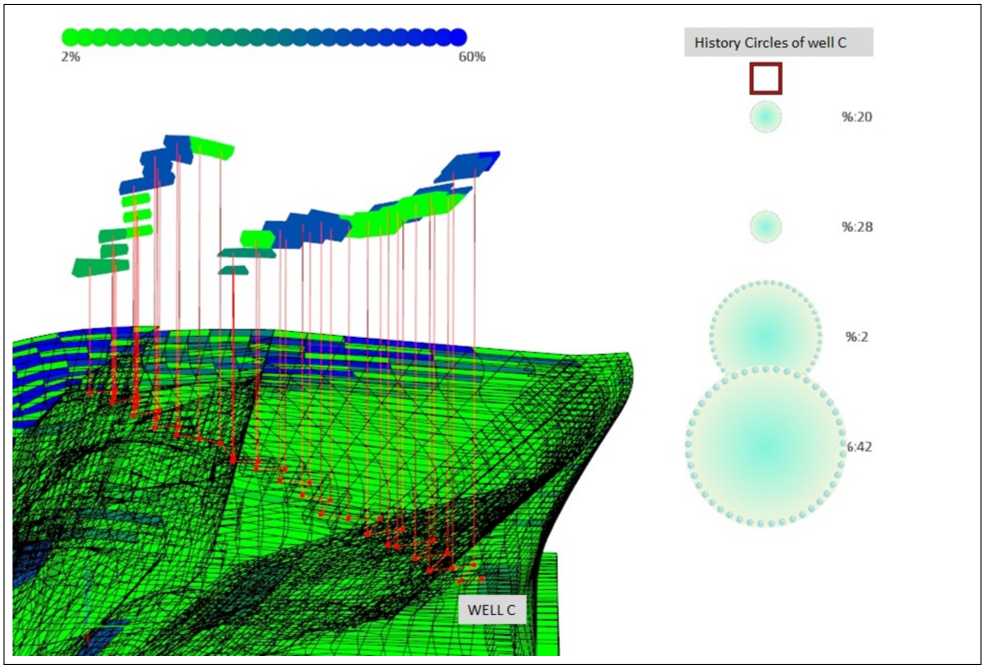


Figure 3.7: History circles of well C.

in an area where the rock formations have more or less similar attributes implying that on most cases the number of circles will not be too many. In the example model we used, even for the longest well (well C - 39 perforation blocks) only four distinct values of uncertainty were found.

Static representation of numbers using shapes however do not indicate the spatial locations of those well blocks and may not be sufficient when more detailed information about the uncertainty of the well blocks is required. Hence, we devised an interaction technique, which would enable the engineer to have correspondence between the circles and the candy visualization.

Figure 3.8 shows how one can tap on an individual history circle and see the corresponding blocks having that uncertainty percentage get highlighted in yellow. From this interaction we can also overcome any confusion in reading that may have cropped up due to the color scale issues (e.g.: two greens that look alike and difficulties telling close shades of two colors apart).

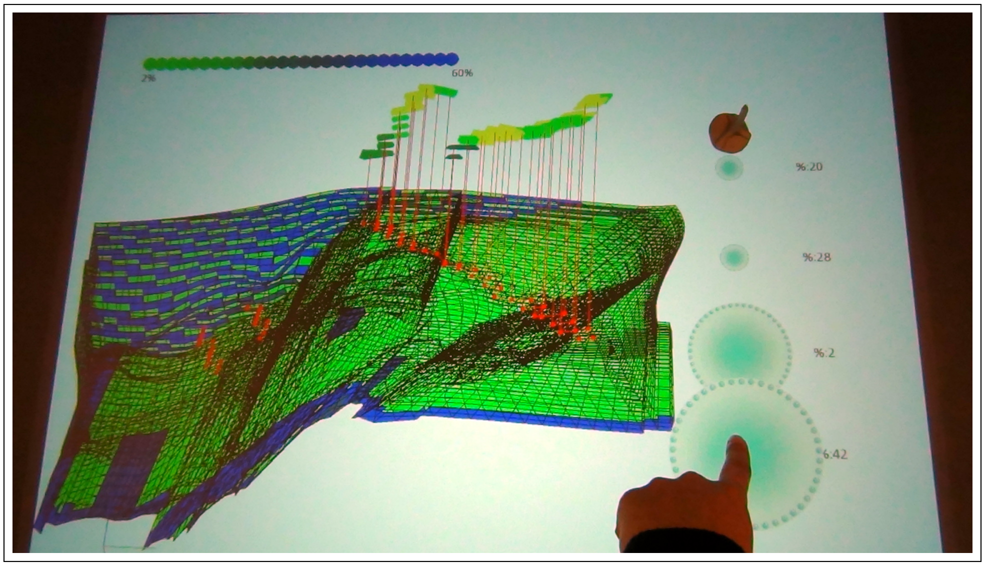


Figure 3.8: Interplay between history circles and candy visualization.

History circles for a well may actually be long in some scenarios. In such scenarios we are perhaps not interested in seeing all the circles at a time. To address that, we designed a *wrapping and unwrapping* method, which would allow us to remove the long trail of circles when required and bring them back when needed. This may be of use even in short list, since it allows us to focus at one circle at a time.

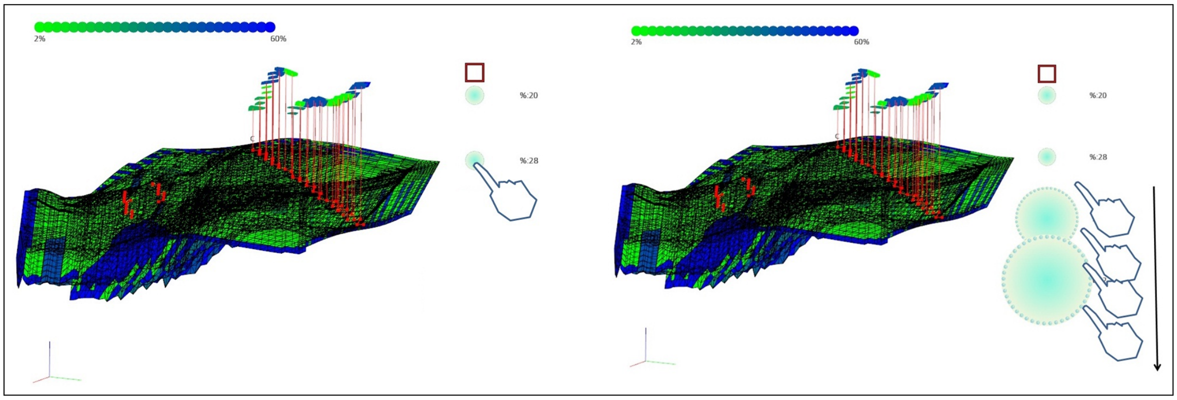


Figure 3.9: Illustration of wrapping and unwrapping history circles

Figure 3.9 illustrates the working of *wrapping and unwrapping*. On tapping on a circle, the circles below the chosen circle will be wrapped or removed temporarily from the display. On sliding or running the fingers down, the wrapped circles get unwrapped.

History circles of multiple wells

We next explored the potential of history circles by visualizing history circles for multiple wells. For this we modified the concept of individual history circles as shown in Figure 3.10.

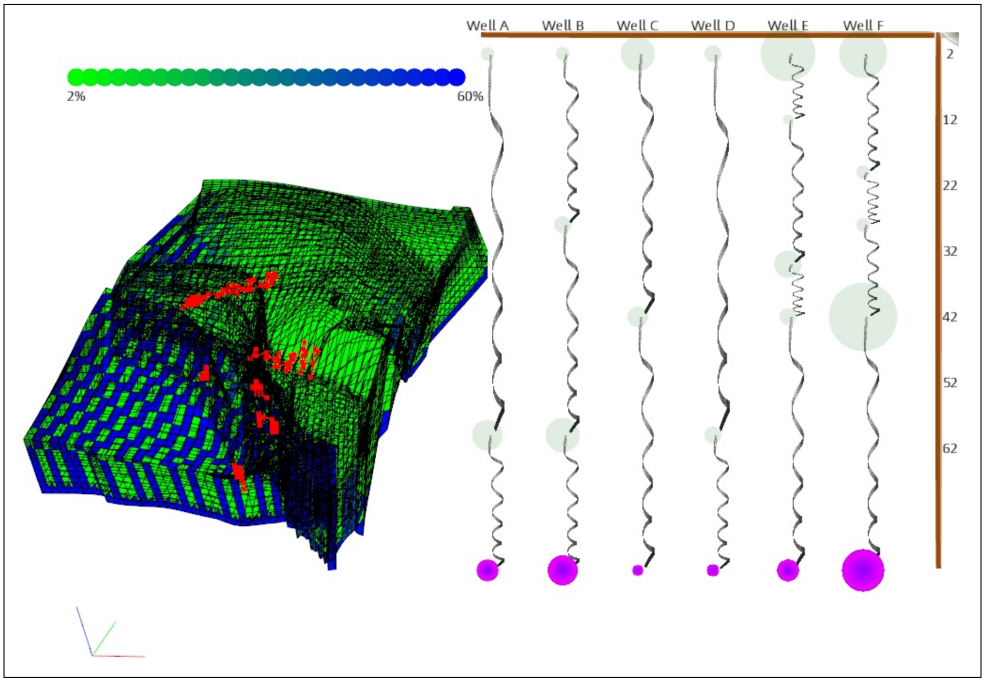


Figure 3.10: History circles for multiple wells.

For this visual the encoding of individual percentages as text, and area of the circle to represent the frequency of the well blocks having that percentage of uncertainty were retained. However, a third element to represent total uncertainty of each well was added (represented by the pink circles).

Figure 3.10 shows the individual history circles of six wells in the reservoir. The history circles have been 'hung' on a horizontal brown pole. The vertical pole shows the scale for the uncertainty percentages. The grey circles are positioned according to their uncertainty percentages on the scale and their area represents the number of well blocks having that uncertainty percentage. The circles are connected by springs. The spring metaphor used here is currently simply a visual element. They are cramped in regions where two circles are very close in terms of their difference in uncertainty values and more spread out in areas of wider differences. The purple balls hanging at the end of the springs represent the total uncertainties (normalised) of each of the corresponding wells. The larger the area of the purple ball, the more is the total uncertainty of that well. This kind of casual representation of hanging the individual history circles was designed to be used for quickly comparing between the information of two or more wells.

To know which list of circle corresponds to which well in the reservoir model, the engineer can tap inside the wire framed triangles as seen in Figure 3.11. To show the correspondence visually, the corresponding circles will be highlighted in blue.

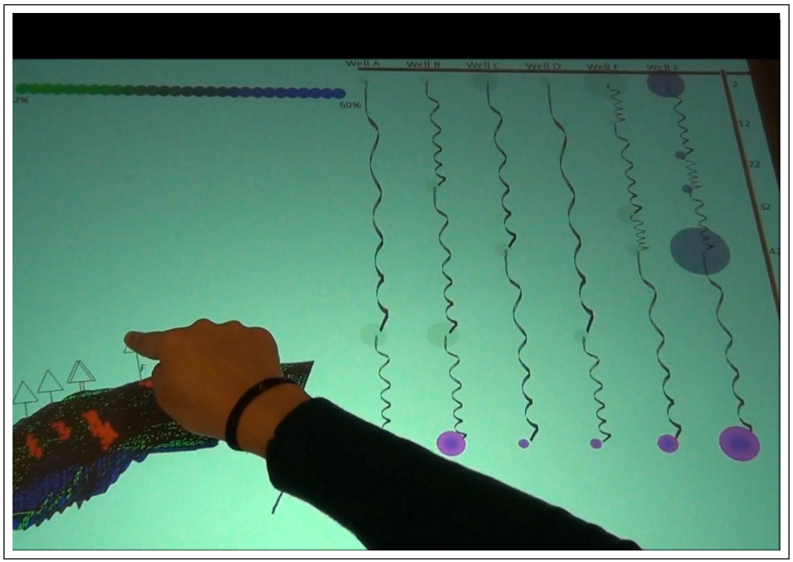


Figure 3.11: Correspondence between well and history circles.

3.3.3 Indicator

The goal of this technique is to allow an engineer to perform a free form exploration of the uncertainty in the 3D reservoir models. To make this free form exploration feel simple and natural we developed this visualization to reflect on the explorations done by sketching. The engineer can sketch on the tabletop using a finger and as she sketches and explores through the reservoir model, a circle appears at the tip of his/her finger indicating the accumulation of uncertainty up until that point. In this prototype the accumulation is a short memory keeping track of the last five cells, a value chosen to demonstrate the purpose of this technique. In the future the prototype can be easily modified to keep track of more than 5 cells or less based on user requirements. The size of the indicator will constantly change either by growing in size (increasing uncertainty), shrink (decreasing uncertainty) or remain the same size. This dynamic change in the size could perhaps serve tasks such as well planning or well positioning.

To illustrate the interaction, first consider Figure 3.12, which shows how an engineer can sketch in 3D on a 2D orthogonal plane using his/her finger. Note that when the user sketches on the 2D planes they are probing only the cells on that plane. The current prototype of the application, allows one to select from three orthogonal planes (Figure 3.13) for navigating through the reservoir model. Figure 3.14 shows both the interaction planes and the indicator overlaid in contact with the touch point. With our indicator, we augment the type of exploration possible by including an interactive indicator of the cumulative uncertainty.

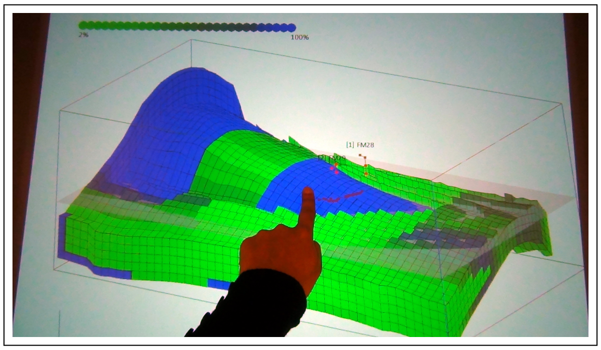


Figure 3.12: Sketching on an orthogonal plane.

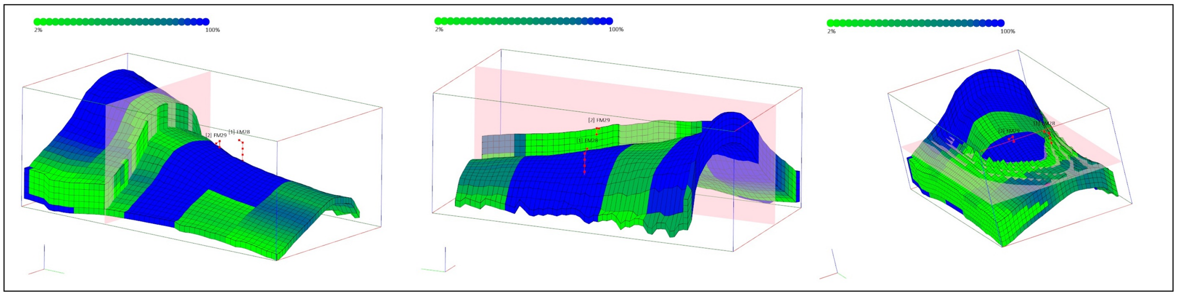


Figure 3.13: Possible orthogonal sketching planes.

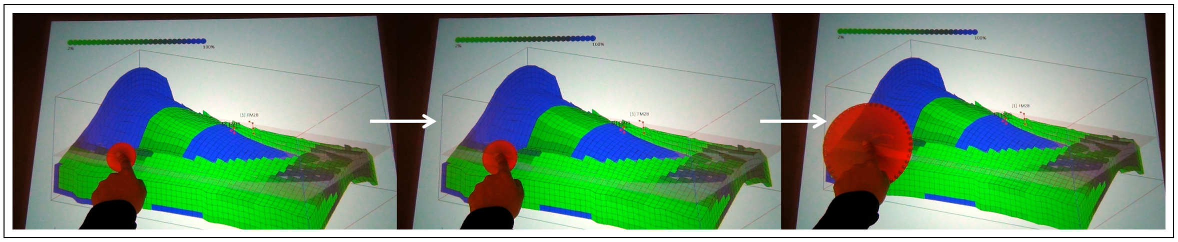


Figure 3.14: Sequence for the growth of indicator size as the accumulation gets bigger.

3.4 Sketching and Cutting Planes

In this section we describe the design and implementation of the sketching planes used by the indicator tool for the exploration of the uncertainty mapped reservoir model.

The three orthogonal sketching planes used for exploring uncertainty are implemented using the concept of binary space partitioning (BSP) [55]. BSP is a method for partitioning space by the use of hyperplane. "A "hyperplane" in n-dimensional space is an n-1 dimensional object which can be used to divide the space into two half-spaces. For example, in three dimensional space, the hyperplane is a plane. In two dimensional space, a line is used" [70].

In our current implementation, our hyperplanes are 2D orthogonal planes that are defined by the walls of the bounding box. The user can select the 2D orthogonal planes by placing two fingers kept relatively close (less than 1 cm) to each other on the walls of the bounding box as seen in Figure 3.15. Selection of a plane is indicated by the appearance of a pink color plane.

Once the plane is selected, it can be moved up or down, left or right or front and back. To indicate the modality of moving the planes, the user has to spread out the two fingers slightly (greater than 2 cm) and move it in the required direction as seen in Figure 3.16.

After positioning of the plane, to facilitate sketching in 3D we need to provide visibility so that the user knows where she is sketching. For this, we convert our sketching planes to function as cutting planes. Upon removal of the fingers from the table, BSP computations are performed using the current plane as the hyperplane. The BSP computations help us identify which cells are to the right and left of the hyperplane.

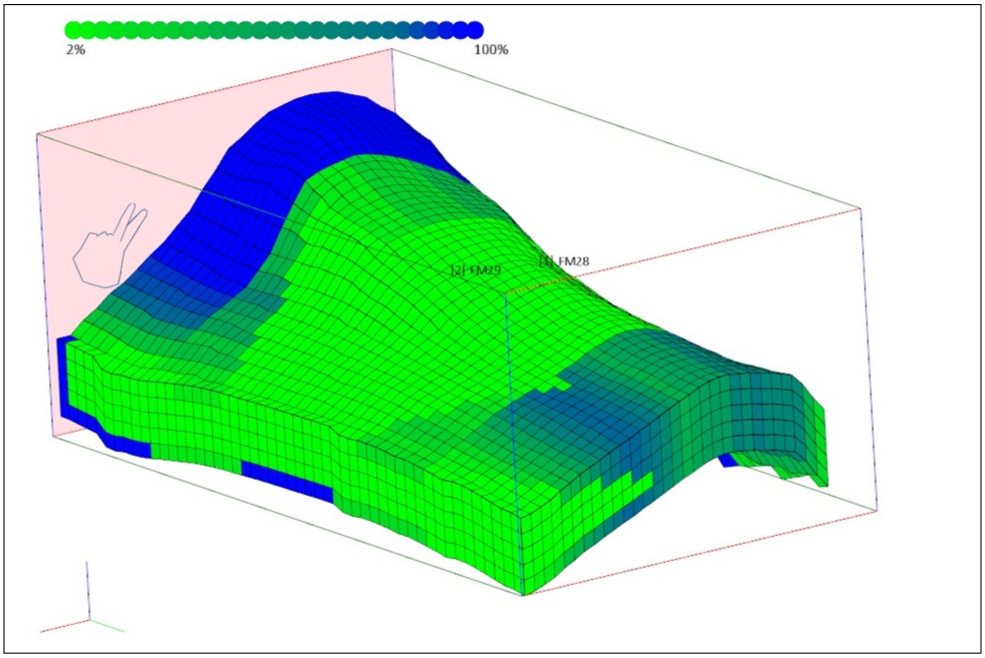


Figure 3.15: Selecting a sketching plane

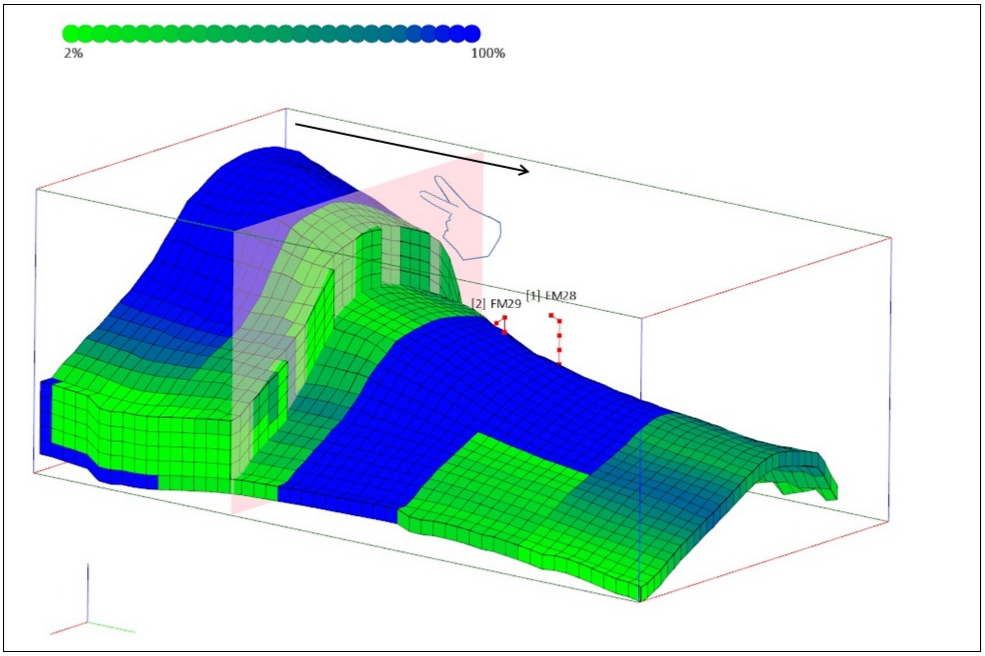


Figure 3.16: Moving the sketching plane

The BSP algorithm is as follows:

1 : find the origin and normal of the hyperplane.

2 : compute: difference = center - origin; where center is the centroid of the cells in the i, j-1 and k-1 direction.

3 : find the dot product of (center-origin), normal.

4 : Using the dot product we determine what is to the left and right of the hyperplane.

In the current implementation, the cells to the right of the hyperplane are removed to facilitate visibility while sketching. However, when looping through all the cells, we loop only till j-1 and k-1 layers so as to not loose the shape of the context completely. Figure 3.17 illustrates the comparison between maintaining some shape information in comparison to cutting precisely into two halves.

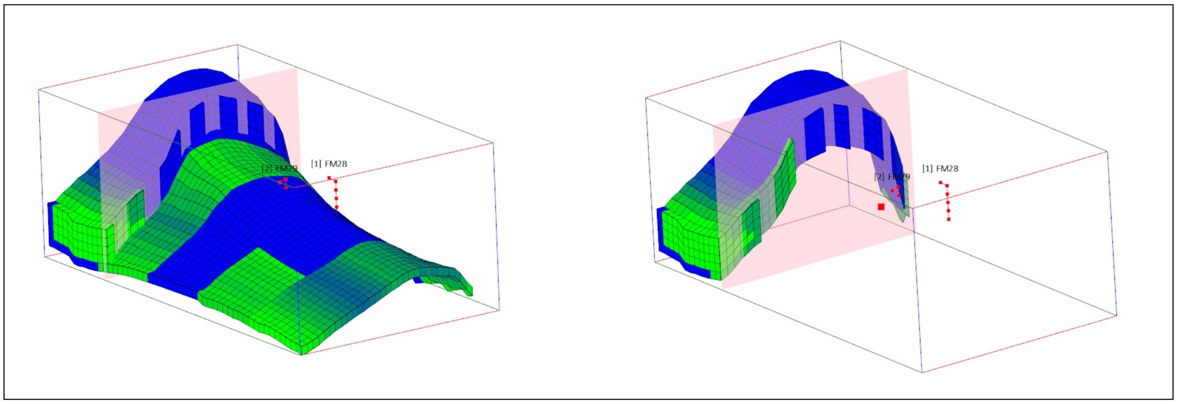


Figure 3.17: Cutting plane (a)when some shape information is retained, (b) when we perform an exact partition among the cells.

3.5 Study

To evaluate our techniques we conducted a preliminary study to observe and discuss subjective insights of our participants from three categories (Figure 3.18). Although the domain experts formed the core group to reflect upon the usefulness of these techniques in practice, participants outside the domain helped us reflect on the simplicity and effectiveness of these visualizations for communicating information, since essentially for them these visualizations were simple visuals representing some numbers.

Figure 3.18: Study session

3.5.1 Study Procedure

Each study session was an integrated demo, prototype exploration and semi-structured interview sessions between the experimenter and the participant. The duration of each session was around 60 to 90 minutes. The sessions started with a brief introduction to the goal of the study followed by an interview of our participants to learn more about their research background. We familiarised the participants to our prototype by demonstrating basic interactions(how to rotate the model, how to translate etc.) and provided explanations about the 3D reservoir model. This was followed by a demonstration of each of the techniques, one at a time. The participants were encouraged to interact with the visualizations and “think aloud” expressing their suggestions, opinions and feedback. During the discussion we asked the participants semi-structured questions reflecting on the usefulness of the techniques, potential advantages and disadvantages and any additional suggestions for improvement. For the purpose of the study we had turned off other features the system supports, such as splitting, changing properties dynamically, time step navigator etc.

3.5.2 Participants

We recruited 9 participants from three groups: three domain experts, three visualization experts and three members from other specializations. The participants were recruited via mailing lists and recruitment posters. Among the 9 participants we had 2 undergraduate students, 4 graduate students (3 PhD and 1 Master) and 3 postdoctoral fellows. Domain experts were researchers from the petroleum engineering department and had prior experience working with reservoir models. Visualization experts were participants whose field of interest is information/scientific visualizations. The participants from the third group (others) had background in electrical engineering, physics and biology. None of the participants from the visualization experts group and others group had any prior knowledge about the domain. Out of the three domain experts, two had some experience of working with commercial visualization packages.

3.5.3 Analysis

All sessions were videotaped to record the interaction and discussions. From these video recordings, we transcribed the audio for every participant. We performed an open coding of the transcribed data in order to group the discussions (verbal comments) under broad categories and identify interesting observations. The codes used for the classification of the comments can be seen in the graphs below (Figures 3.19, 3.21 and 3.22).

We also analysed three time measurements to gain further insights into the thoughts and opinions of our participants regarding our techniques. The time measurements that we performed were based on the following definitions: The total **interaction time** is defined as the total of the spans of time the participant was interacting with the visualization either by directly interacting with the visualization or by model manipulation to view the visualization from varying viewpoints. The total **thinking time** is defined as the total of the fractions of time when a participant would directly stare at the visualization and at times also interact while staring, without any verbal or physical expression for explaining their thoughts and lastly, **discussion time** is the total amount of time the participant was discussing about the visualizations by providing feedback. Each of these time measurements were noted as a percentage of the total time.

3.6 Results

In this section we present results that emerged from our qualitative study. We divide the results section into the following subcategories: (a) technique specific results, (b)technique ranking results and (c)statistical analysis results. The techniques specific results were determined following the process of open coding [72], wherein we noted every verbal comment made by the participant regarding each of the techniques using the videos and latter grouped the similar comments (for each of the technique) to identify some higher level categories for the comment classification.

3.6.1 Candy Visualization

In this section we present the results that emerged specific to the candy visualization technique. The graph in Figure 3.19 presents the codes (x-axis) that resulted from the classification of the various comments we received from the participants regarding this technique. The graph also sheds light on the number of participants who commented on each category of the comment class.

3.6.2 Candy Visualization Related Findings

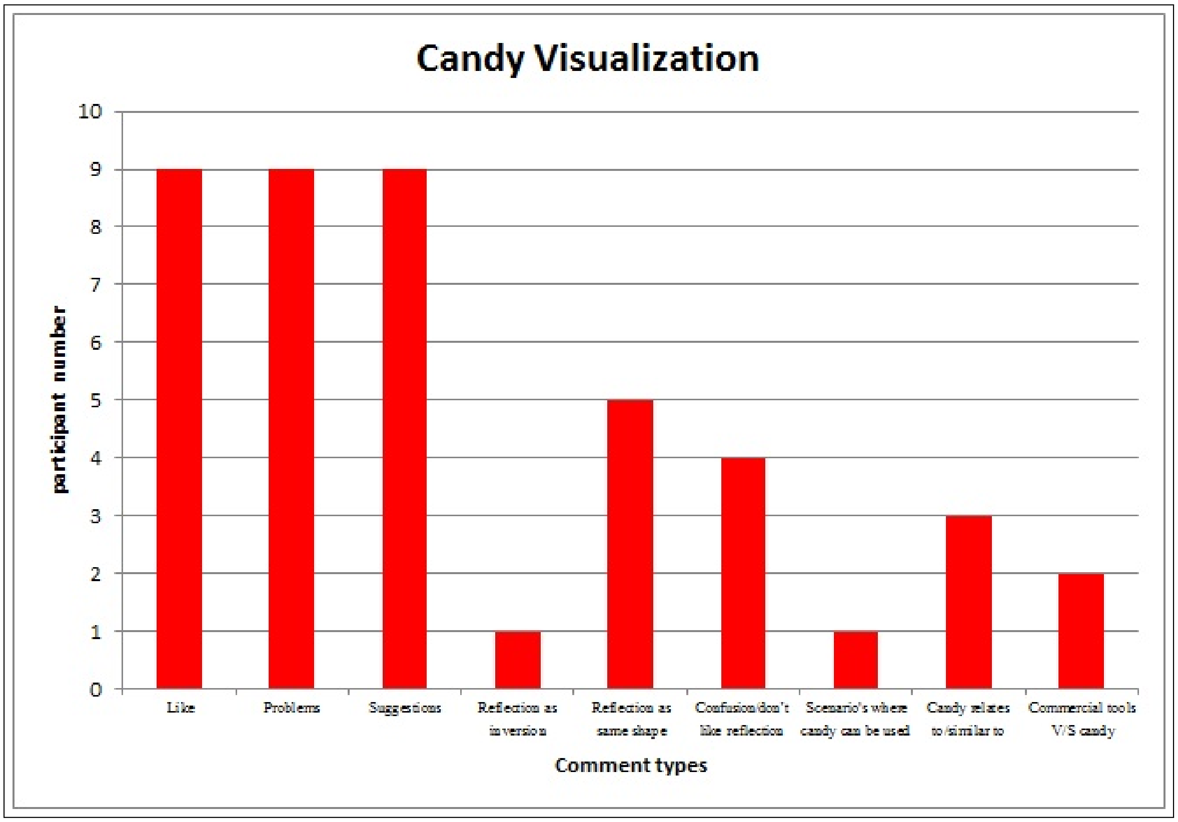


Figure 3.19: Candy Vis: Number of participants who commented for each category of the comment.

From Figure 3.19 it can be observed that all our participants liked the candy visualization and we heard comments such as, *"this is nice because it allows you to extract something and still see its shape in general, without needing to learn a* *new color coding or something like that. So in that sense, it's essentially nice"*, *"i like the candy visualization for the cluttered well as well. I though it was actually some thicker well, but now it is clear that these are individual blocks"*. However, all the 9 participants reported to have problems with the visualization as well. The most common problem stated by our participants was regarding the shape of the well presented by the candy visualization. Only one participant belonging to the visualization experts group liked the way we presented the shape of the well. 5 of out 9 participants preferred to see the original shape of the well as seen in Figure 3.20.

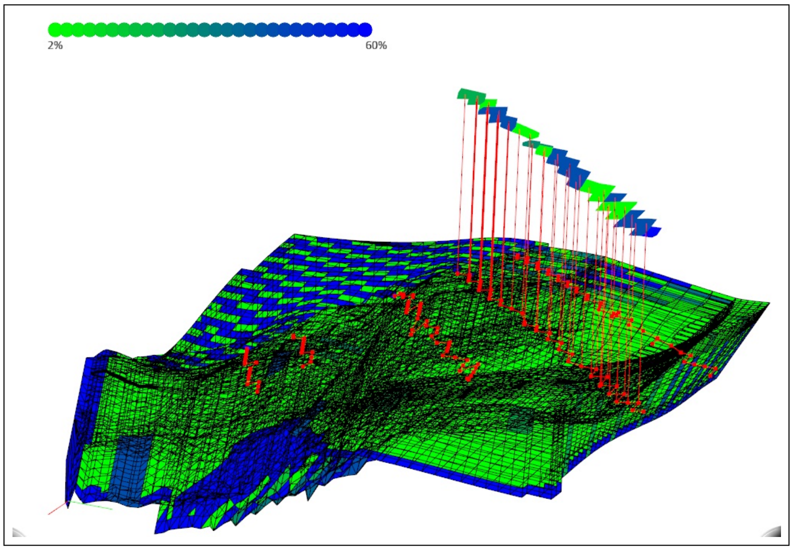


Figure 3.20: Alternative well shape visualization as suggested by participants.

Two other interesting codes observed during the study were the different scenarios and the commercial tool v/s candy code. During the study, participants from outside the domain tried to understand and relate to the visualizations by comparing what they had previously seen. It was interesting to observe how the participant from the electrical engineering background related the candies to the mechanism of data extraction employed in neural networks and found the visualization to be nice and meaningful.

A comment that we heard under the category of commercial tools v/s candy was *“almost something like bubble visualization in Petrel”*, *“but this one is a good idea because you can see this source of bubble diagram for each of those perforations”*. Comments such as these were complimentary and hint at the possible use of such a technique for the domain experts.

We also heard several suggestions about how we could improve our visualization. One such interesting suggestion was the use of two sets of candies for correlation - *“So my suggestion is you regenerate just the same map right and bottom, one with uncertainty and one with pressure or whatever. Or, what you have here (candies), you have at the bottom. One goes down with pressure values and one goes up with uncertainty”*.

3.6.3 History Circle

The next technique demonstrated during the study was the history circles. Figure 3.21 illustrates the codes for comment classification on the x-axis and the number of participants who commented for each category along the y-axis.

Although history circle’s was mentioned to be liked by all the 9 participants, the initial responses by majority of our participants said that the technique was confusing and difficult to understand immediately. We often heard comments such as, *“I was actually trying to mess up the values of percentage and trying to co-relate that with the size of the circles”*, and *“its not difficult, but its certainly not immediate to have 2% in between 28% and 42%”*. Out of the few participants who understood the visualization without much explanation said that they liked the technique and found it to be useful for having a quick glance through the information *(“can read it, can understand it, can quickly scan whatever is going on here in my wells. Its going to be a good idea for sure”, ”I think this is well mapped I could read it easily”).*

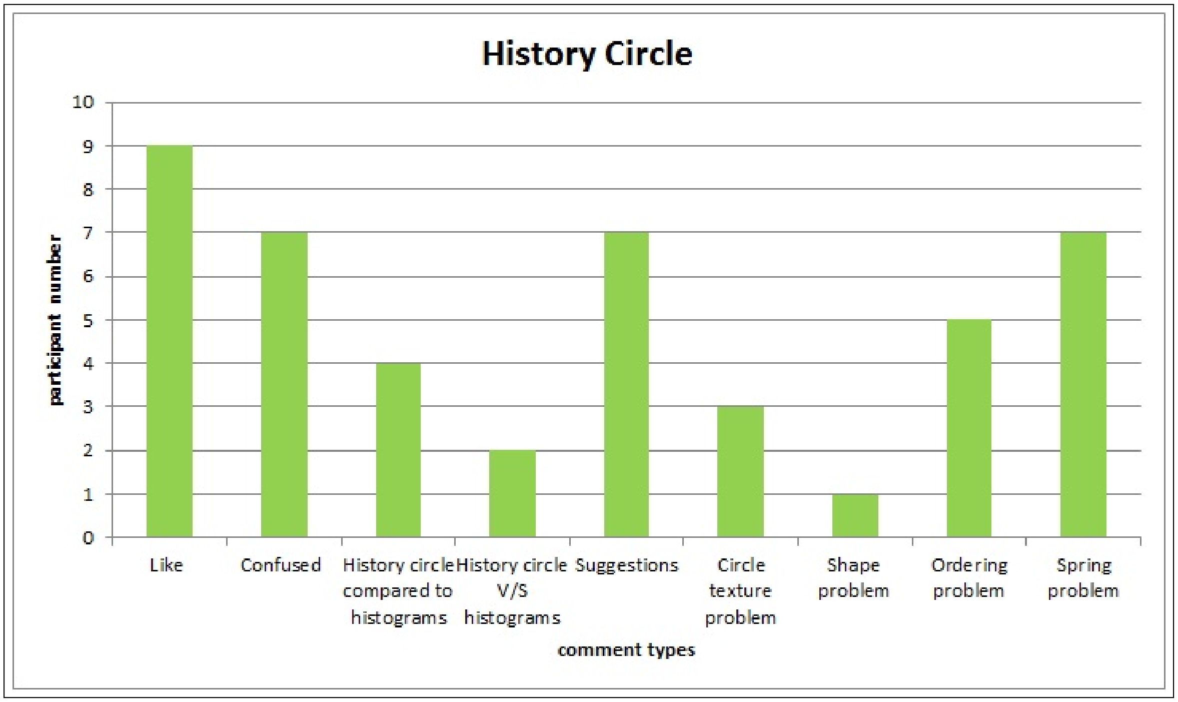


Figure 3.21: History Circles: Number of participants who commented for each category of the comment.

After the introduction to the interaction demo which explained the interplay between the candy visualization and history circles, a few participants liked this technique: *"with interaction I know what it means"* and *"if I knew it, maybe I could read it without your explanation"*.

As can be seen in Figure 3.21, about half of the participants compared the history circles with histograms. While some related history circles to histograms for the sake of understanding *("I think this is the same thing as histograms")*, a few complained that they preferred something more standard and known, instead of history circles *("I feel histograms are easy to interpret, maybe I am not familiar with this method")*.

Apart from the comparison with histograms, we also heard about problems with history circles mostly in the following four categories: texture problem, shape problem, ordering problem and spring problem *("they are circles right, comparing areas of circles is always a little tougher", "the only thing is really that the waves can be* *confusing and mistaken for something else", "these purple circles, in a way they clash with my idea of these circles").*

Majority of the participants gave us several suggestions for improving this particular visualization. One suggestion, which was commonly mentioned by the participants was to have the history circle as a string of information with circles or squares for every block in the well trajectory *("you could just as well grab these guys and visually arrange them here, maybe not keeping the size of the block")* rather than a frequency representation.

3.6.4 Indicator

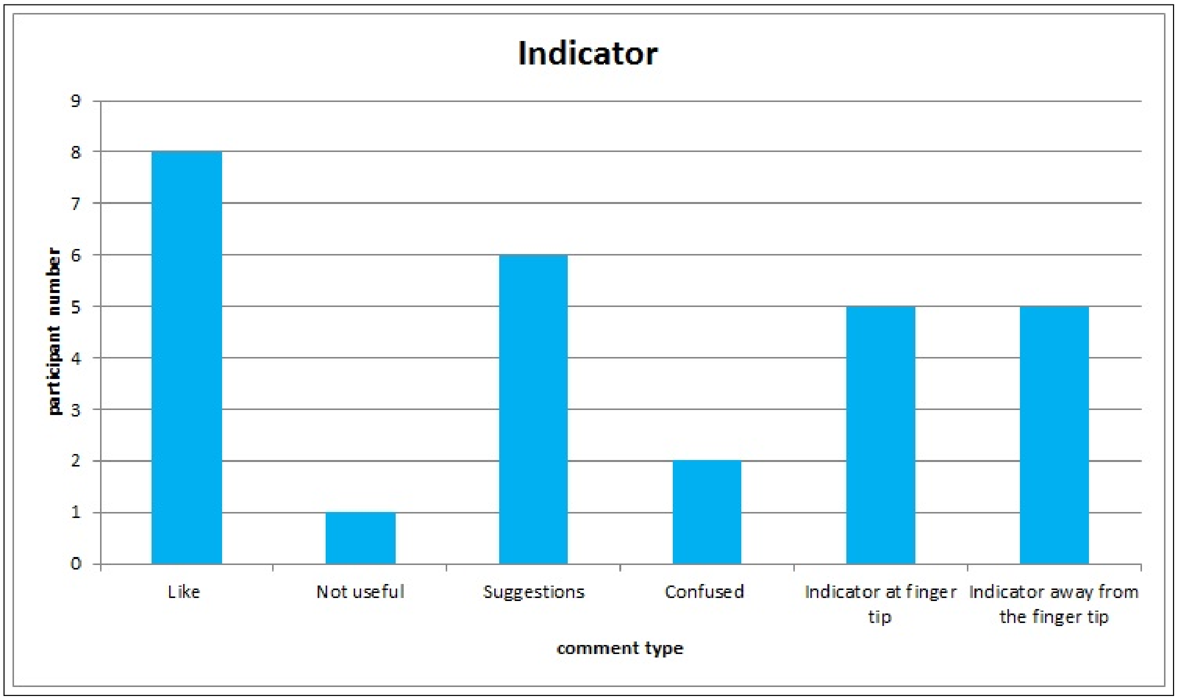


Figure 3.22: Indicator: Number of participants who commented for each category of the comment.

Indicator was liked by majority of the participants *("it is intuitive; you can feel that where is the information there, especially when you move your finger the size of the circle shows you")* as seen in Figure 3.22. The most common discussions regarding this technique were basically about the position of the indicator. In our current prototype, the circle or indicator is placed at the tip of the finger. While half preferred the indicator to be at the tip of the finger *("I think its good that you have it there, then you can see what your pointing at and you can see directly the three")*, the other half, preferred to have the indicator placed with an offset from the finger position *("I wonder if it makes sense to have it somewhere at the side, where I can still see it")*.

We also heard a couple of suggestions regarding how this technique could be useful for real applications in the domain - *"its going to be important when design wells"*, *"this kind of information is useful when you do some sort of prediction of the model"*. Overall, this technique was well accepted by the participants in comparison to history circles.

3.6.5 Color Scale

Apart from specific comments received regarding the techniques, we also heard comments about the color scale chosen for representing uncertainty (Figure 17). While about half of the participants liked the colors scale *("I think its nice to see the contrast between the blue and green. You can really tell that this is certain and this is uncertain")*, the other half found the color scale to be a little difficult to read from *"if there were four colors liked red to orange to yellow, even like the colors of the rainbow, that would let my eye pick up the different. Because if these are different, I am not really seeing it"*, *" and another point thats really important for this is that a color blind person would not in any way be able to distinguish any of these red, green"*.

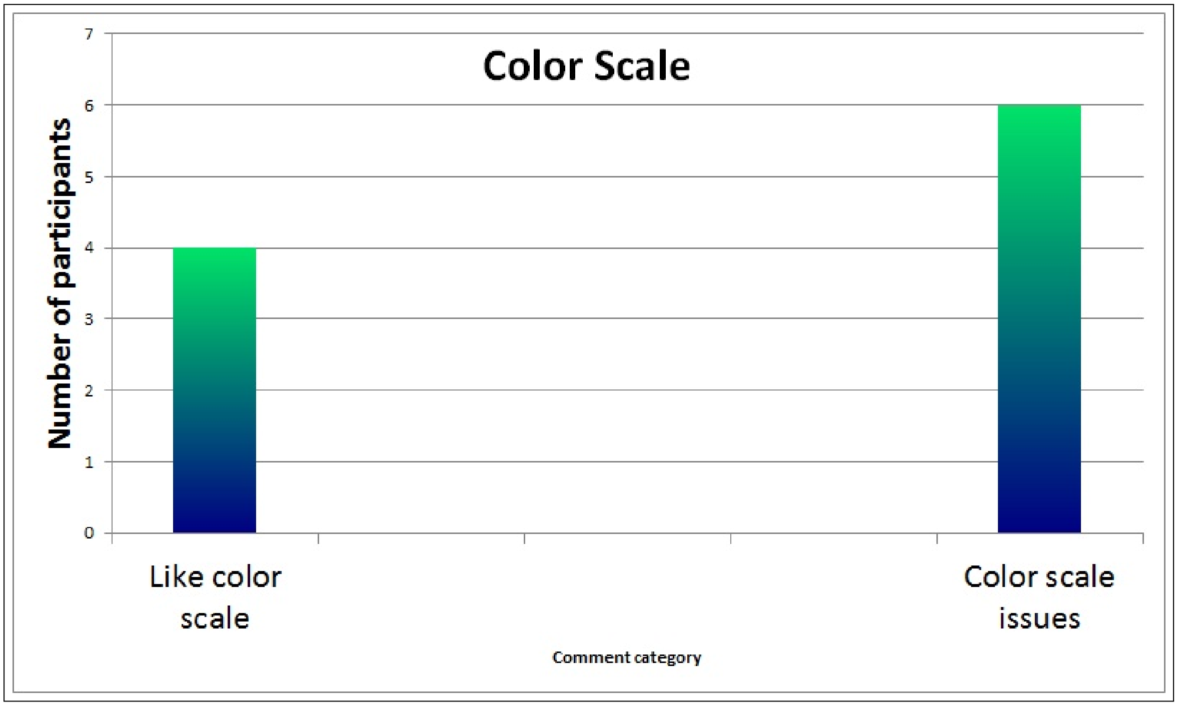


Figure 3.23: Color Scale: Number of participants who commented for each category of the comment.

3.6.6 Technique Ranking

The following Table 3.1 shows the technique ranked best by each of the participant and the reason for picking that technique. These choices were made by the participants after the main study was completed. From the table it can be seen that 6 out of 9 liked candy visualization best among the three techniques while 3 out 9 liked the indicator. Only one person liked the history circles technique and placed it to on equal level as candy visualization. As can be seen from the reasons column, all the three domain experts made a choice based on the usefulness of the technique for performing their tasks, while the other two categories in general helped us to understand about the effectiveness of the techniques in terms of understandability.

Table 3.1: Techniques ranked first best by the participants

Participant	**Group**	**Technique**	**Reason**
1	G1	Candy Visualization	Possible usefulness
2	G1	Indicator	Understandability
3	G1	Indicator	Understandability
4	G2	Candy Visualization and History Circle	Usefulness
5	G2	Candy Visualization	Usefulness
6	G2	Candy Visualization	Usefulness
7	G3	Candy Visualization	Possible usefulness
8	G3	Candy Visualization	Understandability
9	G3	Indicator	Possible usefulness and intuitiveness

G1 = vis experts; G2 = domain experts; G3 = others.

3.6.7 Statistical Analysis

To explore the possible differences between the three groups of participants as well as the possible differences between the three techniques, we performed two types of statistical analysis on the data. Due to the small sample size (n) non-parametric procedures were employed.

Non-parametric Kruskal-Wallis Test

Non parametric Kruskal-Wallis test was performed to investigate any possible group differences. From table 3.2 it can be seen that the three groups are different from each other for the following three variables: candy visualization thinking time, candy visualization discussion time and history circles discussion time. From the mean rank values for each of the groups, we can observe that the differences are mostly between the domain experts and the others. Or in other words domain experts and visualization experts groups were similar in terms of the amount of time they spend thinking about the candy visualization. However, all the three groups were found to be similar in terms of their interaction time for all the three techniques.

Table 3.2: Results from Kruskal-Wallis Test

Outcome	**Vis experts - Mean rank**	**Domain experts - Mean rank**	**Others - Mean rank**	**Exact Sig. P***
candy thinking time	4.33	2.67	8.00	.003
candy discussion time	4.00	7.67	3.33	.024
history discussion time	3.67	7.33	4.00	.048

sample size (n) = 3; * significant at alpha $<$ 0.05 level.

Table 3.3: Results from Friedman Test

Outcome	**Candy Vis - Mean rank**	**History Circles - Mean rank**	**Indicator - Mean rank**	**Exact Sig. P***
interaction time	2.89	1.06	2.06	.001
discussion time	1.33	2.56	2.11	.031

sample size (n) = 9; * significant at alpha $<$ 0.05 level.

Non-parametric Friedman Test

The following test was performed to find the possible differences between the three techniques themselves (see Table 3.3). The three techniques were found to be different from each other for the variables: interaction time and discussion time. This analysis hints at the possibility that if the participants were considered independent of their groups, they were all similar in the amount of time they spent thinking about each of the techniques.

3.7 Discussion

In this section we discuss the results from our study from the following two perspectives: (a) techniques and (b) participants.

3.7.1 Techniques

From the study results we observed a few general trends emerging regarding each of the techniques irrespective of the differences among the groups. Though we had just three domain experts evaluating our techniques, we found all the three to find some use of each of the techniques and heard comments such as: *"This is surely useful"* and *"Good idea"*, hinting at perhaps a small yet successful acceptance of the techniques for real applications. In a way we also believe from the comments of our reservoir engineering domain experts (*"In petrel for example we need to make a slice, but this (candy visualization) is something good. I've never seen something like this before"*,*"I have never seen kind of information (history circles) ever before in my experience"*,*"i like this idea (indicator)"*) that perhaps these techniques have some novelty for the domain. Our discussions with participants from two other groups was also very useful,and specifically helped us to learn about the techniques in terms of ease of understandability and highlighted some very useful improvements.

3.7.2 Participants Re-grouping

From our study, we had collected three types of time measurements : total interaction time, total thinking time and total discussion time (defined in the analysis section). Using thinking time and interaction time measurements we tried to find a relation between the participant's choice of technique and time durations. Figure 3.24 shows the variations in these time measurements for all the three techniques. Using these time measurements we determined that we could re-group our participants into three new groups: (a) participants who liked a technique because they interacted most with it (participants: 1,4,5,6,8), (b) liked a technique because they spent less time thinking about it (participants: 2,4,5,9) and (c) participants who liked a technique after they

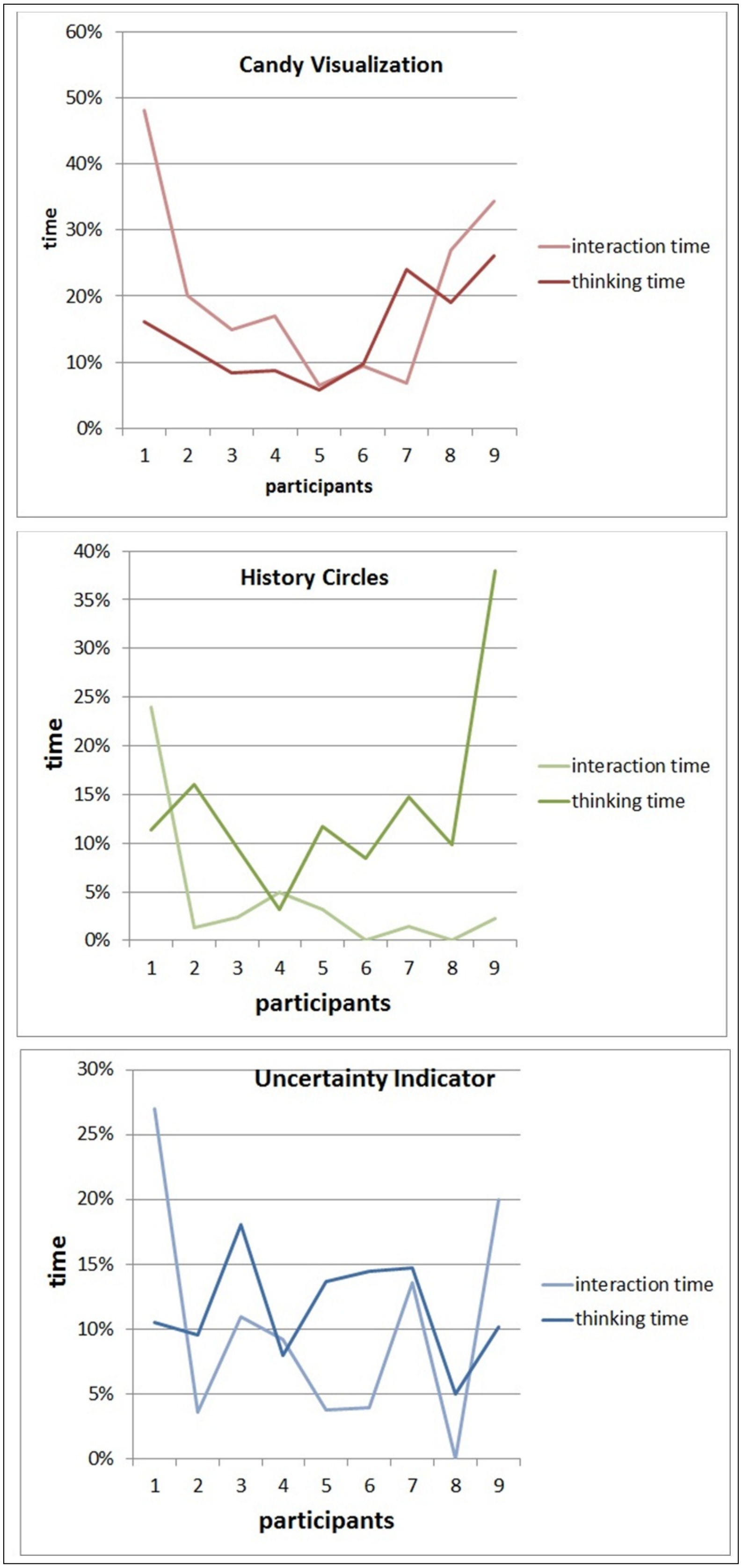


Figure 3.24: Graphs showing the variation in thinking and interaction time among the three groups for each of the techniques.

thought most about that technique compared to the other two (participants: 3 and 7).

Although it could be argued that these results lack in terms of a concrete conclusion since interaction for long periods of time generally lead to making us more comfortable and used to a technique and thinking less might not necessarily mean that the total thinking time meant would have contributed to the amount of time it took for a participant to understand a technique, we believe, that atleast on a more broader term, it gives us a general idea about a user's requirement from a visualization technique. Things which are more engaging, interactive and quick to understand were generally liked by the participants.

3.8 Future Work

In this section we discuss a few design alternatives from the future perspectives.

3.8.1 Region Specific Exploration

An alternative to the history circles technique is a concept involving color coded 2D surfaces to represent the uncertainty of a region. User could sketch over regions of interest and the resulting 2D surface created from such a sketch could be coloured according to the variation of uncertainty found in that region. User's could compare between two or more such 2D patches and also quickly determine if a region is of interest to them.

This design approach could also help engineers while creating well trajectories. As an engineer begins to sketch a well trajectory, a 2D strip colored according to the uncertainty of the cell through which the well is passing could be created. User's could later interact with these 2D representations of the wells for comparing the variation of uncertainty and also the lengths of different well trajectories.

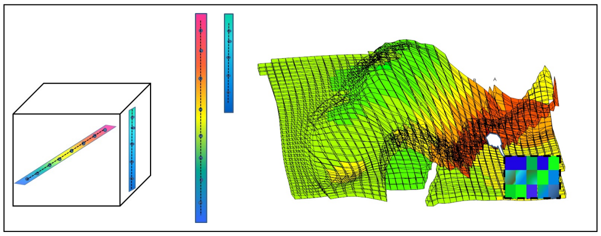


Figure 3.25: Illustration of the concept of color strip visualization.

3.8.2 Layer Specific Exploration

A variation that can be applied to our cutting/sketching planes idea, used for exploring the insides of the reservoir model, is to to allow the user to pull out slices of the reservoir layer and see the uncertainty information in that specific layer (Figure 3.26). This would allow the user to obtain layer specific information as opposed to cell specific information.

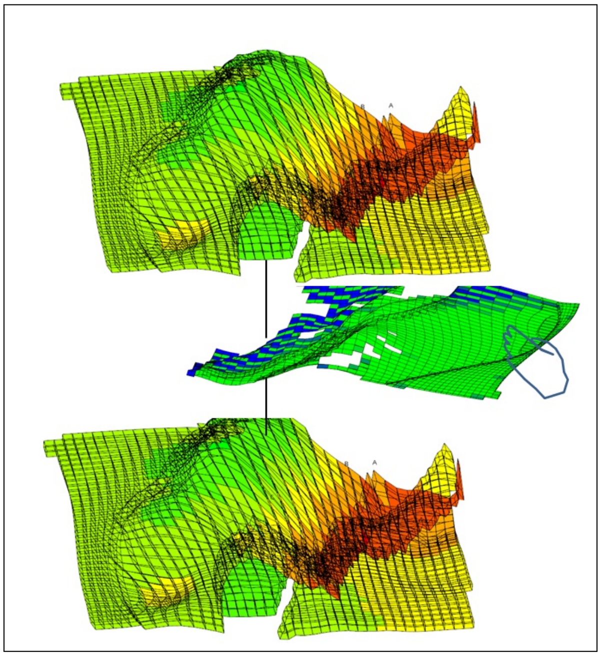


Figure 3.26: Illustration of the concept of pulling out slices to see the uncertainty information.

3.8.3 Candies for Correlation

During discussions with our participants, two participants suggested the use of a set of candies to support correlation tasks (Figure 3.27. The candies could be mapped to different geological properties and compared, so as to gain further insights about the well trajectory in different contexts.

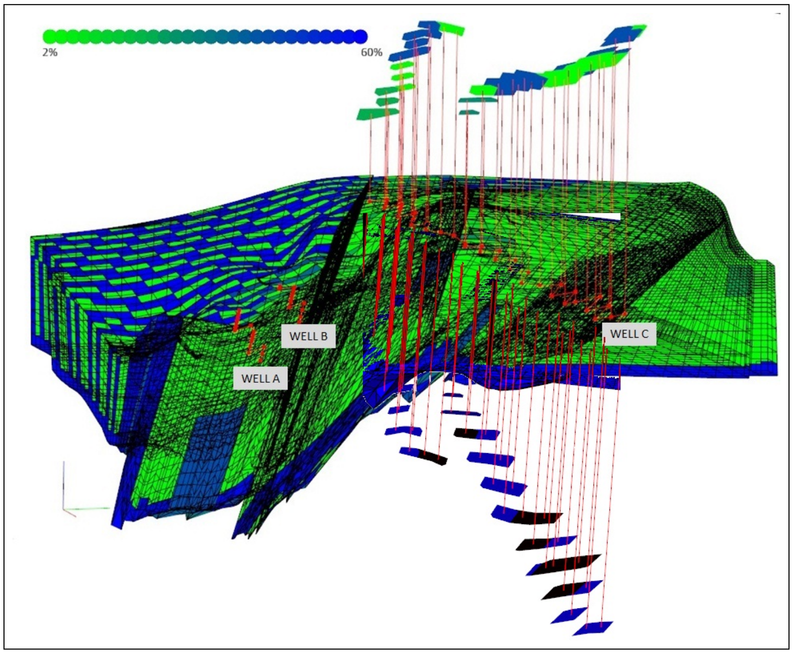


Figure 3.27: Illustration of the concept multiple candies for correlation.

3.9 Summary

In summary, we described three visualization variations for the exploration and visualization of uncertainty mapped 3D reservoir models. We also present our findings from three distinct groups of participants who took part in our qualitative study. Part of the contribution of our work is also blending concepts from scientific visualization and information visualization to come up with techniques that can provide insights about the reservoir models to the domain engineers.

Chapter 4

A Focus and Context Approach to Visualize Well Trajectories

For a reservoir, well trajectories are important entities. Gaining insights about existing well trajectories helps a reservoir engineer understand the rationales behind why a well was placed in a particular region of the reservoir. They could use the information to find similar areas on the reservoir model for identifying future regions for placing new well trajectories.

In Chapter 3 we presented two visualizations (*candy visualization and history circles*) for viewing well trajectories in the context of uncertainty without having to compromise on the context. An earlier design approach adopted by us to visualize well trajectories was by using the technique of 'focus and context'.

Focus and context techniques present mechanisms in which an object of interest is always highlighted, while the surrounding context information is rendered in a subtle fashion [84, 16] or using some sort of distortion [18]. In our visualization we create a 'V' shaped cut to allow the user to view the well and used gradual transparency in the surrounding regions of the well to make the context subtle.

We believe that the advantage of our visualization is that, it allows the viewer to visualize the wells along with information from the surrounding regions of the well trajectory in a view dependent manner. To enhance the visualization we also make use of tangibles, which not only define a modality but is also associated with the task of enhancing the visualization.

In this chapter we present the design and implementation of our focus and context approach on the tabletop, using the advantage of direct touch and tangibles to create an engaging environment and allowing the user to gain insights about the well trajectories. We also discuss the results that emerged from our study with 12 domain experts regarding this visualization approach.

4.1 Design and Implementation

The focus and context approach to visualize wells uses a two step process. First the engineer needs to select a well or a group of wells and then can view them in a view dependent manner.

4.1.1 Well Selection

Well selection mode is entered upon placing a tagged tangible clay model shaped like a well as seen in Figure 4.1. To select the well trajectories, the user can tap on the red markers representing the well using a single finger as seen in Figure 4.2. To give feedback regarding the selected wells a list of chosen wells appears on the top left corner of the screen.

In order to determine which well has been selected a ray is tested for intersection with the marker triangles (ray-triangle intersection [51]). If the intersection is true, than a list is searched to determine which triangle was intersected and the corresponding well id is returned. This well id is then added to the list of selected wells.

4.1.2 Well Visualization

After the well is selected it can be viewed by placing a tagged tangible shaped like a pyramid as seen in Figure 4.3). The tangible was shaped like a pyramid to reflect on

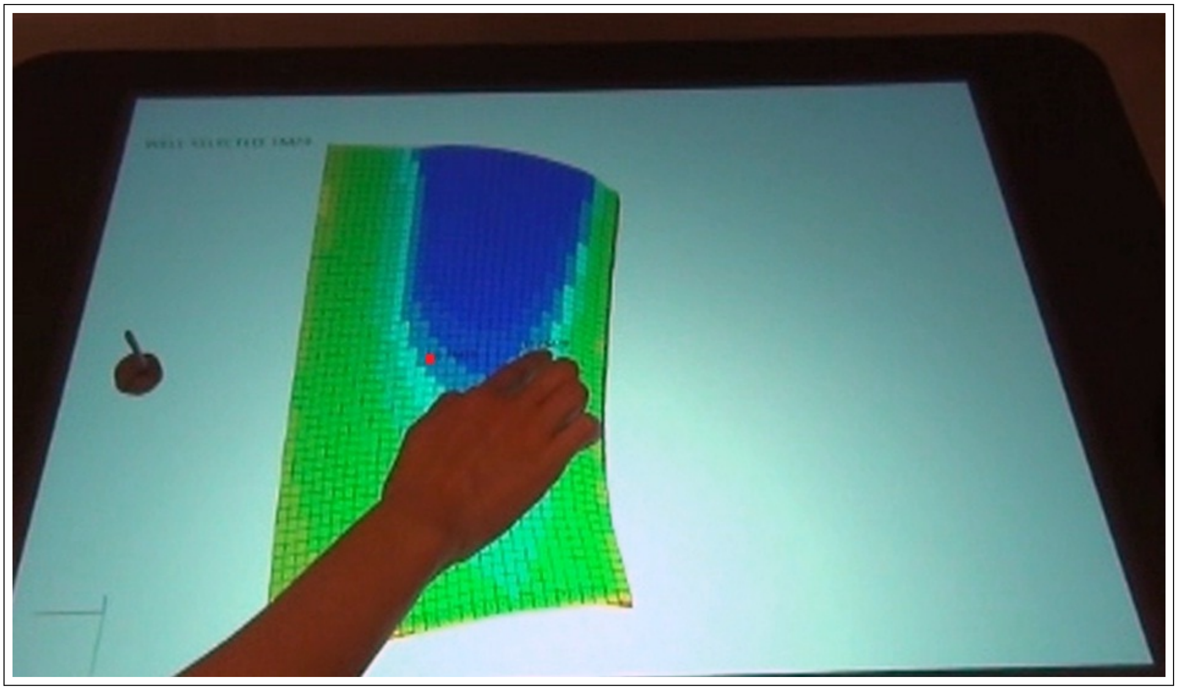


Figure 4.1: Well selection prototype.

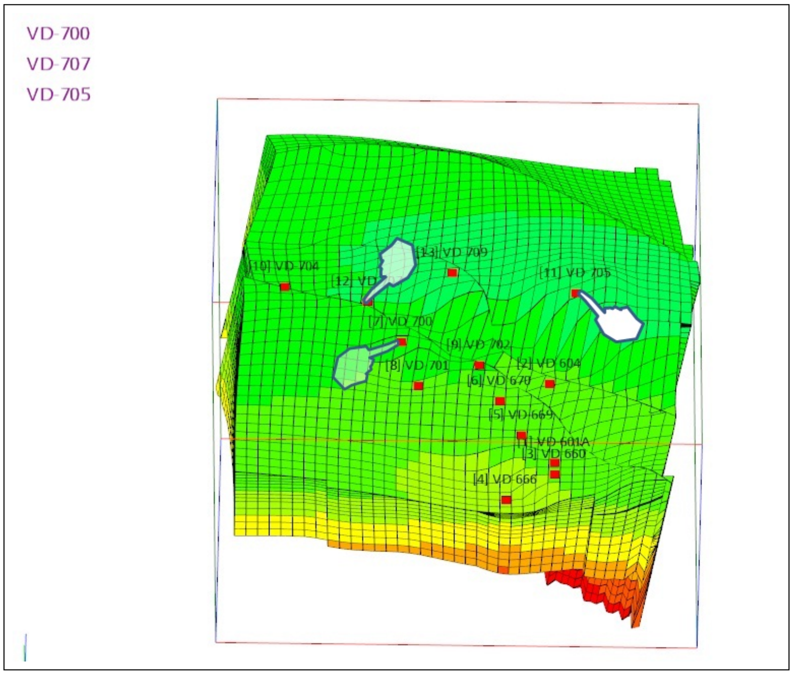


Figure 4.2: Selection of well trajectories.

the ‘V’ shaped opening that is created to make the well (red line) visible.

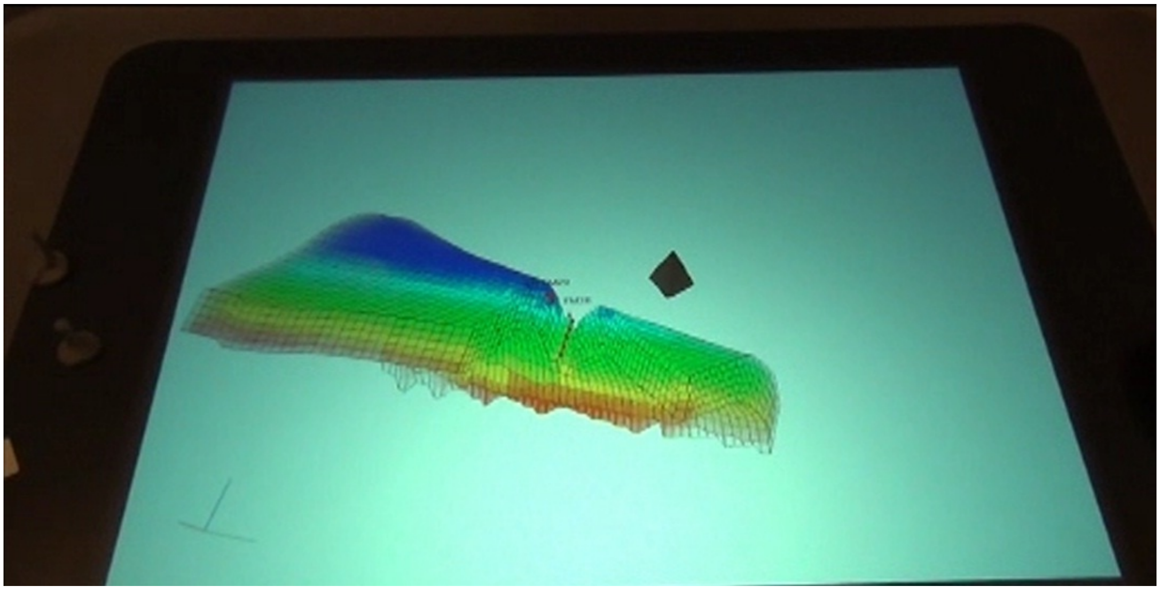


Figure 4.3: Creating ‘V’ shaped opening to view the well.

On placement of the tag, the rendering involves - (1) the removal of cells between the viewpoint and the chosen well, and (2) a gradual increase in transparency on the rest of the displayed cells as the distance from the well increases (Figure 4.4).

To implement the creation of such an opening the following computations are performed: 1. Start with finding a point behind the camera which is the focal point from where the pyramid is constructed. To find the focal point, the following steps are performed:

a construct a bounding box around the well.

b find the bounding sphere: center - center of bounding box, radius -bounding box diagonal/2

c calculate half angle : half of the view angle.

d the focal bound is = camera’s position + some distance

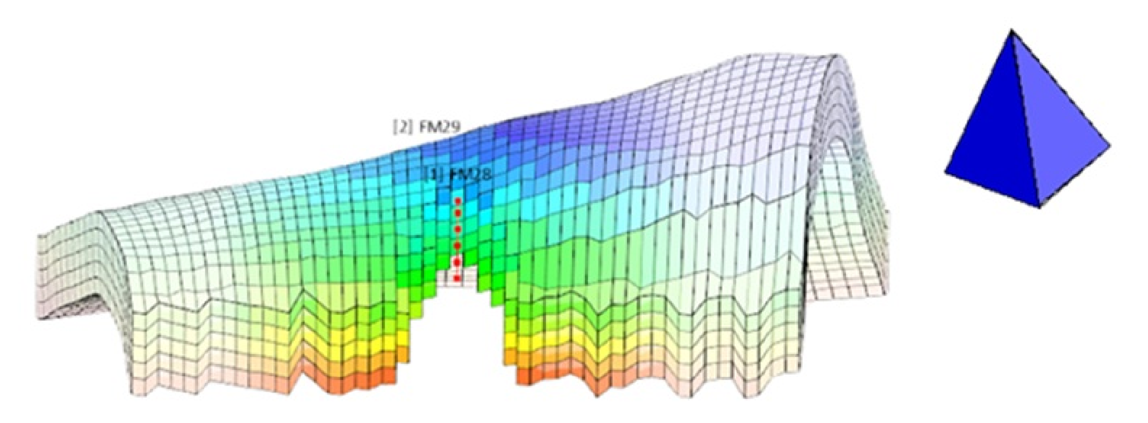


Figure 4.4: With the pyramid-shaped tangible device down, cells are removed between the well and the viewpoint and transparency is applied.

e distance = radius/tan(half angle)

f focal point = bounding box center + (distance * view vector)

2. Next we use the BSP algorithm [55] (explained in Chapter 3) to create the 'V' opening.

The wells can be viewed in different geological properties as shown in Figure 4.5 to allow the user to learn about the well in different contexts. In our implementation the region surrounding the focus is dynamically adjusted based on the view point. After the user rotates the model, the cutaway view is also updated, in order to keep displaying the well (Figure 4.6). The visualization is further enhanced by the use of the pyramid shaped tangible for controlling the angle of opening. The angle of opening can be controlled by the viewer by rotating the pyramid shaped tangible in either clockwise (to increase) or anticlockwise (to decrease) direction (Figure 4.7).

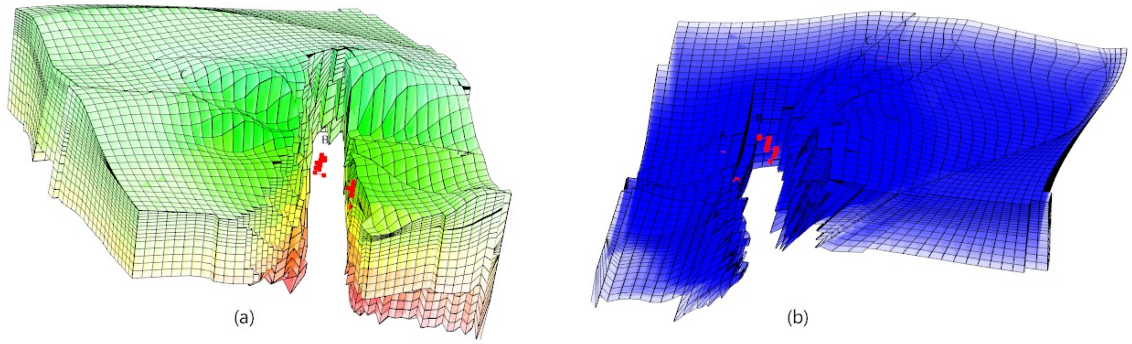


Figure 4.5: Viewing the well in different contexts: (a) Pressure and (b) Permeability.

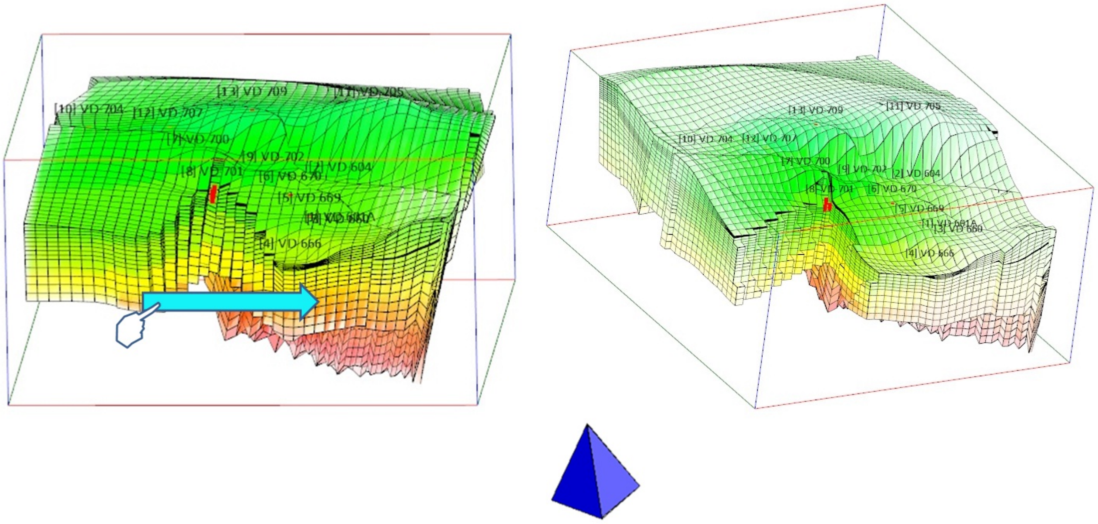


Figure 4.6: The cutaway view is updated after rotation.

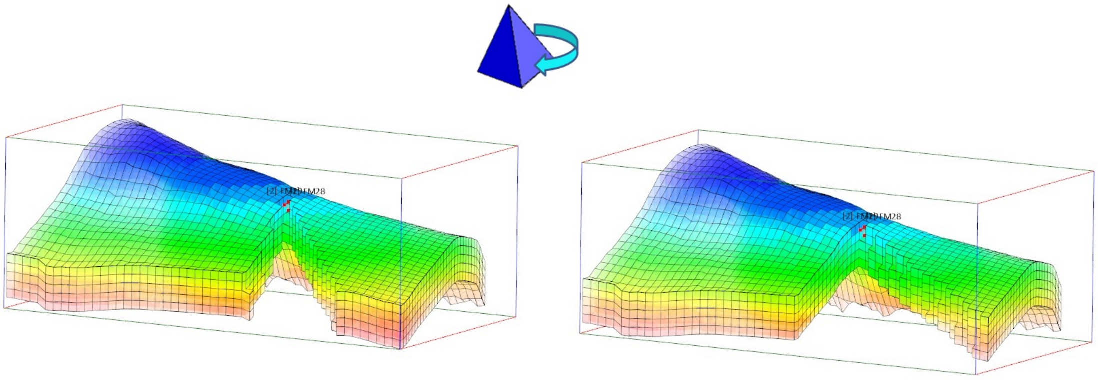


Figure 4.7: The opening angle can be increased or decreased by rotating the tangible.

4.2 Evaluation

A series of formal qualitative studies were conducted to evaluate this technique. The goal of the study was to have a free form discussion with the participants so as to gain insight about the usefulness and problems of this technique. The 'focus and context' tool was evaluated in a study which consisted of three other tools [75]. This technique was latter improved to include the selection of multiple wells.

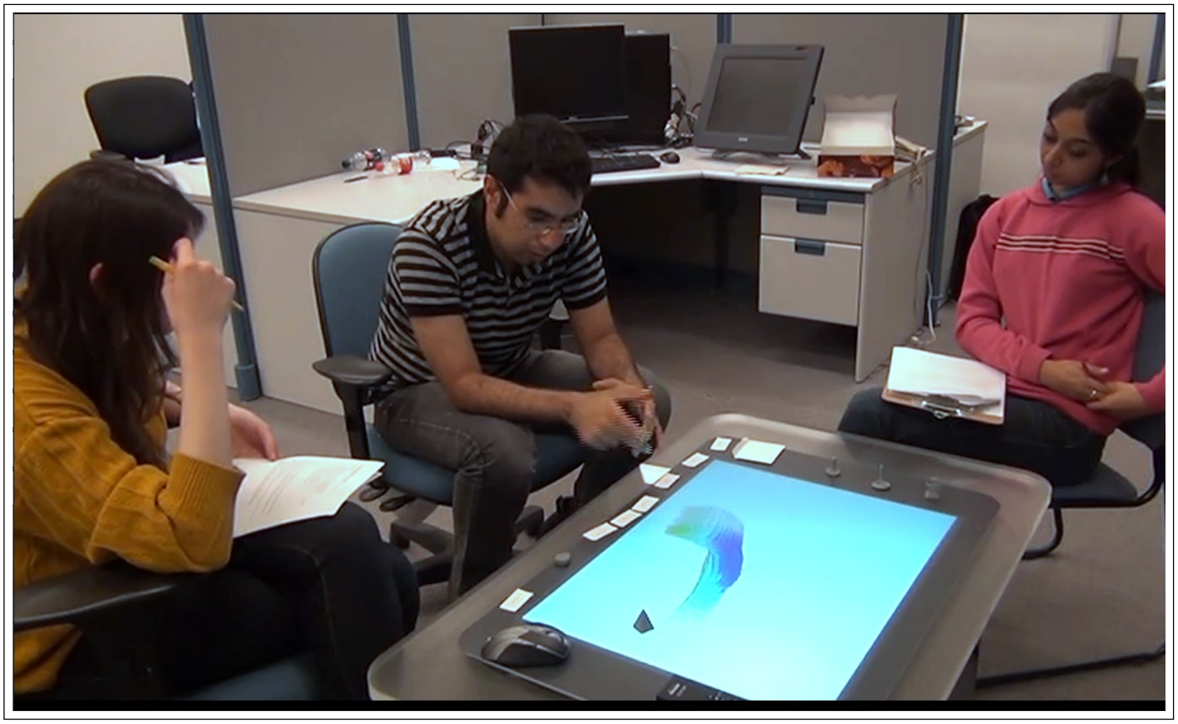


Figure 4.8: Study session.

4.2.1 Study Procedure

The study consisted of a semi-structured interview and demo session. Each session lasted for about 60-90 minutes each. Before the session, the participants were interviewed to learn about their research background and experience in the domain. Post the interview, the sessions started with a brief introduction to the goal of the study, followed by the demonstrations to each of the techniques. For every technique, the researchers asked the participant semi-structured questions regarding the usefulness, problems, and suggestions for that specific tool. During the interactions we encouraged our participants to think aloud and express their opinions and criticism. The study was not task oriented. The participants were encouraged to try out of each of the tools freely while they thought about it.

4.2.2 Participants

The study consisted of two pilot sessions with members from our group (but not involved in the design of the application) and ten external domain experts. Among the 12 participants, one was an undergrad, and the rest had or were pursing a post-graduation degree (Master's or PhD) in petroleum related fields. 11 out of 12 participants had some prior work experience in the domain of oil and gas. Two of our participants were holding a position in the industry at the time of the study. Though all our participants were from petroleum engineering, they had varied specializations, such as experts in - drilling engineering, geophysics, reservoir simulation etc. This mixed group of participants helped us explore the potential of these tools for engineers working at different levels of the oil and gas exploration cycle. The participants were recruited via department mailing lists.

4.2.3 Analysis

Each of the sessions were recorded with the participants consent. One of the participants did not agree to be videotaped. To compensate for it, we made extensive notes during the session. From each of the video recordings, notes were made and categorized into tool specific discussions and general discussions.

4.2.4 Findings

The majority of the users (8 out of 12) found the 'focus and context' tool to be useful, whereas the remaining 4 said that it did not provide any extra insight. The ability to visually highlight a well from any viewpoint was appreciated with comments such as *"I would use this feature for sure"* and *"As you turn you always have a view of your well, you dont have to try and find it again and again"*. Additionally, users reflected on this being a new functionality that does not exist in current non-tabletop software packages.

One person explicitly reported liking the idea of being able to control the view angle. All participants stated the need to be able to select more than a single well for the focus; in this case, we also heard about the need to visualize intermediate regions between selected wells, hinting a need for correlation and 'trends'.

Regarding the balance between focus and context, although one of the participants supported the use of transparency to better highlight the focus, two other participants felt it was not very apt in the domain, since information on the surrounding blocks would be lost. Another two participants also mentioned the fact that we might lose some potential information in the cutaway region, although one of them indicated they believe this is a reasonable trade-off between clear visibility and importance of information in that region.

Suggestions for improvement of this tool included being able to select multiple wells for the focus, possibly using filtering mechanisms or sketch based selection. Three participants suggested including streamlines [81] in the cutaway region, to depict flow movement and behaviour around the focused well. One participant suggested restraining the camera freedom around the focus, so that it rotates around the focused region in a circle, as opposed to the current, full sphere orbiting camera system that the application supports. One user also suggested being able to 'peel' out the walls of the cutaway view, to expose layers further back.

4.2.5 Discussion

As previously mentioned, each participant came from a different background such as - reservoir simulation, reservoir management, drilling engineering, and so on and hence each of them had different needs. Hence, the focus and context tool was considered more relevant by those who are regularly working with wells. This fact sheds light onto the multidisciplinary aspects of the domain, present in various stages of oil and gas exploration and production and the need for task specific tools/techniques.

Out of the four tools demonstrated during the study, the 'focus and context' was one among two other techniques that was generally considered as a novel function. Participants mentioned that they hadn't seen such a functionality in the current desktop visualizations applications available commercially. One of our participant during her interaction with the application said - *"It actually brings some new ways of analysis ... it brings some creativity for sure"*. Our impression is that, this is indicative of how a creative environment might add and facilitate the thought and problem-solving process, as quoted by one of our participants.

4.3 Future Work

In terms of improving the 'focus and context' technique, one of the short terms goals would be to optimize the rendering algorithm while performing the cuts. The current implementation is lacking in terms of speed of response. When the tangible is rotated the re-drawing of the cut region is not as responsive as would be expected. It could also be improved by providing more visual feedback to the user by drawing lines over the reservoir, indicating to the user where the cuts would be formed.

A long term goal, would be develop methods that can perform free-form cuts, rather than just a ‘V’ shaped cut. Users could sketch on the reservoir, to indicate the kind of the cuts they would like. This would perhaps allow for more intuitive ways of exploration of not just the well trajectories, but also other areas of interest.

4.4 Summary

In this chapter, we present the design and implementation of the focus and context technique for visualizing wells in the context of different geological properties. The technique uses the affordances of tabletops to enhance the interaction. We also present the results of a qualitative study with 12 domain experts, and discuss the feedback we received about the techniques in terms of its potential strengths and weakness.

Chapter 5

Exploratory Prototypes for Well Trajectory Creation

A critical task in the reservoir engineering workflow consists of creating and/or modifying well placement in reservoir post processing simulation models for fine-tuning subsequent reservoir simulation runs of the same model [22]. Exploring existing wells and other entities of the reservoirs is important to identify possible locations for drilling a well. An engineer experiments by placing well trajectories in different regions of the reservoir model followed by running a simulation to learn about the production of the reservoir. The stage of well creation is however difficult and cumbersome in the current commercial WIMP applications. In this chapter, we discuss three prototypes we designed and implemented to explore different ways to assist an engineer to create simple well configurations using touch and tangibles.

While, the prototypes were only an exploratory effort and are more conceptual, they help to shed light on the challenges involved in performing such tasks. The three prototypes take different approaches and can be seen as almost incremental efforts, trying to address the problems of each of its previous prototypes. While some efforts were more fruitful than the others, we did not evaluate them in a formal study. In this chapter, we present the design and implementation of each of these prototypes followed by discussions presenting design critiques for each of the techniques.

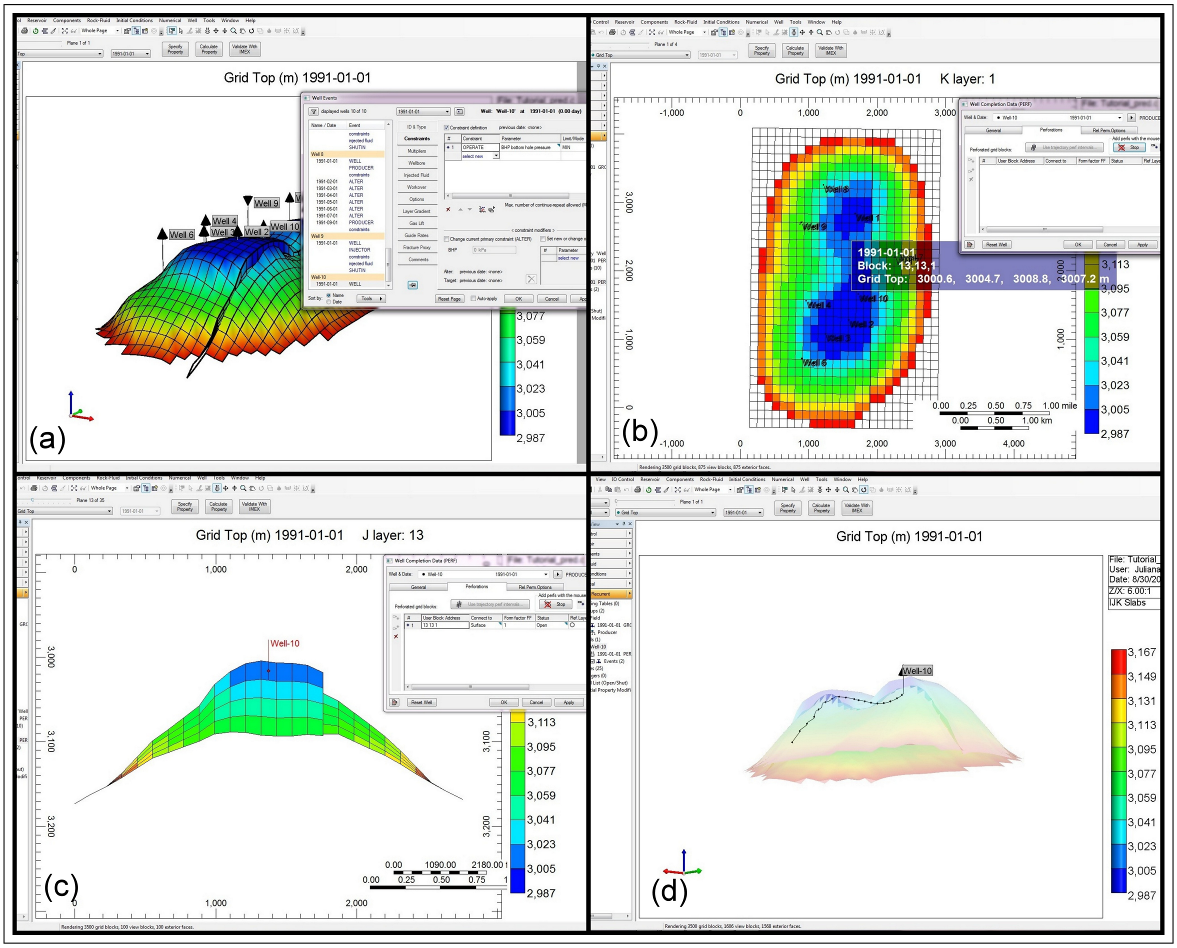


Figure 5.1: Steps to create a well trajectory using CMG Suite [2]: (a) Create a new well type - producer/injector, (b) Select the first perforation cell on the top most layer of the reservoir model, (c) Select the type of well to be created and change the plane to select the other perforation blocks and (d) Created well.

5.1 Motivation

The task of well positioning is supported on most commercial packages such as CMG[2] and Petrel[6]. Currently, this task involves numerous manual steps before the actual perforation blocks can be selected as seen in Figure 5.1. Creation of a new well trajectory, generally, involves clicking on the cells that the well has to pass through and then manipulating the control points to get different configurations (horizontal, vertical or lateral)(Figure 5.2). The rest of the well points, passing through the internal cells, can either be are selected by the engineer by changing between planes, manually entered cell positions or automatically generated by a program run by the application in the case of horizontal or vertical wells.

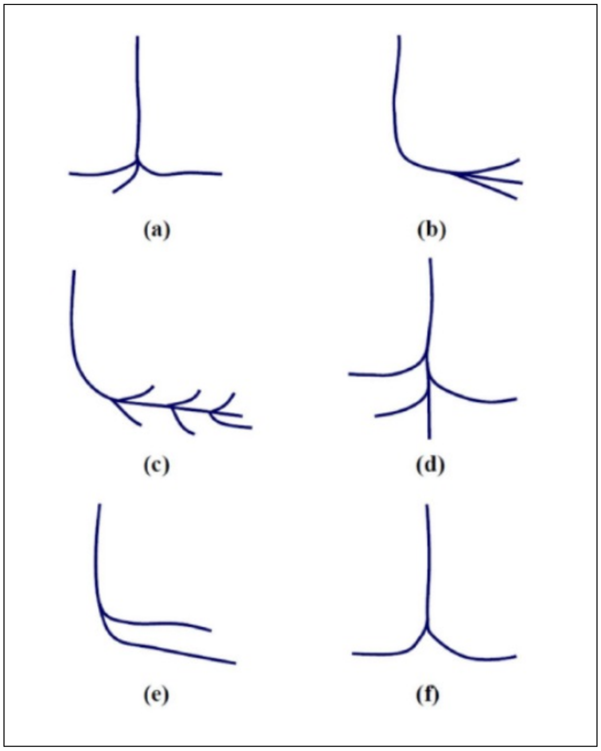
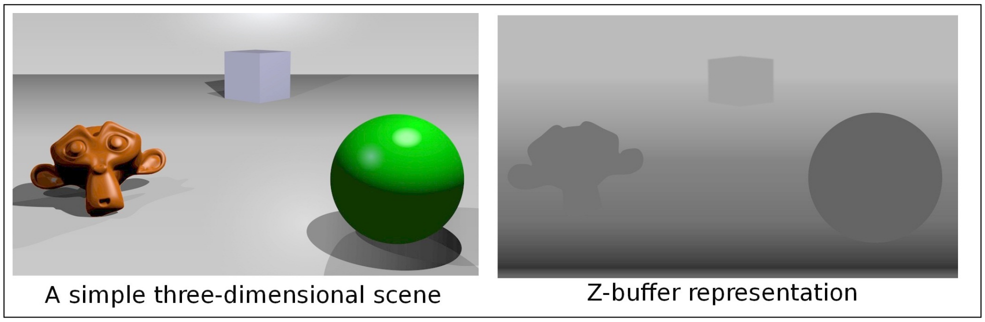


Figure 5.2: Common multilateral well path configurations:(a) multibranched, (b) forked and (c) laterals into horizontal hole, (d) laterals into vertical holes, (e) stacked laterals and (f) dual-opposing laterals.

In this chapter we present our efforts for attempting to perform this task using the affordances of tabletops in the 3D model of the reservoir. One possible approach to this problem is to consider use the facility of sketching to create the well trajectories. On a tabletop a user can sketch with fingers or tangibles. Sketching may actually be more intuitive than clicking on individual cells and manipulating control points, since sketching is a more natural solution to creating strokes or lines in comparison to clicking. However, the main challenge to this approach is finding ways to sketch in 3D space keeping in mind the various restrictions a well trajectory imposes.

5.2 Depth Buffer Based Approach

Depth buffer [8] in computer graphics is a buffer that maintains per-pixel depth information (z axis information) for every rendered primitive (see Figure 5.3). The most common use of the depth buffer is to solve visibility problems in a 3D scene. Z-culling is a method which determines what is in front and back in a scene, helping us render the scene with the required depth perception. Our first approach to navigate 3D space and create well trajectories was using the depth buffer values of a set of guiding lines to determine the depth levels. To test the concept, we implemented this prototype first as a desktop version using a mouse to create the sketches.


A simple three-dimensional scene

Z-buffer representation

Figure 5.3: Illustration of depth buffer rendering.

5.2.1 Design and Implementation

To experiment this method, we created a simpler version of a reservoir by mapping it to a regular 3D cube with eight internal cells (Figure 5.4). The z-buffer representation of this cube is as seen in Figure 5.5. As can be seen in the figure, the lines have varying depth indicated by the variation in the color, going from dark grey to light grey.

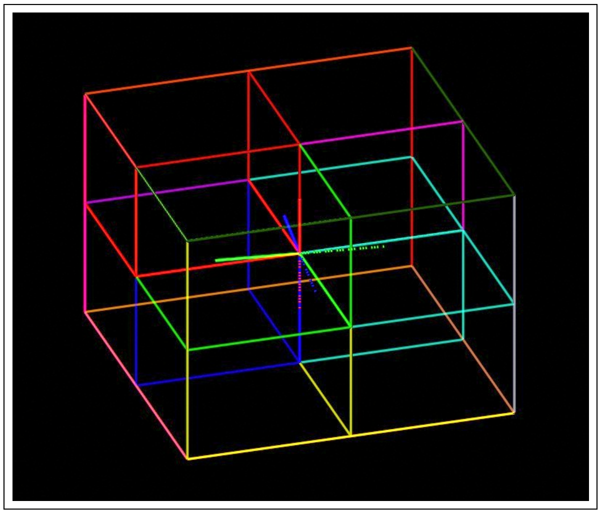


Figure 5.4: A 3D cube with homogenous division to represent a reservoir model.

The depth buffer values can be accessed using the code shown in the Figure 5.6. However, there is a lack of precision of the returned values. This problem increases further when two objects are very close to each other - "z-fighting"[8].

To navigate within this 3D cube, we created what we call 'guide lines' (white lines) as seen in figure 5.7. The idea behind using these lines is that we can make use of their depth values to move in the 3D space. When the user selects a point on these guidelines lines, the 2D mouse coordinates are converted to the corresponding 3D world coordinate points at that depth value. The user can move over these guide lines to create free form 3D sketches. When a new 3D position is determined the center of the guide lines is moved to that corresponding position in space as shown in

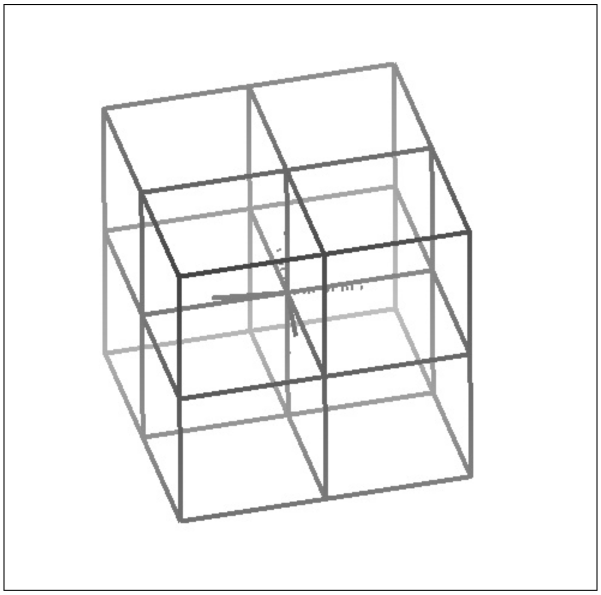
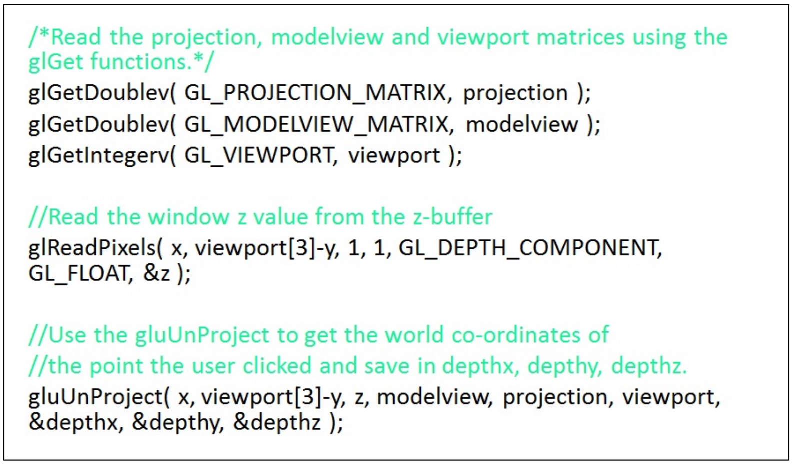


Figure 5.5: Z-buffer representation of our simple cube reservoir.



```
/*Read the projection, modelview and viewport matrices using the
glGet functions.*/
glGetDoublev( GL_PROJECTION_MATRIX, projection );
glGetDoublev( GL_MODELVIEW_MATRIX, modelview );
glGetIntegerv( GL_VIEWPORT, viewport );

//Read the window z value from the z-buffer
glReadPixels( x, viewport[3]-y, 1, 1, GL_DEPTH_COMPONENT,
GL_FLOAT, &z );

//Use the gluUnProject to get the world co-ordinates of
//the point the user clicked and save in depthx, depthy, depthz.
gluUnProject( x, viewport[3]-y, z, modelview, projection, viewport,
&depthx, &depthy, &depthz );
```

Figure 5.6: Snap shot of the code to access the depth buffer values.

Figure 5.8. Since the guiding lines are moved, the program has access to changing depth values of the guide lines, allowing access to different regions of the cube. The path shown in purple is the sketch drawn by the user. These sketches in 3D can perhaps correspond to creating free-form sketches of well trajectories.

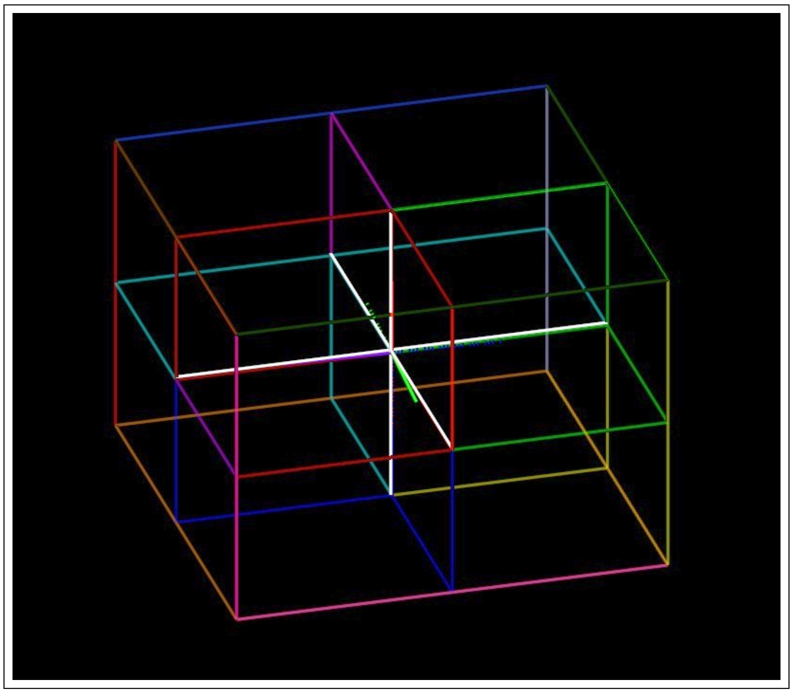


Figure 5.7: Guide-lines shown in white.

In a reservoir model, well trajectories are usually constructed with either of the two types of information: (a) by joining the centroids of the perforated cells or (b) by joining the free form 3D points placed by the user. To explore the case of centroid based well trajectories, we further extended this technique. As the user sketches through the cube reservoir model, we determine if the point is in one of the 8 cells found inside the reservoir. As the user sketches through the cells, the centroids of the cells are joined to create the line drawing. Figure 5.9 illustrates the creation of such a centroid based well trajectory shown in yellow.

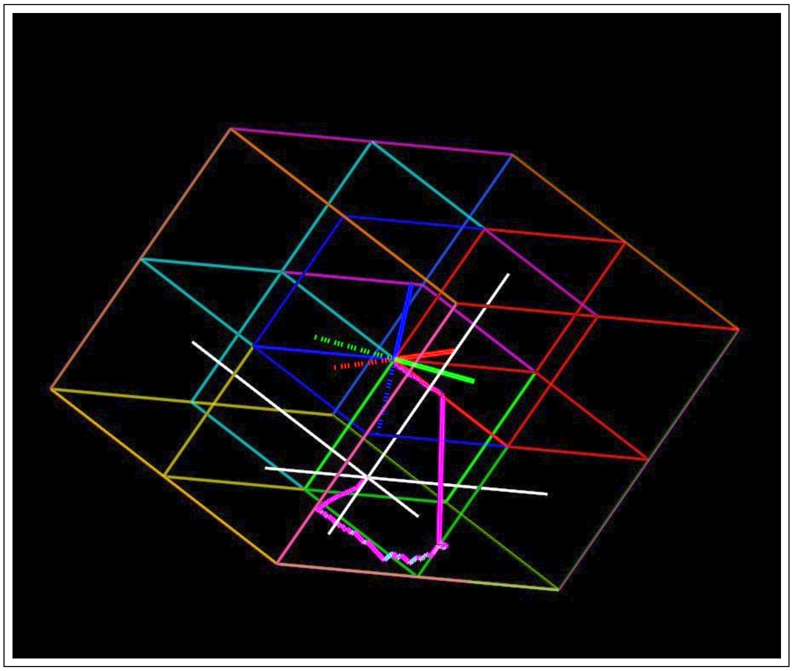


Figure 5.8: Sketching in 3D space using the guide-lines.

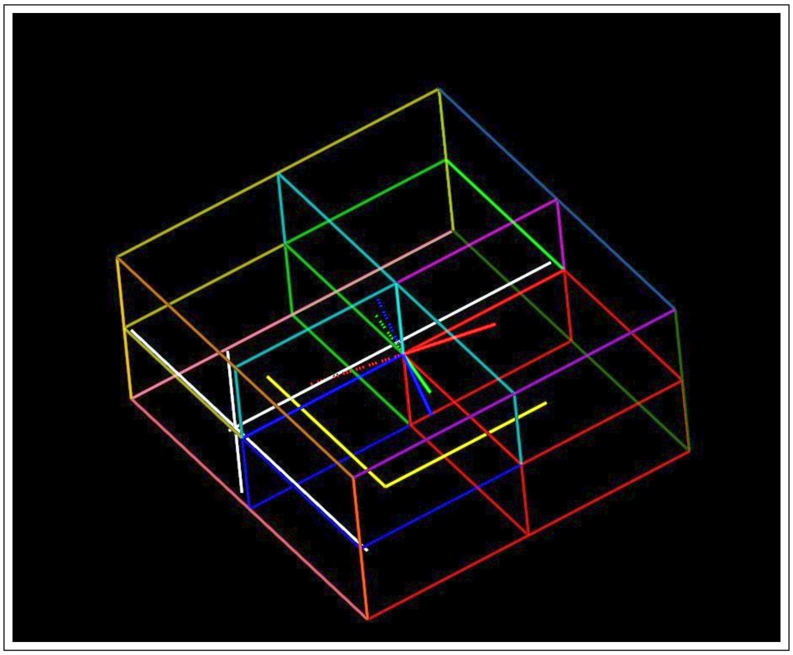


Figure 5.9: Centroid based line sketching.

5.2.2 Discussion

This attempt had several shortcomings. One member of our group always found this technique to be confusing. Apart from difficulties in understanding this technique, this approach also has technical limitations and drawbacks. The first limitation is because of the way depth values are handled. When a user decides to move the guidelines, he has four possible directions to choose from. When the center of the guidelines is dragged to create a sketch, there are usually two points of intersection or sometimes even three, leading to confusion. The point that is closest to the user is chosen in such cases. In essence, even if the user is trying to move along a straight line, the resulting points will be positioned in a zig-zag manner. Alternatively, clicking on distinct points on the line can in some ways help to overcome this problem, but clicking on parts of the guiding line is not interactive. Another limitation of this method is the inability to support going back precisely to some previous position, following which creation of multi-lateral wells is going to be difficult using this technique.

5.3 Dive-In Approach

The next attempt to address the task of well planning was by making use of tangibles and the layered nature of the reservoir models to guide the depth perception. The concept was to keep the technique similar to the act of drilling. The tangible can be compared to a drill bit and its rotation controls the depth of the well (Figure 5.10).

5.3.1 Design and Implementation

A reservoir model has a predefined number of layers and these layers correspond to how deep a well can be drilled. Taking advantage of these fixed depth layers, we devised a method wherein the user can control the layer at which the well is being

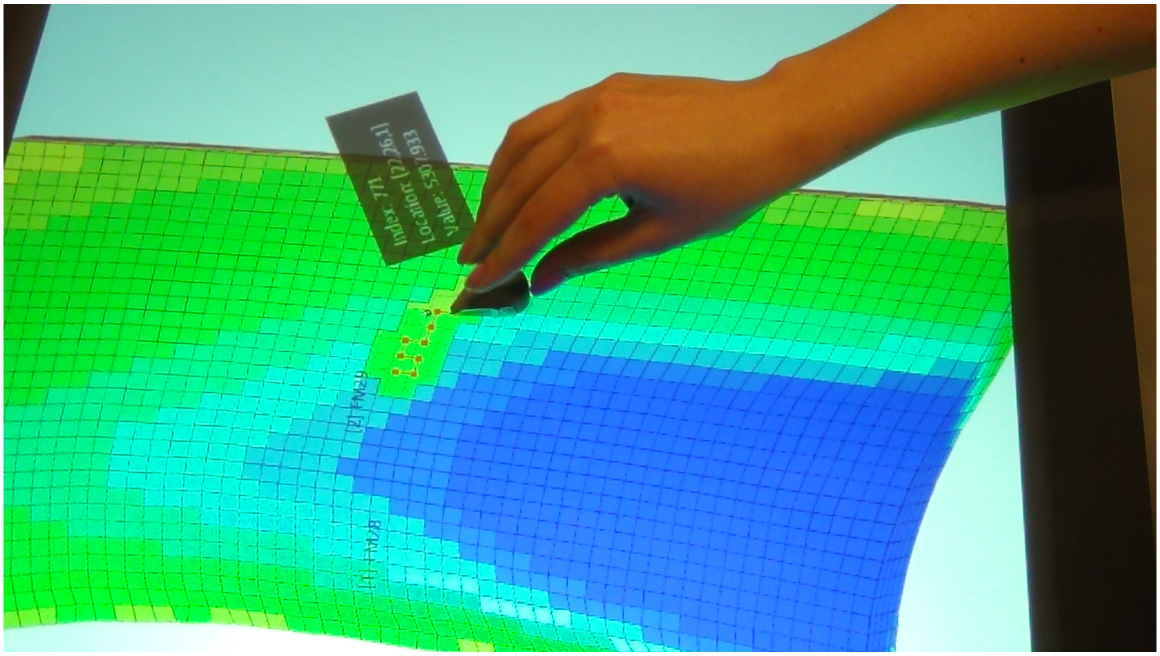


Figure 5.10: User trying the dive-in approach to create a well trajectory.

drilled by rotation of a tangible. By default, the user starts at depth layer one. By rotating (angle greater than 30 degrees) the tangible, the user can move further down the depth layers. The user can continue to rotate to move back from a deeper layer to a higher layer. We make use of the probe tangible discussed by Sultanum et al. [73] for this technique to overcome the precision issues that arise from "fat-finger" problem. The information of the block being selected is displayed in the panel to the side of the probe. Figure 5.11 shows a sequence of steps for creating a well trajectory.

Ray-triangle intersection [51] test is performed to determine the cell being selected by the probe. Since the rotation of the angle tells us the depth at which the point has to be located, we determine the intersection between the cell and ray at that particular layer or depth. In other words, we perform a layer specific cell search to determine the perforated cell. When the user begins to sketch the well, the perforated cell and its adjacent cells are removed to allow the user to see where the well is being sketched.

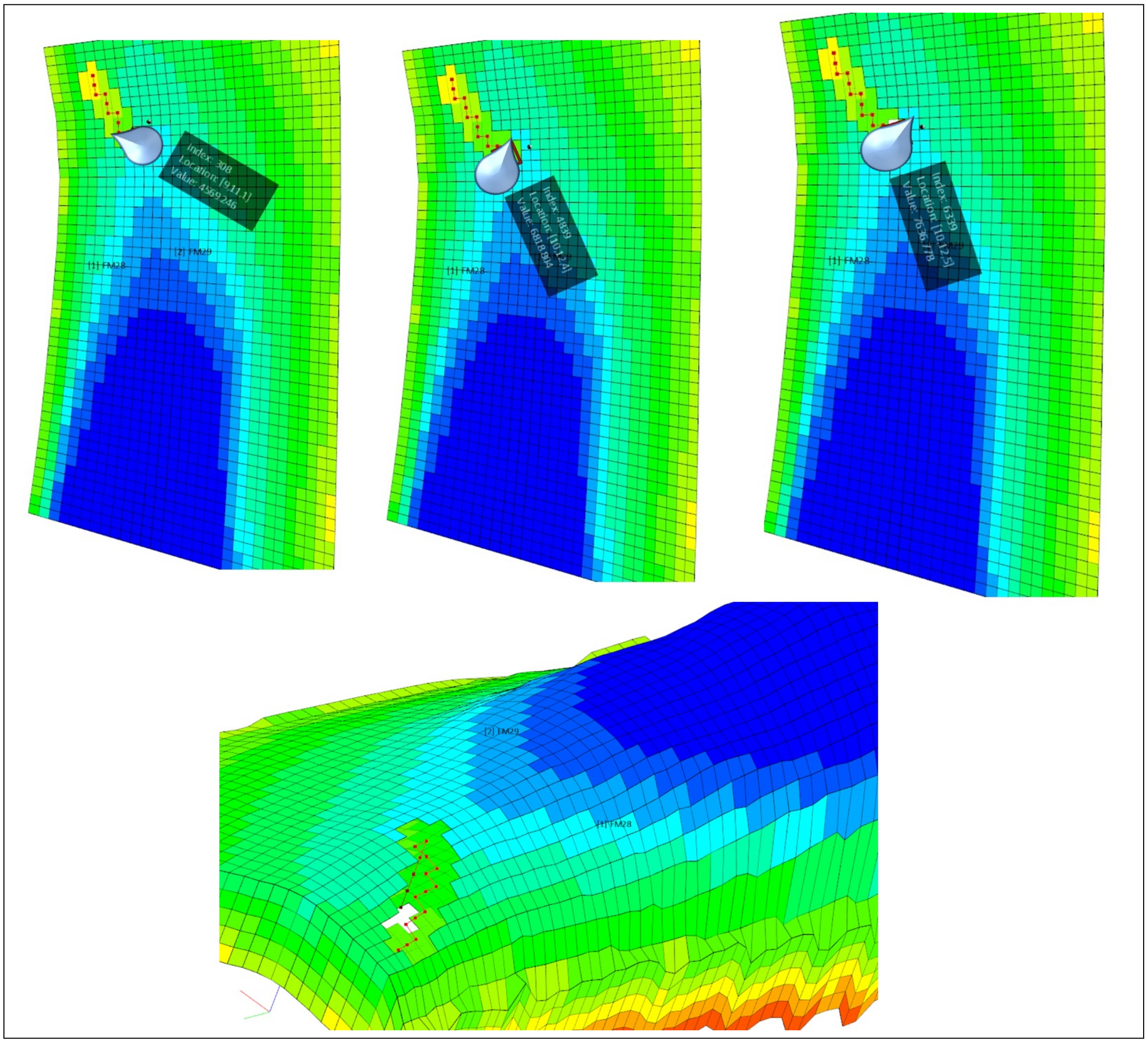


Figure 5.11: Sequence for creating a sample well trajectory.

5.3.2 Discussion

While this method was an improvement compared to the previous prototype in terms of precision of depth selection and allowed the user to create diagonal trajectories more easily, it still had a few limitations and drawbacks. The first drawback was the use of the same tangible for both the purpose of sketching and rotation. While the user was sketching, they may accidentally rotate the tangible leading to change of depth level and needing to start all over again, since our prototype did not support tools such as erasing portions of a line segment. Perhaps, keeping another entity for depth selection would have been a slightly better solution. The next problem that was observed during our discussions was the lack of visual cues. When rotating the tangible, the text panel was the only source of information indicating the depth layer. It was hard to understand visually how deep we had drilled without having to see the layer number. This divide of attention between the actual sketching and need for information did not help in performing this task intuitively. A possible alternative to this would be have another view presenting only the well trajectory as it is being created by the engineer.

5.4 2D Planes Approach

The next approach adopted by us was to use 2D sketching planes, similar to those in ILoveSketch [9] and Napkin Sketch [90] (Figure 5.12). The advantage of using 2D planes is that it gives the user a clear idea about the area he is sketching on. Hence we prototyped an application to allow users to select between three orthogonal 2D planes and rotate them using a rotation widget along fixed axis. The current prototype that we use for navigating through the 3D space of a reservoir model (Chapter 3,section 3.5) was built around this prototype. While we improved some aspects of it and removed functionalities such as rotation of planes, there are still other aspects that have to be investigated to support a real well planning task.

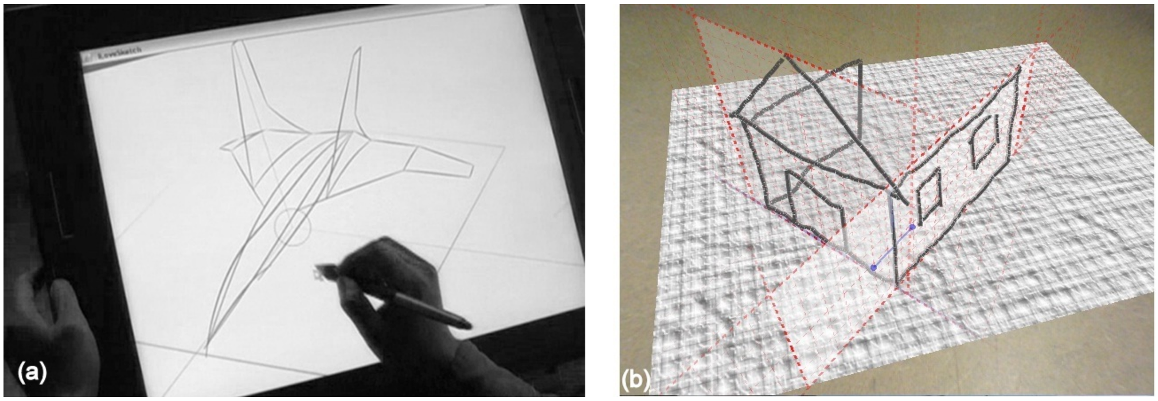


Figure 5.12: Using 2D planes for sketching: (a) IloveSketch [9] and (b) Napkin Sketch[90].

5.4.1 Design and Implementation

To create a well using this approach a user would perform either or both of these steps: (a) plane selection using a plane selection widget and (b) plane rotation using the rotation widget (Figure 5.13). Once the plane is fixed, the user can sketch on the planes using a single finger as described in Chapter 3 (section 3.5).

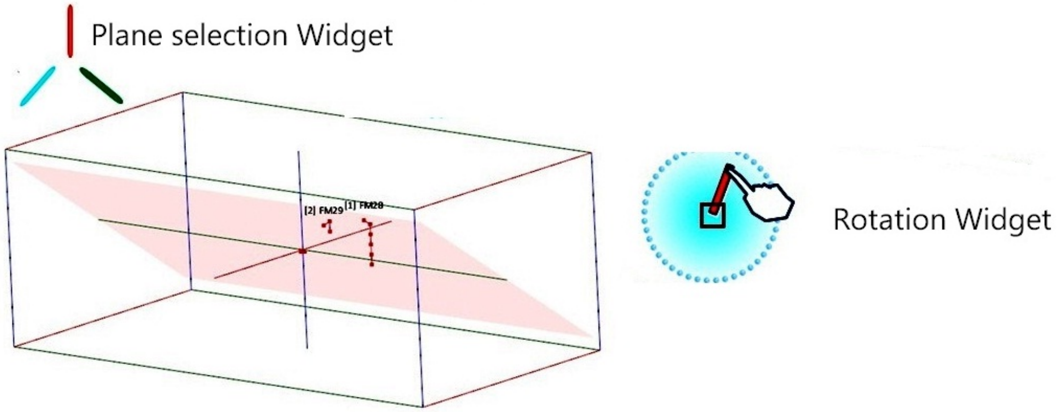


Figure 5.13: Components of the 2D planes prototype.

Plane selection

By default the XY plane is selected. To change between the three orthogonal planes the user can tap on the plane selection widget using a single finger as shown in Figure 5.14.

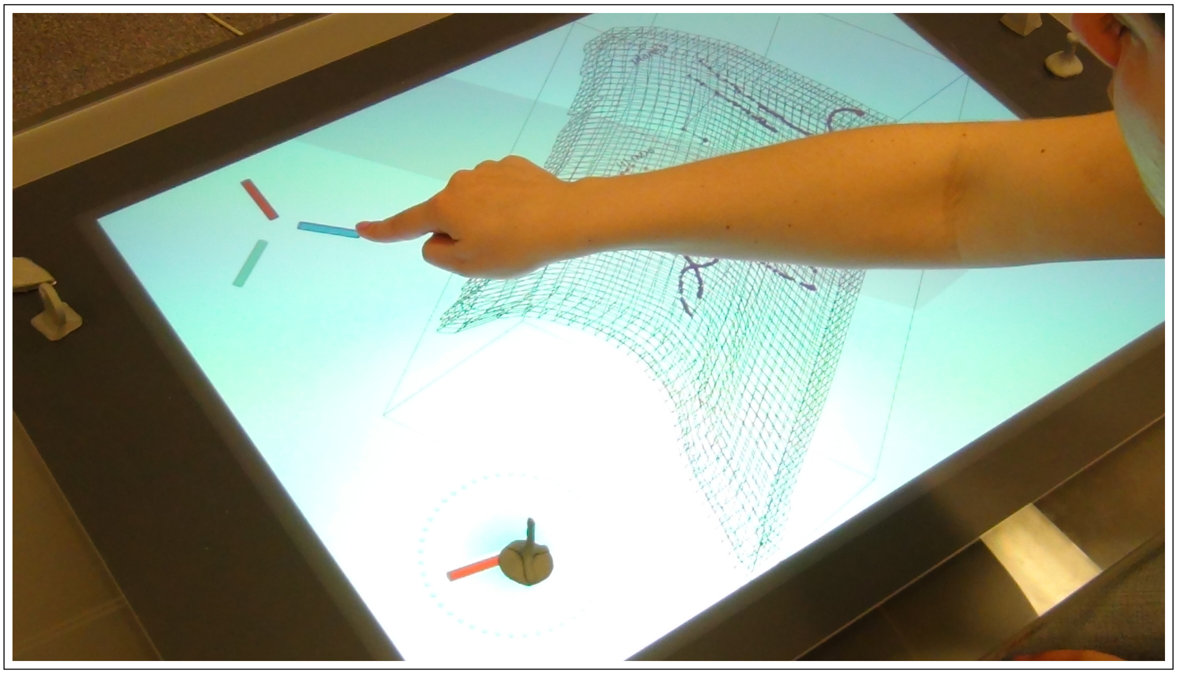


Figure 5.14: Plane selection.

Plane rotation

The selected plane can be rotated using the rotation widget as seen in Figure 5.15. The rotation widget consists of a rotating stick which can be rotated by the user using a single finger, to get the desired angle of rotation. The rotation widget appears at the position of the tangible that defined this modality. Hence, the widget can be positioned in a place that the user finds convenient to reach on the tabletop. Although the angle of rotation can be selected by the user, the axis of rotation is restricted by the implementation in this prototype. The XY plane is rotated only around the X axis, YZ is rotated around the Y axis and XZ is rotated around Z axis.

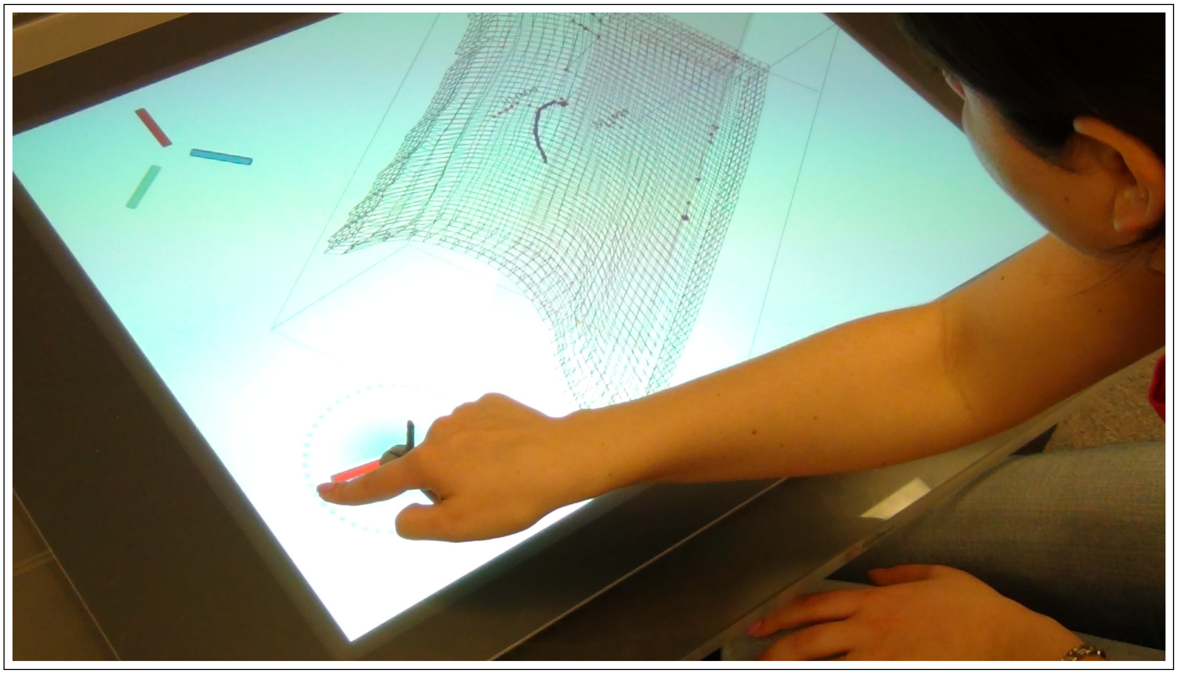


Figure 5.15: Plane rotation.

5.4.2 Discussion

The following points discuss the advantages and disadvantages of this prototype:

- *Visibility of drawing area*: One of the main benefits of this approach is the fact that the user can visually see the plane that he is drawing on, for example if a user identifies that he wants to drill a horizontal well through a region, then it can be achieved more easily using this approach compared to the previous two, since the engineer can visually see the plane and the region that he is drawing on.

- *Region versus single point*: When we define a plane, in essence we are defining an area for sketching. Unlike the dive-in approach where a user has to think of a well as a selection of well blocks that he would like to perforate at different depth levels, using a plane he can think of a well as a sketch in an area, which may have cells from different depth levels, since the layers of a reservoir model are not necessarily horizontal. For example, consider a scenario wherein a user wants to create a horizontal well trajectory. Figure 5.16 shows a single layer of a reservoir model with a horizontal well perforating some cells of that layer. The portion of the well which is in free space will intersect with cells from another layer. If this had to be achieved using dive-in approach, the user would have to have clear information about the depth values of each of the perforation cells, but with a plane, it wouldn't be necessary, since the line lies in the XY plane at that position.

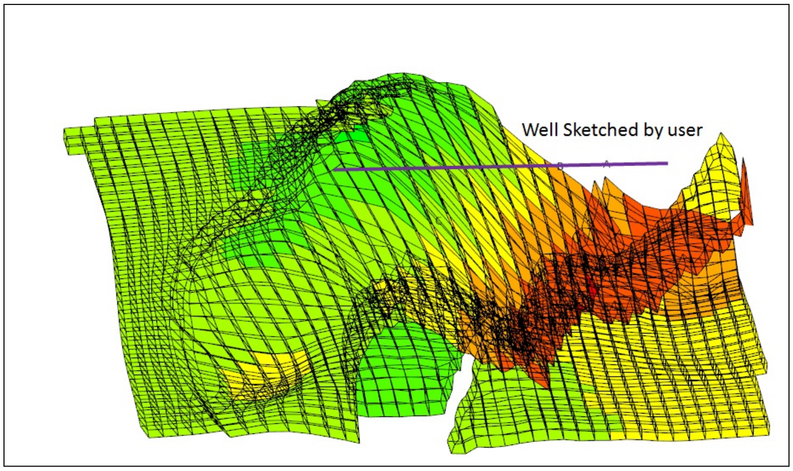


Figure 5.16: Sketching horizontal wells.

- *Selection of planes*: In this prototype, we made use of the selection widget to chose the three orthogonal planes. However, widgets of this sort are problematic since they require the user to move away from the sketching area each time the plane has to be changed. We latter improved this in our current implementation to allow the user to chose the sketching planes by touching the walls of the bounding box using two fingers as explained in Chapter 3. Although touching the walls may serve better than widgets, it still requires the users to remember to change the gesture from single finger for sketching to two fingers for plane selection. It will be interesting to incorporate methods that can sort of approximate the way a sketch would continue following hints from the previous 3D position placed by the user to select the next plane to be used.

- *Sketching surfaces*: Going beyond planes, it would be interesting to consider sketching well trajectories on surfaces defined by a user. Surfaces gives the user to define different shapes, which could help when a user wants to create curved wells or wells along a fault.

5.5 Combining Visualizations and Well Trajectory Creation

Although the well creation prototypes did not lead to a fully functional system, we experimented coupling some of our visualizations (discussed in Chapter 3) with the last well creation prototype (2D planes approach) as seen in Figure 5.17. In this section we present a brief discussion about the visualization and creation coupled prototype.

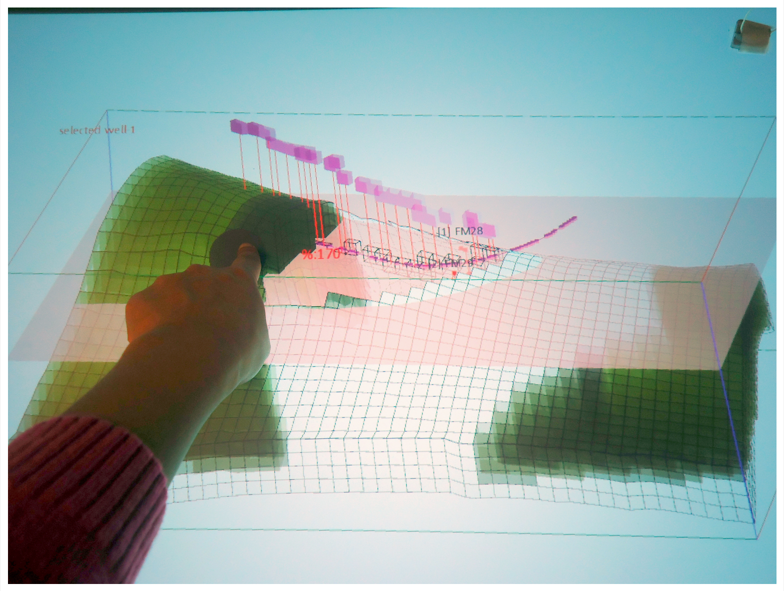


Figure 5.17: Assisting the sketching process with information from the uncertainty indicator and candy visualization.

Figure 5.17 shows a user creating a well trajectory through a section of the reservoir model. While the blocks are perforated, the corresponding candies are displayed dynamically. The candies are coloured according to uncertainty values of the cell (light purple corresponding to lower uncertainty and dark purple corresponding to high uncertainty). The uncertainty indicator at the tip of the finger indicates the accumulation of uncertainty upto that point. We also extended the prototype to allow a user to create multiple trajectories since it can be beneficial in situations when a user wants to compare between well trajectories at different locations (Figure 5.18, 5.19). Figure 5.18 shows a user sketching on the tabletop to create the second well trajectory (first one drawn in purple and indicated by the black marker). The gesture to indicate the end of a well trajectory is to put down three fingers on the tabletop. As can be seen from Figure 5.19, each well trajectory is presented in a different color.

As discussed earlier, well placement is a crucial task for reservoir engineers. An engineer takes into account several parameter constraints before deciding an optimal location for a well. To reach the bigger goal of having a system that can assist in such a task, we believe our efforts present the initial steps. We present an exploration assisted by uncertainty information as a proof of concept, to present the possibilities that can be explored for such tasks.

To take this attempt further there are several initiatives that can be taken. First, it would be interesting to conduct a task oriented user study to comprehend if sketching well trajectories using physical touch can benefit engineers and make this task easier. Currently the prototype can create horizontal and vertical well trajectories relatively easily than multi-lateral well trajectories. It would be necessary to improve the prototype to make sketching different configurations easier. Going beyond the domain requirements, it would be interesting to explore the potential of tabletops for performing such tasks. We attempted to create well trajectories using physical

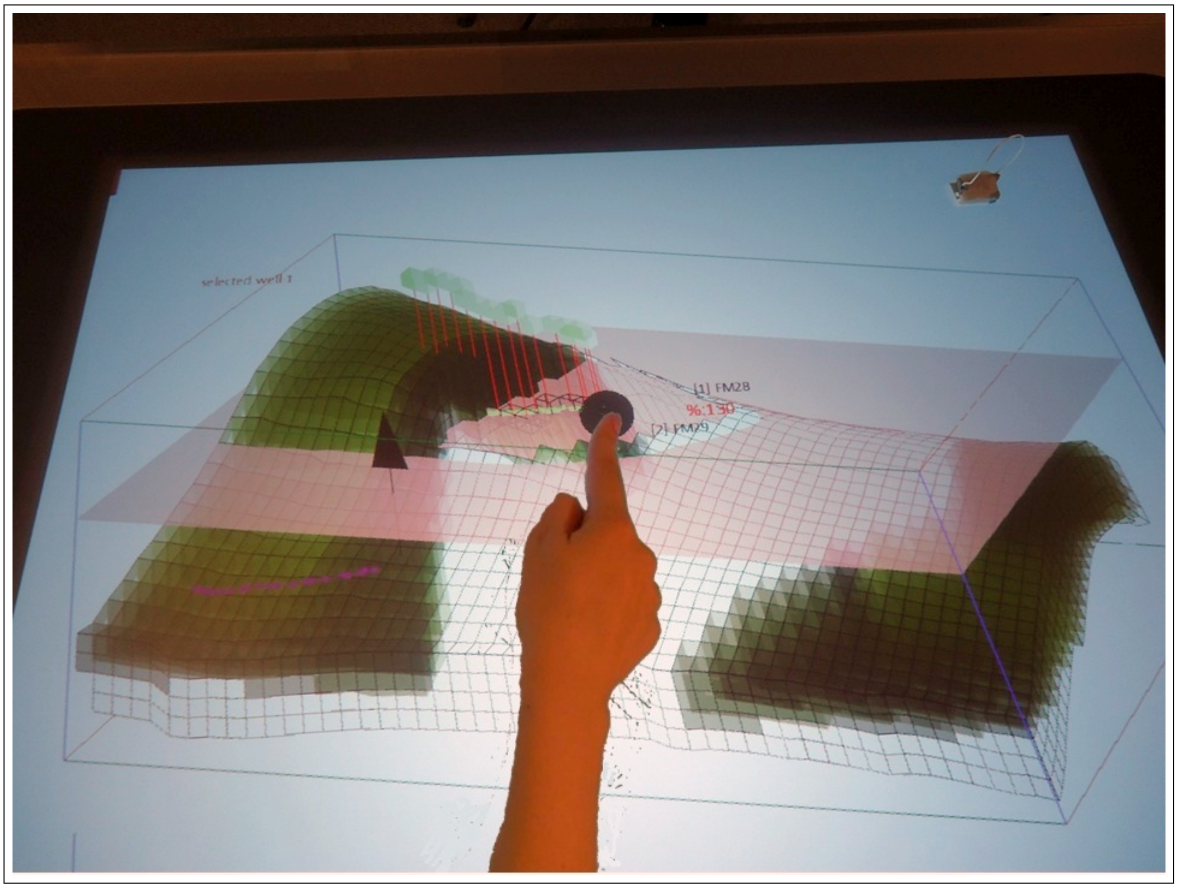


Figure 5.18: User creating multiple wells in the reservoir model.

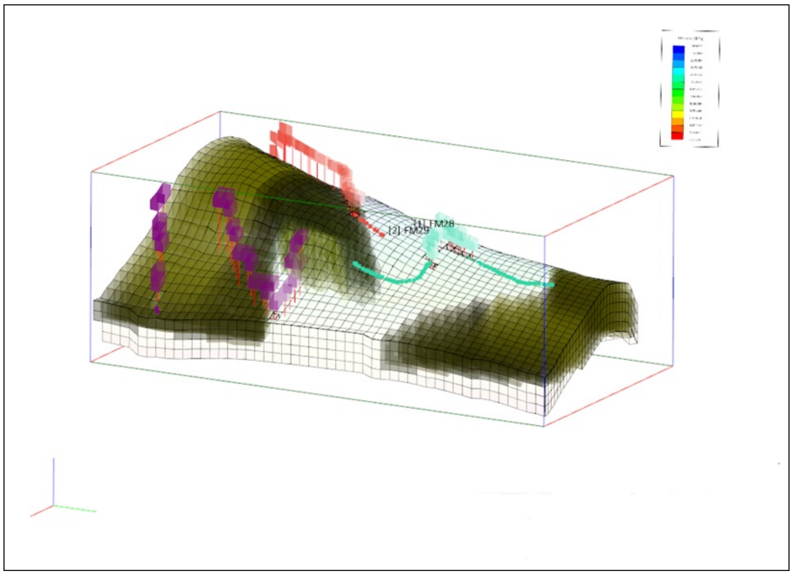


Figure 5.19: Candy visualization of the different well trajectories created by a user.

touch and tangibles, however it would be interesting to explore other solutions such as coupling tabletops with virtual-reality based solutions or other physical tangible interfaces.

5.6 Summary

In this chapter, we present three exploratory prototypes for well creation. We believe each of them is a step towards achieving the bigger goal of having interactive systems that can be used for tasks involved in well planning. Although the prototypes helped to shed light on some of the challenges involved in this task, there is a lot more to explore. Sketching in 3D is a challenging task and is an open problem. Sketching wells using physical touch and tangibles is also new to the domain of oil and gas to the best of our knowledge, allowing us to explore further. In the following two chapters we present a robotic tabletop assistant that explored the physicality of tabletops for the benefit of exploration tasks.

Chapter 6

Spidey - A Tabletop Robotic Assistant

6.1 Introduction

Robots have profound social impact on people, their mere physical presence and agency deeply affect and change even simple and familiar interaction scenarios [15, 29, 91]. Regardless of whether a robot is smart and autonomous or simple and fully controlled its physicality, form and body language will dramatically change the way people interact with it [33, 62]. If designed well, the powerful physical characteristics of robotic interaction can benefit people in various interaction scenarios where the physical presence of 'the other' changes the interaction experience (e.g. various educational scenarios where the physical presence of a teacher affects the learning experience, and various other collocated collaborative tasks). Digital tabletops have been established as interaction mediums geared towards enabling collaboration, where the tabletop confined interaction space allows each collaborator to be aware of the others presence and to benefit from it [80]. We think that introducing robots into such interactive environments will change the current models of human-human interaction around a tabletop. We believe that tabletop robots physicality will enhance the interaction experience in ways that are difficult to replicate with agents confined to the visual realm. We believe that the integration of tabletop robots would allow the tabletop interface to be more engaging, enabling it to more effectively weave the physical and virtual layers of tabletop tasks.

In this chapter we present the integration of a tabletop robot, Spidey (Figure 6.1), into a reservoir engineering tool [74, 75]. Given the novelty of this approach, our first question was whether a robotic tabletop collaborator would even be acceptable by people and by domain practitioners specifically. Given acceptance, we were also hoping to find out whether the inclusion of a robotic tabletop assistant has the potential to be meaningful, beneficial and effective within the context of valid tasks. Furthermore, we believe that the introduction of a physical agent to the tabletop interactive environment is not addressed by the current models of tabletop interaction and were hoping to discover how interaction with a tabletop robot can be viewed through theories of proxemics [36] and how it would affect social and territorial usage patterns of tabletop interfaces.

In the field of human-robot interaction (HRI), interactions between the robot and humans have been classified into two categories remote interaction and collocated or proximate interaction [33]. As a tabletop robot Spidey clearly belongs to the category of proximate interactions, sharing the tabletop virtual and physical space with the human user in what can be seen as almost a contention for limited interaction resources. However, this need to share a small space can also benefit the interaction potentially enabling collaboration between the participant and the robot. To study the behavioral reaction to the robot we propose a new proxemics model which is influenced by existing human-robot and human-human proxemics model. However, in an attempt to address the uniqueness of introducing a robot to the tabletop environment our proxemics model is shifting the attention away from both the participant and the tabletop, focusing mainly on the robot as the dynamic center of the proxemics zones and social distances.

The current Spidey prototype is a mere first step and the tasks we present in this chapter were mostly designed for a proof of concept. However, we believe that they do provide a reflection on the concepts novelty and practical potential, as well as new theoretical insight on how to model tabletop robot proxemics. This chapter is divided as follows: we first present the design and implementation of *Spidey* and its role as an assistant in a set of reservoir engineering post processing tasks. Next we detail the findings of a user study we performed with *Spidey*. We then detail the emerging proxemics patterns we identified, from both the user perspective and the robots. We finally conclude with perspectives for the future.

6.2 Design and Implementation

This section discussed the design considerations taken while implementing the *Spidey* prototype. Following the discussion of *Spidey's* design and implementation we present the design considerations for the proxemics model used for studying this prototype.

6.2.1 ***Spidey*** Design and Implementation

The current prototype of *Spidey* is designed as a tabletop robot situated on Microsoft Surface 1, multi-touch tabletop (Figure 6.1).

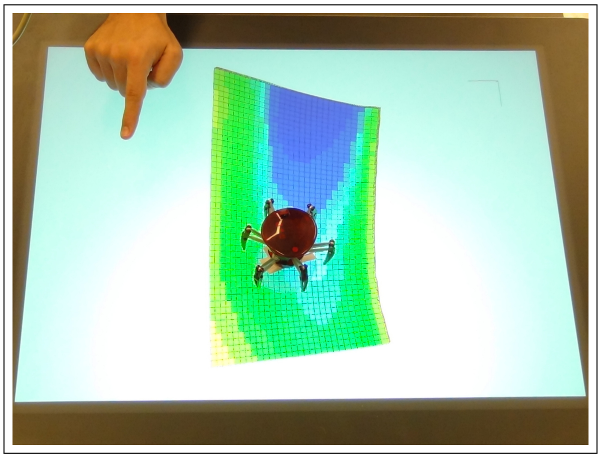


Figure 6.1: *Spidey* on the MS surface.

A tabletop robot must take into account the interaction space, and in the case of the MS Surface 1 (22 X 27 X 42.5 inches) this implies that the robot will be small in size. The need to restrict the size of the robot is direct: on a relatively small tabletop space, we need a robot that refrain from hindering physically or visually the users ability to interact with the tabletop and can walk around the tabletop without causing interferences or major occlusions of the digital content. To meet this requirement we chose for our *Spidey* prototype a commercial toy robot manufactured by Hexbug^{TM} (Figure 6.2a). The spider robot measures 4.33 X 4.33 X 5.12 inches in size and weighs 2.82 Lb. *Spidey* is small in size and has 6 legs (Figure 6.2b), beyond the spider zoomorphic metaphor, *Spidey* legs touching the tabletop are arguably not dramatically different than human fingers.

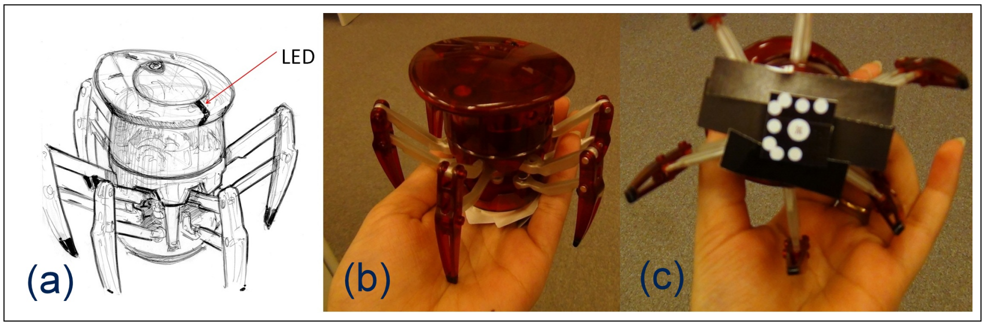


Figure 6.2: *Spidey* (a) schematics, (b) size compared to a hand and (c) byte tag on *Spidey's* bottom, enabling tracking.

Spidey is controlled using an IR remote control which is located at almost ceiling height, above the MS Surface, pointing down. This setup (Figure 6.3) allows the remote to emit its signals to *Spidey*, either directly or via reflection from the surface, thus dramatically reducing the chances of occlusions from the users hand .

Spidey can move forward, backward as well as rotate 360^o in clockwise or anti-clockwise direction. The front and back direction of the robot is determined by the direction the LED (placed in the head region of *Spidey* Figure 6.2a) is facing. To enable real time tracking of the robot on the tabletop we attach a byte tag to the bottom of *Spidey's* body (Figure 6.2c). The size of the byte tag has restrictions (the

Figure 6.3: Setup for controlling *Spidey*

black region on the byte tag should be atleast 0.75 X 0.75 inches in size), requiring that the base to which the tag is attached is broad enough.

To control *Spidey* programmatically, we connect the IR remote to a USB data acquisition interface unit (ADU ONTRACK 100) (Figure 6.4). The digital pins of the USB unit are connected to the four buttons on the IR remote, allowing appropriate signal to be sent to the remote to activate the button-action (e.g. to move the robot forward, the signal pattern sent to the remote is 0111).

6.2.2 Proxemics Between Tabletop Robots and Human Users

As discussed in Chapter 2, theories of proxemics have been studied to improve interactions in various scenarios. However, proxemics between tabletop robots and people is new. Tabletop robots uniqueness is that they maintain very close proximity to their users, sharing with them a very limited interaction space. This intimacy can be challenging when designing interactive experiences as the robot can be viewed as competing of the limited tabletop interactive space. However, this intimacy may also

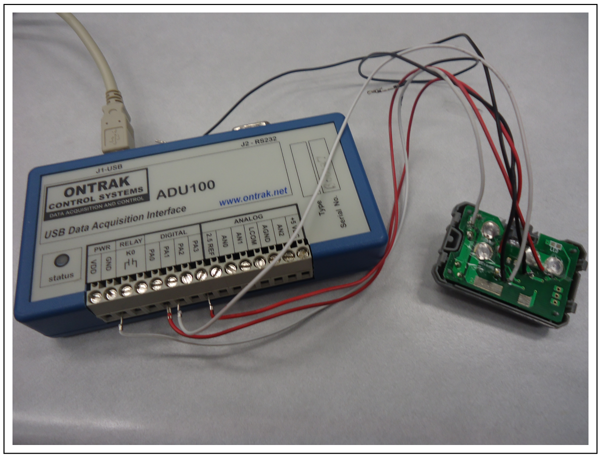


Figure 6.4: Connecting the IR remote and USB data acquistion unit for controlling the robot

benefit the interaction design, potentially creating experiences for the user, which closely relate to the robot's actions, perhaps leaning more towards accepting them as being helpful and assistive.

Proxemics between a tabletop robot and human to the best of our knowledge is still unexplored. In most instances of research that explored human-robot interaction model [53, 78, 87] (discussed in Chapter 2), the robots were humanoids, *Spidey* on the other hand is a toy robot whose zoomorphic appearance is close to a spider but its physical appearance is constrained [12] (no explicit physical features such as eyes, hand etc.). On a higher level it can almost be considered an interactive abstract physical shape, an elaborate tangible user interface. For such robots, perhaps one of the only parameters that can contribute towards understanding the interaction model is the physical distance between the robot and human user, as used by Mumm and Mutlu. [53] and Bethel and Murphy [12]. However, the inter distances are influenced by perception [36]. Thus for formalizing our proxemics model we use two parameters: the physical distance, which is defined by dynamic zones we defined around *Spideys* current location and the users intention, such as touching *Spidey*, away from *Spidey*, near *Spidey* and far from *Spidey*.

6.3 Interaction with Spidey

Collaboration with a collocated human companion will often rely on direct communication. One of the most basic requirements of a direct communication channel is the ability to refer or call out to another person using their name, pointing or waving at them. When designing the basic interaction with *Spidey* we had to come up with simple tabletop-related mechanisms that would allow users to refer to the robot.

We see touch visa the tabletop medium as the simplest and most natural way to refer to a tabletop robot. Following, *Spidey* can be called visa two methods: (a) tap and call and (b) draw and call, both employing the facility of direct touch.

6.3.1 Tap and Call

Using this method the user can ask *Spidey* to come to different regions of the surface by simply tapping on the destination point using a single finger (Figure 6.5). Upon removing the finger, *Spidey* begins to walk towards the destination and stops upon reaching it.

6.3.2 Draw and Call

An alternative simple way to interact with *Spidey* is by sketching paths for *Spidey* to follow (Figure 6.6). The user can sketch a stroke or a path using a single finger, and upon removing the finger, *Spidey* begins to trace the path, walking towards the destination, eating up the path it already covered. In Draw and Call *Spidey* is restricted to the path that the user drew for it (unlike Tap and Call where *Spidey* will devise its own path to the destination).

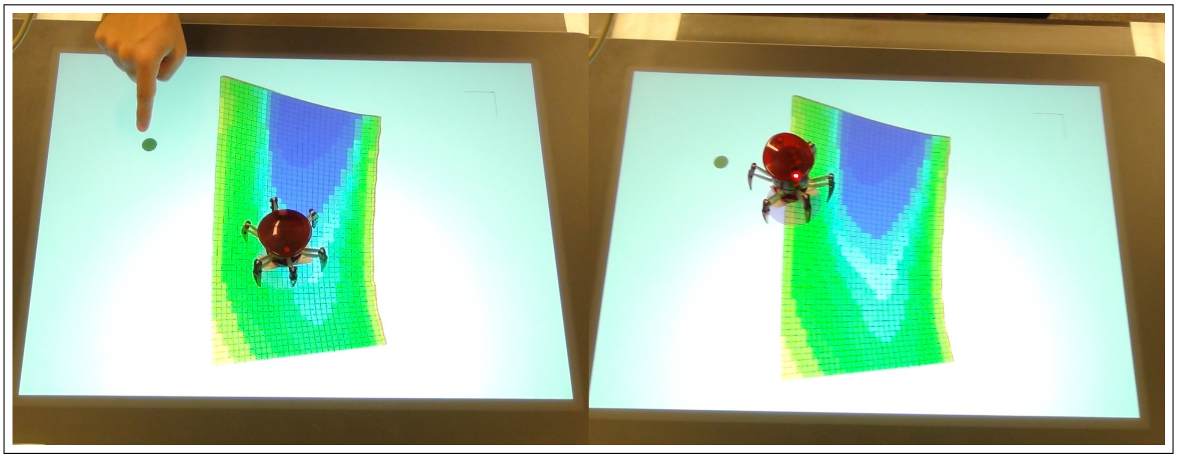


Figure 6.5: Tap and Call: calling Spidey by tapping at a destination point on the surface

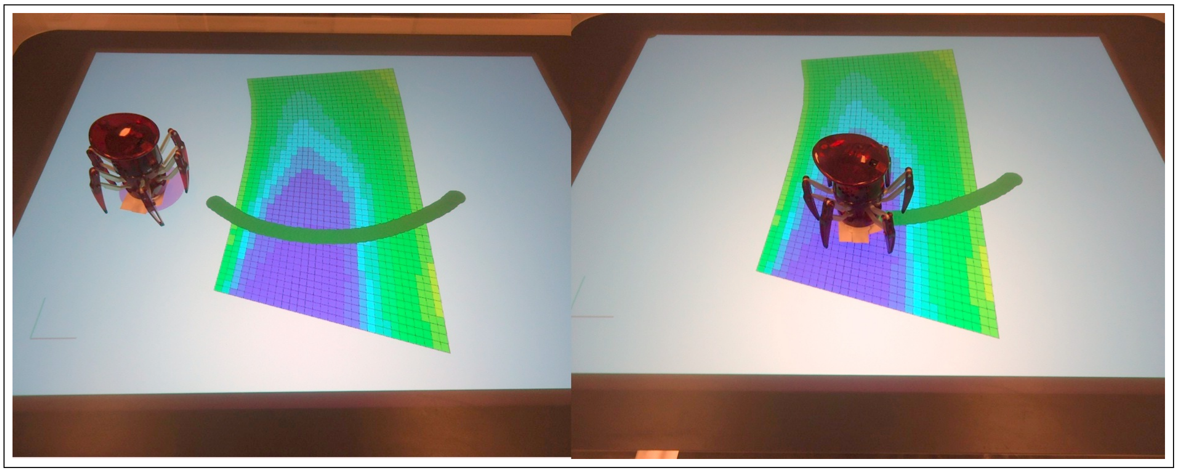


Figure 6.6: Draw and Call: Telling Spidey to reach a destination by following a sketched path.

6.3.3 Wayfinding Algorithm

The simple algorithm used for directing *Spidey* to reach any specified destination on the tabletop is based on changing the position of *Spidey* by small increments. At every step, a direction vector (cross product between the vector from old position of *Spidey* to new position, and new position to the destination) is being calculated and on the basis of it decisions are being made regarding the next step (forward, backward, rotate left, rotate right). The direction of movement is determined by the direction the LED is facing as shown in Figure 6.7. One of the limitations of the current *Spidey* prototype relates to the way it rotates. Rotation of the robot only affects the top half of the body, leaving the orientation of the attached tag at the bottom of the robots body unaffected, preventing us from precisely tracking its orientation until forward or backward movement is being performed. While our algorithm compensates for this limitation the resulting movement is arguably not extremely agile.

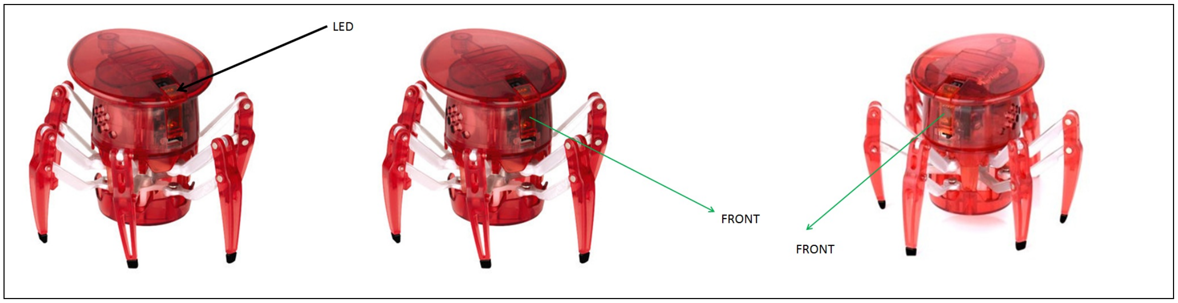


Figure 6.7: Determination of *Spidey's* front and back based on the direction the LED is facing.

In the case of draw and call method, a list of 2D vectors is maintained. The stroke is then sampled to have a collection of points equidistant from each other. The ordering of the points in the list has the same sequence as that of the user's stroke. Meaning, the starting point of the stroke, is the first destination point in the list. This way, *Spidey* knows where the stroke begins and ends. The above explained algorithm is then applied to this sequence of points. When *Spidey* reaches each point in the list, the point is marked to be a finished destination and the points behind that index are removed from the list, to give the user an impression that *Spidey* is 'eating up' the points as he goes (Figure 6.6). Finally when the last point on the stroke is reached, the entire stroke is erased so as to provide feedback regarding the completion of a task.

6.4 Spidey in Reservoir Engineering Tasks

To study the role of *Spidey* as an assistant, and learn more about the nature of the interactions between an individual and the tabletop robot, we integrated our *Spidey* prototype in an existing work of reservoir post processing tabletop visualization application developed by Sultanum at al. [21, 22]. The tabletop visualization application allows the user to interactively visualize, manipulate and explore 3D reservoir simulation models. A reservoir model is a 3D grid representation of a subsurface pool of hydrocarbons contained in porous or fractured rock formations. Each grid cell of the reservoir model contains static attributes (i.e. rock characteristics) and dynamic, time varying (fluid flow) values [74, 75]. *Spidey* is integrated into this visualization application environment by sharing the workspace of an engineer and can perform a set of simple assistive tasks at the users request. The reservoir engineer can interact with *Spidey* by calling it to different regions of the reservoir, and direct it to explore and provide insights about the 3D reservoir model.

To evaluate the assistive behavior of *Spidey* in the domain of oil and gas, we focused on three simple tasks that would allow *Spidey* to assist the reservoir engineer. In this prototype the first two tasks reveal and rotation (Figures 3c, 3d) are straight forward and present *Spidey* as a tool. While we agree that the tasks are simple and could essentially be accomplished by a single engineer even without *Spideys* assistance, however, from an observers point of view, calling *Spidey* and waiting for it to present the information creates the illusion that *Spidey* is an expert who knows the information that the user is requesting. In the third task playback, *Spidey* plays back actions that were performed in a previous time, by a different user, potentially in a completely different location, acting like their physically "recorded" fingers. Playback explicitly highlights the assistive characteristic of *Spidey* as it becomes a physical mediator of past actions, arguably allowing the user to experience the presence of an expert that used the system in the past, sharing a deeper view of their insight and approach to the engineering problem at hand.

Our prototype allows the user to perform the set of tasks via a simple set of interaction techniques (tap/path), with the active assistance of the robot. Arguably, all of the tasks presented in this paper could have been performed with the assistance of a virtual agent presented on the display rather than a physical robot. However, unlike a virtual bot, a tabletop robot has physical presence which we believe affects interactions and presents an engaging environment. Impressions of participants interacting with *Spidey* are presented in the results and discussions session.

6.4.1 Reveal

A reservoir engineer often requires seeing two or more properties at the same time [75]. For example, an engineer would like to learn how porosity varies in some patch of a pressure mapped reservoir model. Such information could inform the engineer if some region is optimal for positioning oil wells. Using this as a possible task requirement, we designed the reveal task wherein *Spidey* extracts pressure information from porosity mapped reservoir as per user discretion.

The idea behind this task is to call *Spidey* to different regions of the reservoir

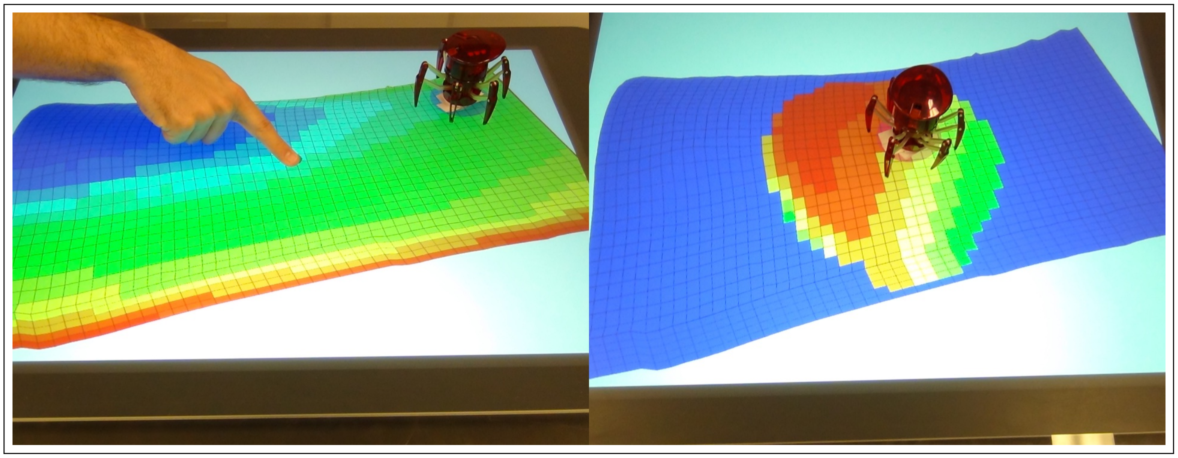


Figure 6.8: *Spidey* performing the reveal task.

model, and when the destination is reached, *Spidey* selects a cylindrical region of fixed radius around the destination point (Figure 6.9) and displays one geological property inside that region (oil pressure, in the current prototype) and another geological property outside the selected region (rock porosity, in the current prototype) as seen in Figure 6.8. When performing the reveal task *Spidey* is essentially acting like a physical filter, which can select and show the internal properties relating to specific regions of the reservoir model following the reservoir engineer wishes.

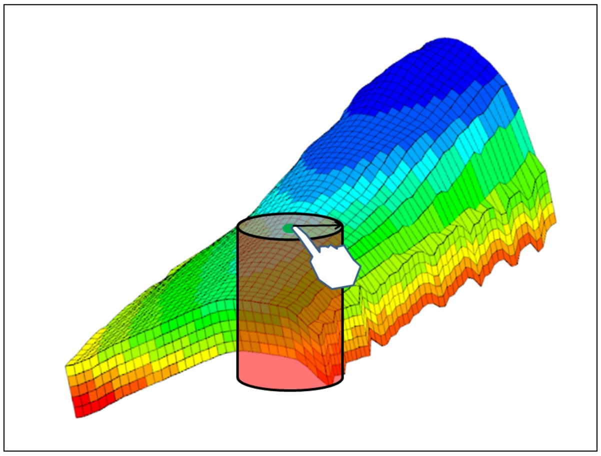


Figure 6.9: Cell selection for the reveal task.

A practical extension to this task would be to allow *Spidey* to batch process several such requests, allowing the user to concentrate on performing other tasks. Completion of the task could be indicated by the robot via speech or other body gestures [62] well known in social HRI.

6.4.2 Reveal and Rotate

The reveal and rotate task is designed to show the potential of using *Spidey* for physically manipulating the model. The idea behind this task is that an engineer may want to explore the model by looking at some region of interest and then change the view to continue to perform further exploration. In reveal and rotate (Figure 6.10) *Spidey* extracts (as in the reveal task) information at the destination region and then rotates the model for further exploration.

The angle of rotation in the current prototype is a randomly generated number between 0^o 360^o to give the perception that the robot is actually performing something new each time. Physical feedback for the virtual rotation action is indicated by the rotation of the robots head. Note that our current prototype is not sensitive to user input in regard to the angle of rotation, which is an obvious limitation. The task is designed to demonstrate the capability of the tabletop robot to perform manipulation tasks on behalf of the user allowing users to reflect on the concept in its somewhat unrefined current prototype form.

Manipulation tasks such as these could be beneficial for demonstration purposes. For e.g., an engineer could previously teach *Spidey* some angles of rotation which present areas of interest and during presentations *Spidey* could physically perform these manipulations while the engineer concentrates on presenting the details to his peers.

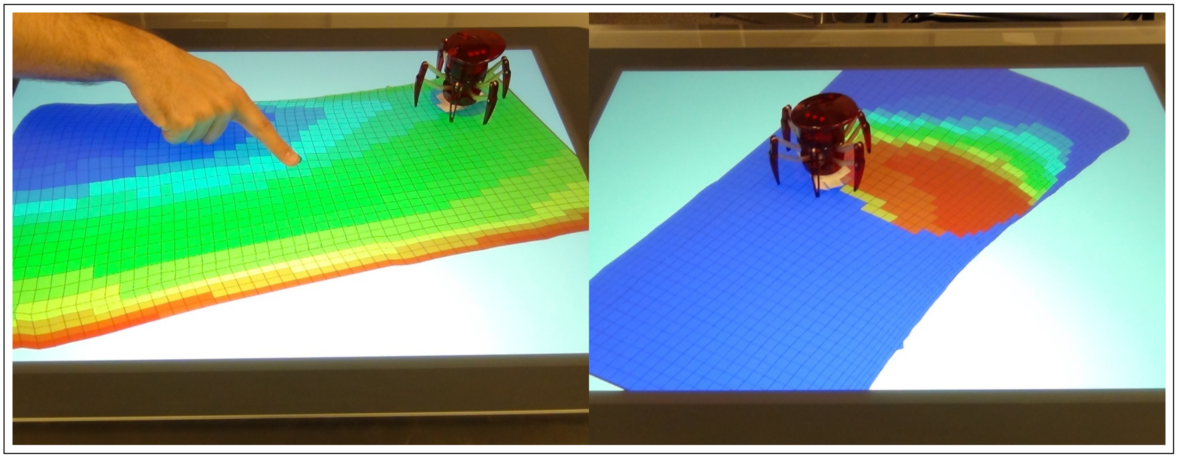


Figure 6.10: *Spidey* performing the reveal and rotate task.

6.4.3 Playback

While the previous two tasks demonstrated the ability of using *Spidey* as a tool, playback presents an explicit use case of *Spidey* as a peer or mentor taking advantage of its physicality. In Playback *Spidey* is playing back a previously recorded set of actions. *Spideys* actions reflect on this past sequence of actions, performing them as if physically imitating the past users fingers touching the Surface. Playback can be helpful in situations where for example collaborators cannot meet at the same time, but would like to learn from the expertise of each other. Alternatively, Playback could also be useful when novice users need to learn and gain insight by watching a complete exploration sequence of an expert reservoir engineer. Other examples could be when a user wants to revisit actions performed by her, or to present them to, say, management. *Spideys* playback can be seen as a physical imprint of the sequence of actions performed by an engineer, capturing the exploration process in its full physical extent, rather than just the end result.

Figure 6.11 illustrates a playback example sequence: First, *Spidey*, walks up to a point on the reservoir (Figure 6.11a), upon reaching the destination *Spidey* resets the property and then splits the reservoir into two halves (Figure 6.11b). *Spidey*

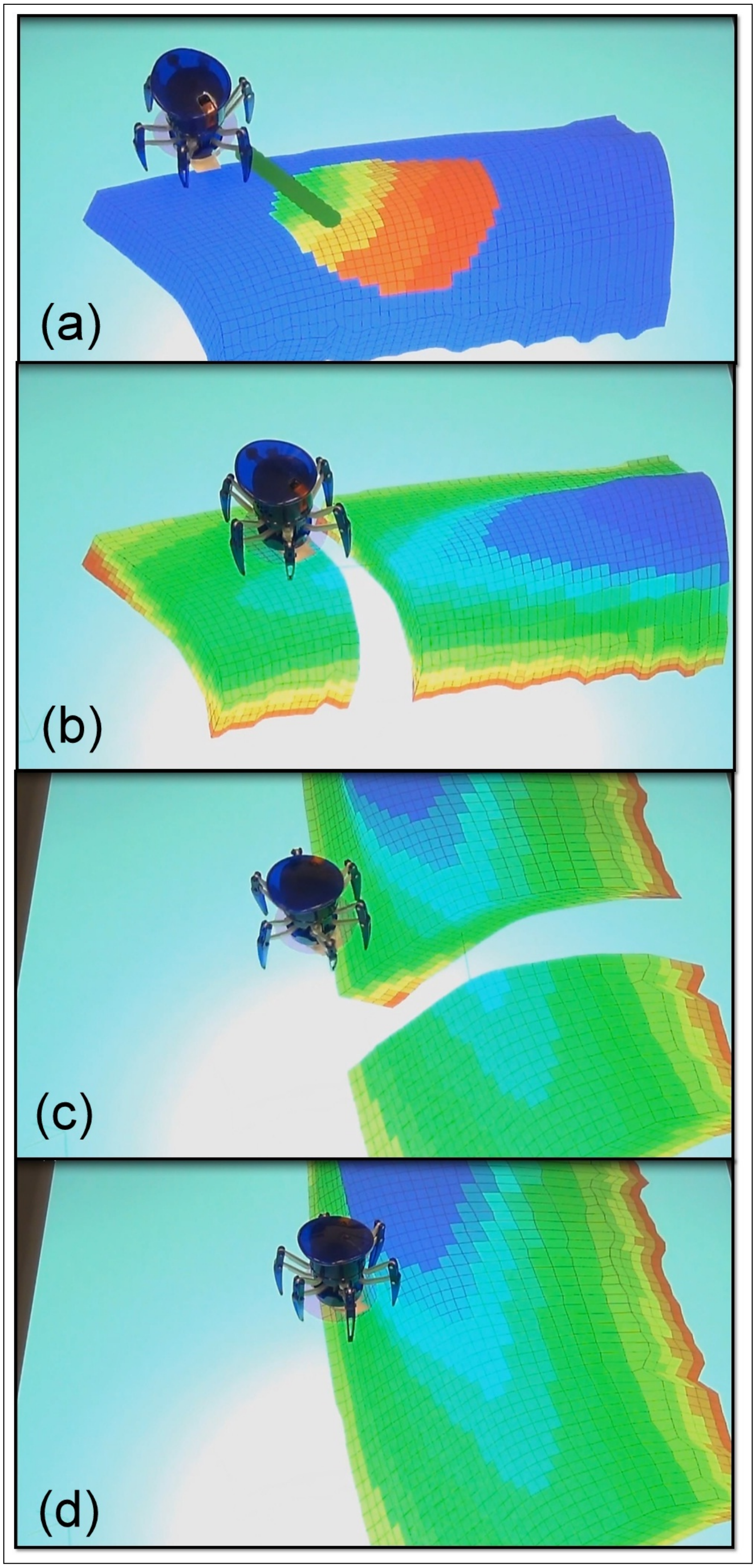


Figure 6.11: Playback Sequence: (a) *Spidey* walks to the point of contact (b) *Spidey* splits the reservoir, (c) *Spidey* rotates and zooms the model (d) *Spidey* merges back the split reservoir.

then plays back a sequence of rotation and zoom (Figure 6.11c) and finally, glues the reservoir model back together by merging its two separated halves. (Figure 6.11d). During playback *Spidey* is providing physical feedback for its actions, beyond its physical movement and the virtual corresponding changes to the reservoir model on the tabletop: rotation of head to indicate rotate action, walking in place to indicate the attracting and merging the two halves of the model together etc. The overall user experience is designed to create the illusion of *Spidey* physically performing all the pre-recorded actions as they visually unfold on the tabletop visualization. In the current prototype, *Spidey* plays back manually composed sequences of actions and not real captured interaction session. The main goal of the task was to assess the effect and validity of this task, rather than our ability to correctly record sessions.

6.5 Study

We conducted a series of qualitative studies to evaluate the Spidey prototype. The goal was to observe the interaction between the domain experts, from two specific fields (reservoir engineering and computer science) and to learn more about the limitations and potential benefits of integrating a tabletop robot assistant in an interactive reservoir engineering exploration application. Beyond the domain-specific goals we were also hoping to shed light on proxemics between a tabletop robot and a tabletop human user, when both are attempting to collaborate in a set of tasks.

6.5.1 Participants and Methodology

Our evaluation targeted two populations of domain experts: participants with strong background in either reservoir engineering or in computer science, hoping that these two populations will help us with at least preliminary reflection on *Spideys* applicability and validity. Altogether we recruited ten participants (9 male and 1 female): 5 reservoir engineers and 5 computer scientists, all graduate students or post-doctoral fellows in our University. The participants were recruited via a mailing list and were compensated monetary for their time.

The study sessions which lasted for about 50-60 minutes each, included three major components: two questionnaires and a demonstration of 5 simple tasks (interaction techniques and domain specific tasks), where we invited the participant to try each of the tasks at least twice. The study pattern consisted of the following sequence: (a) brief introduction to the goals of the study, (b) pre-questionnaire, (c) demo and interaction session and finally (d) a concluding questionnaire. During the interaction session or the main study, we encouraged participants to "think-aloud" expressing their opinions, suggestions and any feedback they may have regarding *Spidey*. We asked the participants to reflect on *Spideys* shortcomings, strengths and potential effectiveness. The pre-session questionnaire was used to learn more about our participants, asking about any previous experience they may have working with robots of any kind; how comfortable they are when interacting with new softwares and technologies and general questions relating to their area of research and expertise. To reflect on the participants expectations and definitions of an assistive robot we asked them to define the word assistant using three short sentences. In the post-questionnaire, we used a set of HRI questionnaires [10] to learn more about *Spideys* emotive effects in the following five areas: anthropomorphism, animacy, likeability, perceived intelligence and perceived safety. In the anthropomorphism questionnaire, we slightly modified one original question, which dealt with the likeliness of the robot to a machine or human [10], to instead reflect on the robots likeliness to be that of a machine or animal. All the sessions were videotaped with participants consent, and coded

6.5.2 Analysis

We collected three types of data from each participant: questionnaires responses, verbal comments during the study and the following discussions, and coded interaction patterns between the participant and the robot. The responses to the questionnaires were analyzed both qualitatively and quantitatively. We used open coding [72] in order to analyze the participants actions and to reflect on emerging proxemics patterns between the tabletop robot and human user.

6.5.3 Proxemics Zone Measurement

To understand proxemics between the tabletop robot and the user we used physical distance as one of the parameters of measurement. For the sake of measurement convenience we divide the tabletop into dynamic zones using *Spideys* current position. Scott and Carpendale [64] discussed zoning using a fixed space division method, wherein a circular table could be divided into different zones using directions (N, NW, S, SW etc.) and radially varying divisions (center, midway etc.). Our method however is less focused on the tabletop but rather defines the territory as an active notion which centers on *Spideys* current position. *Spidey* is constantly moving, changing its position and thus dynamically influencing the participants area of interaction. Hence, our proxemics zones are concentric in specific distances around *Spideys* current location. Figure 6.12 illustrates our division of the tabletop surface into four proxemics zones, touch, near, far and away, around *Spidey*. The definitions of the four zones are as follows (Figure 6.13):

Touch - direct touch between the user and *Spidey*.

Near - *Spidey* is roughly within hand reach (palm plus fingers) from the user current hand position.

Far - beyond the near zone but still within the tabletop.

Away - the users hand is positioned away from the tabletop, not above it. Note that away is the only zone that is defined by the tabletop and not by *Spidey*. When the user is in the away proxemics zone the distance to *Spidey* becomes irrelevant, as *Spidey* is confined to the tabletop, which the users hand disengaged from.

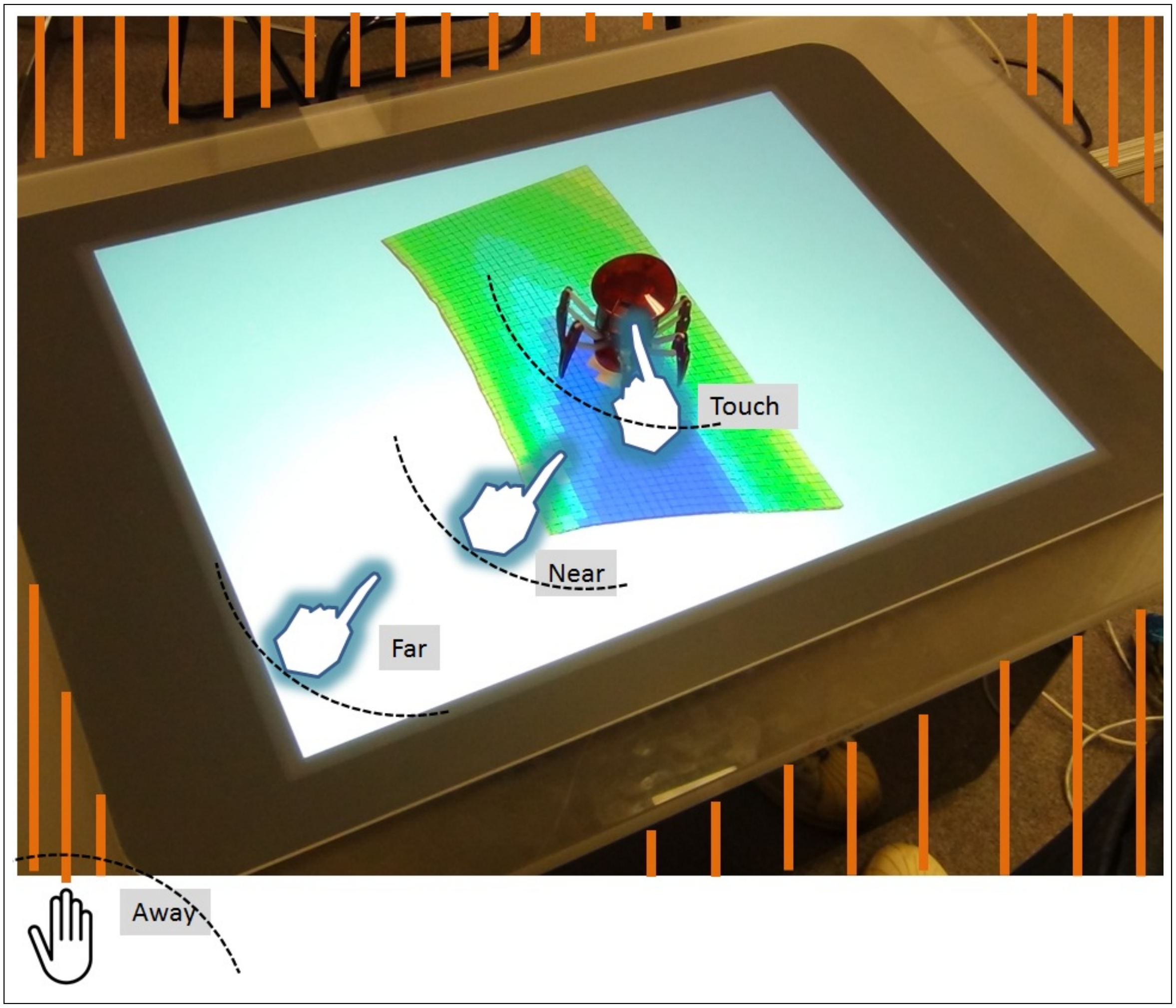


Figure 6.12: Four concentric proxemics zones around *Spidey*.

While we believe that our proxemics approach is well defined, it is not precise and does not include for exact, metric distance measurements. We were hoping to express the proxemics in a manner that would be meaningful to the user on the very visceral

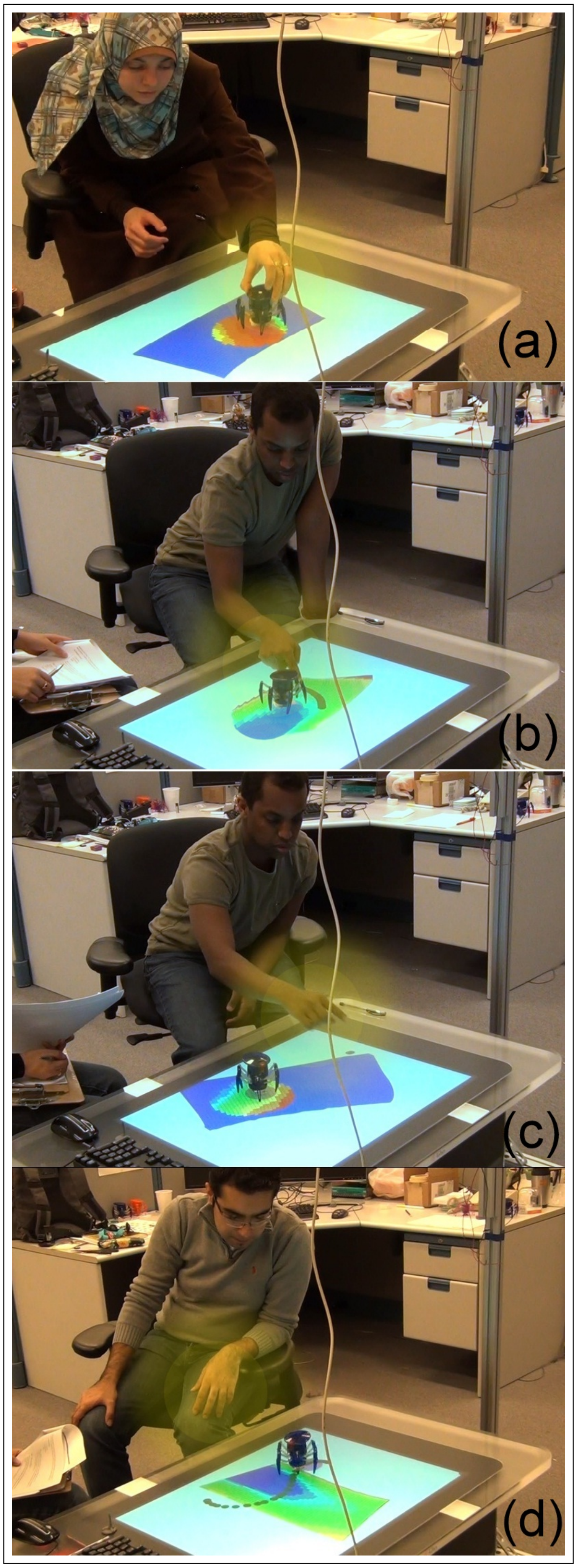


Figure 6.13: Interaction with a tabletop robot, proxemics zones: (a)touch, (b)near, (c)far and (d) away.

level: am I touching Spidey? (touch zone), can I touch Spidey instantly? (near zone), etc. Using hand length measurement units also provide freedom in dynamically adapting the range of each zone for every individual according to their hand length. Also, using the hand length allowed us to approximate the proxemics zone visually, without needing to calibrate and measure absolute metric distances between the users hand and Spidey (see Figure 6.13 for a view of participants interacting with Spidey in the different proxemics zones).

Given the definition of the four proxemics zones our analysis also included the possible transitions between the zones. Transitions can be from: near to far, far to away, near to away, touch to far, touch to near, touch to away (as well as the six opposite transition pairs: far to near, away to far, etc.). Following, our open coding analysis included, per each participant, all the proxemics zones and transitions between zones that occur during the interaction. For example Figure 6.14 shows a participant drawing a path starting from the near zone, transitioning to the far zone, and once Spidey begins to move, transitioning further, into the away zone.

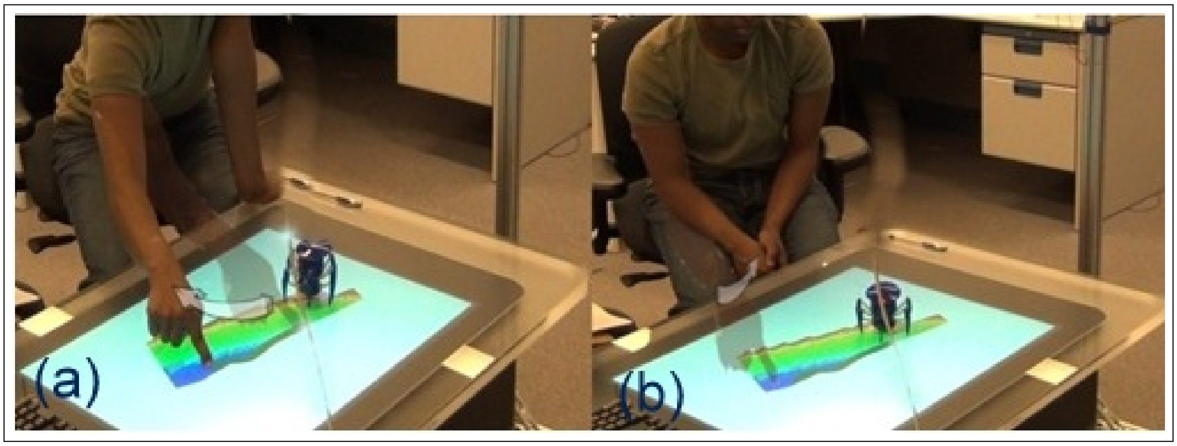


Figure 6.14: (a) Transition from near zone to far zone and then (b) from far zone to away zone.

6.6 Results

In this section we present results that emerged from our qualitative study pertaining to how individuals and a tabletop robot interact on a tabletops physical space. Our results emerge from the following four probing layers we employed in our analysis: proxemics/interaction pattern, responses to the pre-session questionnaire, responses to the post-session questionnaire and comments and thoughts the participants provided throughout the study via verbal comments. In this section we present our findings from the proxemics analysis, as well as from the pre- questionnaire and postquestionnaire. We include some verbal comments which are more anecdotal in nature later in the discussion section.

6.6.1 Proxemics

Analysing the study video recordings we coded for every participant all the proxemics zones and the transitions between them during all the study tasks (excluding the preliminary study admin demonstration sessions).

In total we coded 305 proxemics zones transitions. Eight participants had most of their interactions with *Spidey* occurring in the near zone, with only two participants choosing to be in the far zone for the majority of their interactions with the tabletop robot. Table 1 details the number of transitions based on the proxemics zone in which the transition started (at the top row) and the proxemics zone in which it ended (in each of the columns). The total at the bottom row shows the total number of instances of transitions that started from each zone, and the total at the rightmost column shows the total number of transition instances that ended in each zone. Beyond mapping the transitions, Table 1 is also helpful in understanding in which proxemics zone interactions occurred, since a transition that started in a specific proxemics

Table 6.1: Observed transition between proxemics zones.

From: To:	Touch	Near	Far	Away	Total
Touch	🟥	1	0	0	1
Near	5	🟥	28	69	102
Far	2	42	🟥	35	79
Away	1	63	59	🟥	123
Total	8	106	87	104	305

zone naturally implies that the user interacted with *Spidey* in that zone prior to the transition. We can see that most of the transitions started from the near zone, with transitions starting from the away zone being a close second, we can also see that majority of the transitions were to the away proxemics zone (Table 6.1).

6.6.2 Pre-session Questionnaire

In the pre-demo questionnaire, we asked our participants general questions regarding their current academic title, their area of research and if they had any previous experience with robots. Apart from these, the questionnaire included two specific questions regarding the participants thoughts about an assistant and how comfortable the participant is when using a new interface medium. To know more about the definition of an assistant in the minds of our participants, we asked them to define the word assistant using three short sentences or three words.

For the question regarding any previous experience of our participants with robots, 2 out of 10 participants mentioned having worked with Aibo, Sony robots, previously. None of the 5 participants from the domain had any previous experience with robots. Though some of our results might have been affected by this first time experience and added a confounding factor, we believe that the extensive evaluation methodology and the discussions that followed in the sessions indicate that the core of the results are fundamentally valid and can provide insights for prototypes of this sort.

To learn about how comfortable our participants are while interacting with new interface mediums, we asked them provide us a response by rating on a scale of 1-5 (1 indicates not at all comfortable and 5 is very comfortable) their acceptance to new technology. From the responses, the average for the domain engineers group was found to be 3.6 and that for the computer science group was found to be 4.2. The average of all the ten participants put together was found to be 3.9. Indicating, that generally all our participants were more inclined towards being comfortable with new interfaces.

The results from the question regarding the definition of the word assistant was found to be interesting. Figure 6.15 illustrates a visualization of the collection of words used by the participants to define the word assistant (this visualization was created using Wordle^{TM}, an online visualization tool). As can be seen in the figure, the most common word associated by our participants for an assistant was *task*, followed by *helpful*, *performing*, *punctual*, *smart* and *quick*.

Figure 6.15: Words used by the participants to define an assistant.

6.6.3 Post-session Questionnaire

Our post-session set of questionnaires (closely based on [2]) investigated various layers of participants perceptions of *Spidey* from a human-robot interaction perspective. The post-session questionnaire touched on various layers of perception of a robot fake, natural, artificial, lifelike, dead, alive, friendly etc. [2]. Out of the 21 questions four questions had mean values that were less than 3.0 (machine-like/animal-like: 2.40, moving rigidly/elegantly: 2.70, mechanical/organic: 2.70, artificial/lifelike: 2.80), lowering the overall mean value to 3.4524. One way repeated measure ANOVA based on 21 characteristics were performed and a statically significant characteristic effect was noted (F(20,180)=4.310, p¡0.001), indicating that responses for questions that relate to *Spidey's* physicality, e.g. relating to perceiving it as machine-like/animal-like (mean 2.40) were significantly different (and lower, or weaker, in their values) from questions that relate to *Spidey's* non-physical attributes, e.g. unfriendly/friendly (mean 3.80). Responses to whether participants liked or disliked *Spidey*, had a mean of 4.0, hinting at an overall successful acceptance of *Spidey* as likable by our participants. In the post-session questionnaire we also asked our participants if the interaction with *Spidey* felt like working with a companion, and the mean of the responses was found to be 3.50. One surprising outlier was a reservoir engineering domain expert who answered that as an application assistant *Spidey* scores 5 on companionship. While the overall responses were average, none of the participants failed *Spidey* on companionship.

At the end of the study, we also asked our participants to relate their recent experience with *Spidey* to their preliminary definition of an assistant. This helped us infer how *Spidey* fared in being accepted as an assistant by the participants. Table 6.2 shows the definitions provided by the participants and the corresponding mapping to their recent experience with *Spidey.* Table 6.2 for participant one can be read as follows: the first participant (first row of the table) defined assistant as someone who can be helpful, give suggestions and will not intrude while the participant is performing a task (column one). Mapping back his experience with *Spidey*, participant one mentioned that *Spidey* was helpful and also provided feedback (found definitions (a) and (b) to match *Spidey's* performance - column two), but found its performance intruding (column three - definition (c) did not fit his overall experience with *Spidey*) since he had to remove the robot from the working area to perform basic manipulation tasks (reason for why definition (c) was not found to be apt for *Spidey* - column four). As can be observed from Table 6.2 two participants found *Spidey* to match all their three definitions of an assistant. Five participants reflected that two of their assistant definitions matched their interactive experience with *Spidey*, and three participants found only one of their definitions to match the behaviour of *Spidey.*

The responses provided for why some of the participants definitions of an assistant did not match their experience (Table 6.2 - column four) can be broadly classified into three categories (a) implementation and interface issues (e.g. *"not really quick"*), (b) need for better tasks (*"Spidey is capable of understanding independently, but cannot suggest strategies or solutions"*) and (c) limited capabilities of *Spidey* (*"one of them was sharing ideas, that would not be applicable to robots"*). However, it is notable that none of our participants found *Spidey* to be completely unrelated to any of their earlier definitions of assistant.

6.7 Reflections

Interaction experience between two individuals or between an individual and an entity is formed by continuous reflection on the counterpart person or entity. We observed

Table 6.2: Word association response

Definition	**Agree**	**Disagree**	**Reason**
(a) Helpful; (b) give feedback or suggestions ; (c) doesn't intrude when doing a task	(a) and (b)	(c)	Intrusion just because removing *Spidey* and placing him again interrupts the work flow
(a) Helps organise parts of the job workflow; (b) helps doing simpler tasks; (c) helps making arrangement for the task to be done	(a) and (b)	(c)	It is able to do simple tasks and it helps a little for automation of some parts of the work
(a) Helpful; (b) quick; (c) smart	(a)	(b) and (c)	Not really quick or smart due to path calculation problem
(a) Team player; (b) punctual ; (c) sharing ideas	(a) and (b)	(c)	One of them was sharing ideas, that would not be applicable to robots
(a) Helpful ; (b) smart; (c) easy to work with	(c)	(a) and (b)	Not too helpful, but did what he was told
(a) Help me in achieving tasks that I need; (b) quick response; (c) well understands the tasks required	(b) and (c)	(a)	Helping achieving a task needs more improvement
(a) Listen; (b) act; (c) speak	(a) and (b)	(c)	It doesnt speak
(a) Helpful; (b) punctual; (c) responsible	(a), (b) and (c)	-	-
(a) Can answer queries; (b) can perform a task on my behalf for me; (c) makes performing task easier	(a), (b) and (c)	-	-
(a) Capable of understanding interactively ; (b) good output, can suggest; (c) independent as if he/she can do the rest of the job	(a) and (c)	(b)	*Spidey* is capable of understanding independently, but cannot suggest strategies or solutions

the interaction with *Spidey* from both a tabletop-robot point of view, as well as from a tabletop proxemics point of view. It is quite obvious that these two threads, the robot and the proxemics, are far from being independent, and are seamlessly integrated within the act of interaction. Attempting to divide our reflections to the *Spidey*-related, and the proxemics-related findings of our research we dedicate this section to discussion of the findings relating to *Spidey*, the robot; we discuss the findings relating to proxemics between the user and the tabletop robot only later, in the following section.

6.7.1 Spidey Reflections

This section presents the participants opinions of *Spidey*.

Liability, Physicality and Form

Our interactions are closely dependent on the way we perceive the other person or entity [36]. When sitting around a tabletop interacting with other people our experience can be expected to be quite different than when interacting with a robot walking upon the table.

Somewhat to our surprise *Spidey* was found to be quite acceptable and even likable going beyond its zoomorphic nature. Although, our selection of the spider form for *Spidey*, the reservoir engineering assistant was based on technical convenience and raises major concerns for some people (2 participants in particular in our study), it is important to note that when using an animal robot, it is necessary to keep in mind what the zoomorphic metaphor of the robot form conveys. In the case of *Spidey*, one needs to relate to arachnophobia, the fear of spiders. Personal experiences with robots resembling pets however have been observed to help facilitate better interaction with animal robots [78].

From our study, we found that 2 participants explicitly stated that spider robots may perhaps be “creepy” for few people, *“maybe its creepy for some people, because it is a spider”.* Three participants reflected on the spider robot as not being scary, but perhaps a bit of a misfit for the task context: *I dont have a problem with a spider really, but in the context of reservoir engineeringits off”.* Two of these participants suggested using a car robot or a robot with wheels instead of *Spidey*, and one suggested using an even thinner robotic entity, so that it does not cause any occlusions, or perhaps a robot that does not have legs.

From the perspective of being an assistant, the majority of the participants liked *Spidey* and thought that *Spidey* could meet their expectations or definitions of an assistant (*“It is able to do simple tasks and it helps a bit for automation of some parts of the work”*); however, we agree that our tasks were simple to bring out the assistive nature more explicitly. Although it has been observed that people prefer human-like robots for performing tasks [32], it was surprising to observe that even with an animal-like robot, that is neither a pet nor an obvious choice for form, majority (mean 3.50) of the participants associated and liked Spidey to be performing tasks for them (*“I should pay him, because he did his job right!”*).

Beyond the somewhat questionable spider zoomorphism participants were overall enthused about the ways the robots physicality and movement were integrated in the tasks, e.g. *“the feedback is pretty good, because its all physical”*, *“so this is like its head twisting?”* Although considering robots to be almost “alive” is not so surprising [29], it was interesting to observe similar effects with *Spidey*, *“Well its pretty visual, because its physical and it moves pretty quickly. I like the light (LED) actually; it gives a sort of personal feeling. He is not just a robot”*

During the discussions we observed how some of our participants would associate the kind of tasks to be done by *Spidey* with its physical appearance. 6 out of 10 participants explicitly associated the physical appearance of the robot to the task it was performing. We heard comments such as, *"how he can select? Because I feel that the only thing he can do is moving"*, *"its kind of intuitive, its cool, because of the way he looks, like five fingerslooks like a hand!"*. While the robot appearance and capabilities has some obvious implications [32], from the perspective of a tabletop it is important to note that the size of tabletop robots have to be small so that it does not occlude portions of the tabletop content.

Responsiveness and Accuracy

Our participants were commonly commenting on *Spidey* responsiveness and accuracy. One repeated comment related to the amount of time *Spidey* took to reach a destination: *"for a large model it may take timethere should be an optimization to detect the minimum path to reach the destination"*. Though, one participant commented that *Spidey's* speed was adequate *"it moves pretty quickly"*. Apart from speed, *Spideys* accuracy was also of a concern: *"if you want to do something like that, you want to be exact in the reservoir"*.

However, when considering the speed of a tabletop robot it is important to recognize that such an assistive robot cant actually be too fast: a very fast moving robot can probably be very disturbing to the user who is sharing the tabletop with the robot and may even raise safety concerns. Hence, an optimal value of speed needs to be determined based on the required performance expectations. Similarly, the amount of accuracy required depends on the kind of task the robot is performing. For example, if it just needs to move from one point to another, it could loosely follow a path to reach the destination, but if on its way to the destination it needs to find some information, it needs to be highly precise while doing so. From the perspective of reservoir engineering, both these factors were found to be very important but we suspect that the issue of accuracy and to some extent responsiveness may be less of a concern in other non-engineering related applications.

Gender association

Nine participants explicitly associated *Spidey* with a gender. The majority of these associations (8 out of 9) addressed *Spidey* as a male, e.g. *"he is looking!"*. One participant even used a somewhat more formal tone: *"I want to say, Mr. Robot go to that block of pressure"*. While studies have considered the gender of the participants [76] to understand the interaction of the robot, effect of gender roles in the design of robotic assistants we believe is still an open question. Overall, we believe that when interacting with the robot users crossed the barrier of willing suspension of disbelief [67], arguably treating *Spidey* as an autonomous assistant, and definitely not interacting with it as a remote controlled toy (which objectively it never ceased to be).

6.7.2 Proxemics Reflections

Overall we believe that our proxemics approach to the tabletop robot interaction proved to be helpful (though not perfect) in analyzing the patterns of proxemics related interaction that emerged in our studies. Below we discuss these patterns, focusing on both the user perspective as well as the robots view. (Note that the definition of the spatial characteristics of personal territory being used in this section is the same as that defined by Scott and Carpendale [64]).

Designing for User Proxemics

Most of the users were found to work within *Spideys* near proxemics zone for a majority of the interaction time, initiating or maintaining interaction with the robot by entering or sharing its personal territory. Possible explanation may relate to users simply feeling comfortable around *Spidey*, an explanation that is supported by *Spidey* generally being perceived to be quite likeable and as observed by Mumm and Mutlu [53] (physical distance decreased if the participant liked the robot). Another possible explanation for this seeming ease of working within the near proxemics zone may relate to users wanting to ensure that *Spidey* reaches its destination quickly, believing that working closely to it may nudge it along, helping it to be more efficient and quick: *"The reaction time, if I want to do something with it You want it to be done quickly"*.

However, we noticed that as *Spidey* began to move and came closer to an individuals personal territory, initiating a near proxemics interaction that perhaps was not desired by the human user, participants often moved away from *Spidey* and from the near proxemics zone, not allowing the robot to enter their personal territory. This transition from near to away, increasing instantly the physical distance from *Spidey*, was observed to be due to fear in the case of 2 participants, similar to observations by Murphy et al. [54] in the case of rescue robots. The rest were observed to simply transition wishing to sit back and observe *Spidey* as it performs its tasks. A characteristic that is somewhat similar to the observations by Scott and Carpendale [64] regarding personal territories sometimes being used to monitor a collaborators activity.

As stated previously, two participants chose to start the majority of their interactions from the far zone. Once again, this may be due to these 2 participants possibly finding *Spidey* to be scary or *"creepy"*. Other possible reasons could be that they wanted to observe *Spideys* actions from afar, or test the robots capabilities. A comment that hints that one of these participants perhaps felt less confident about *Spideys* ability said, *"you know I actually, intentionally, put the point here (far from the robot) because you (the study admin) showed a close one, maybe it is too easy for* *him"*.

Based on these preliminary observations, we believe that overall users felt comfortable interacting with *Spidey* in different proxemics zones, as long as they felt that they were the ones initiating and selecting the interaction proxemics zone, and thus are in control of the interaction experience. Participants on the other hand were generally less open and much more sensitive to the tabletop robot initiating a near proxemics zone interaction, and entering their own personal territory. We suspect that this sensitivity can scale if we had more than one robot working on the tabletop with the user. This suggests that tabletop robots need to be aware of their proxemics zones (by being aware of where the users hands are), and understand the implications of crossing boundaries and entering what the user may feel is a personal territory. Robots may be able to alleviate this problem by physical cues [62], for example by demonstrating physical hesitation (e.g. slowing down, rotating the head as if looking around) or gestures before entering what may be perceived by the user to be a near proxemics zone.

Designing for Robot Proxemics

We believe that our findings demonstrate that within the tabletop work environment *Spidey* was viewed as a collaborator, though one that is still limited in its capabilities. Assuming *Spidey's* point of view, the robot is working for the human user and performing tasks on her behalf. *Spidey* is never intentionally competing with the user for any tabletop resources or territory. It is quite content to allow the engineer to enter its personal territory. It is interesting to note that this overly generous proxemics approach by *Spidey* generally reflected in the participants reactions and in our findings, and is probably advisable for an assistive tabletop robot. However, is not unconceivable to think of scenarios (e.g. games) where a tabletop robot attempts to be assertive, or perhaps even somewhat adversary in its behavior, retreating when the user initiates a near zone interaction and thus creating a different user experience.

From the perspective of tasks, the proximity maintained between the user and the robot over time can influence future actions by the robot. If the robot can learn from the actions of the users, for instance if the first time a user approached the robot she chose the near zone, next time *Spidey* can remember that this user is comfortable interacting with it working nearby. Proximity can be considered one potential candidate to build a memory for the robot.

Apart from the role of a collaborator, *Spidey* is the main source for defining the proxemics zones. As it moves, the zones change, redefining the territories of the individual and its own, constantly. This change of proxemics zones boundaries by *Spidey* was found to profoundly impact the way an individual is interacting on the tabletop. The robot needs to be aware of the effect of its behavior, awareness that could help make the emerging interaction experience more comfortable and enjoyable.

6.8 Future Work

We believe that our current *Spidey* prototype is merely the first step in exploring the design space of assistive tabletop robots. The potential of it as an assistant and a tabletop robot has a lot more to explore and improve upon.

The short term goals for improving *Spidey* would be to revisit the wayfinding algorithm. A more stable and flexible algorithm has to be implemented to address the issues concerning selection of the shortest path and more accuracy.

Specific to the domain of reservoir engineering we are planning to redesign the tasks Spidey can assist with, and to further enhance the prototype validity as an acceptable assistant.

In the long term, we would like to explore the concept of having more than one assistive robot working on the tabletop with a group of users as well as to expand the robot capabilities to other tabletop tasks and applications beyond reservoir engineering.

6.9 Summary

We presented the design, implementation and assessment of a tabletop robotic assistant Spidey, which can perform tasks in the context of reservoir engineering. We also discussed proxemics between the user and the tabletop robot and suggested a proxemics model that addresses this new interaction experience. The goals of this prototype was to validate the impact that an active assistive agent can have while working in shared workspaces with reservoir engineers. Although, *Spidey* is still an early prototype, we beleive it has the potential to be both task oriented and socially valid in its role as an assistant. An overall above average acceptance for *Spidey* by our participants serves as a stepping stone for exploring this prototype further.

Chapter 7

Discussion

In this chapter we present a set of discussion points that evolved from our exploratory efforts in the previously described four experiments. We attempt to divide the discussions into two main categories reflecting on insights relevant to consider for both the virtual and physical exploration. At the end of the chapter we also present some open ended implications for future design.

7.1 Virtual Exploration

Chapters 3, 4 and 5 encompass the concept of virtual exploration on tabletops. The visualizations presented in Chapter 3 and 4, presented ways we could transform the reservoirs to facilitate further analysis and allow the engineer to gain further insights. Beyond gaining information about existing entities of a reservoir model, reservoir engineers also want to create new entities such as well trajectories to simulate new scenarios. Motivated by this, we presented three exploratory prototypes for well creation using the affordances of tabletops in Chapter 4. In this chapter we discuss some important highlights that emerged throughout the work presented in Chapters 3, 4 and 5.

7.1.1 Maintaining Context

Visualizations can be defined as visual representations of data that help viewers to gain awareness of the details. They present a new perspective for the original form. While we work to design a new presentation, it is perhaps important to understand that every pertinent information is part of a context. Irrespective of spatial or non-spatial data, a context always joins the pieces of the informations that is being communicated. Thus, perhaps an important aspect to remember while creating visualizations is the need to maintain context. In the simplest form, for 3D data, this can be understood as retaining the structure of a model while the area of interest is highlighted - focus and context. While maintaining context does not necessarily mean the entire structure of the model has to be retained, but the visualization should perhaps always hint at the original form. The advantage of maintaining atleast portions of the context is that it facilitates users to relate to the displayed information in comparison to the rest of the structure helping to gain further insights, instead of just seeing the relevant information as an independent entity. For instance, in a reservoir model, if a well trajectory was visualized simply as a line segment in space, the engineer can study the shape of the well and also learn about the perforation blocks of the well, however he cannot gain any information about the spatial location of the well, its neighbouring regions or if a new well can be placed in the surrounding region of this well. Having a mechanism that would allow users to quickly and effectively switch between seeing an entity independently and within a context is perhaps very important considering the extra information that can be gained. This particular aspect was seen to be of high importance in the context of reservoir engineering, where the engineers always looked for trends and neighbouring areas.

7.1.2 Visual Analytics

Thomas and Cook [82] defined visual analytics as a *"multidisciplinary field that includes the following focus areas: (i) analytical reasoning techniques, (ii) visual representations and interaction techniques, (iii) data representations and transformations, (iv) techniques to support production, presentation, and dissemination of analytical* *results"*. In short, visual analytics can be defined as the need for sense making. Following this definition, it is evident that visual analytics is important to almost any visualization. Multi-dimensional and multi-disciplinary data sets such as reservoir models are good examples of those which can take advantage of having visualizations that can be assisted via some analytic reasoning. Domains such as these, where several experts come together to make decisions using several parameters, it is important to have visualizations that can provide information which was otherwise going to be difficult to assimilate. For instance, combining the value of two or more properties to filter the regions of the reservoir is a difficult task to perform if the visualization supports only one mapping at a time. It would be difficult to disseminate the variation of two or more properties if the engineer had to learn about it using two different images. Thus visual analytics is an important aspect to keep in mind when designing visualizations for analysing the details of the reservoir model or any other multi-dimensional datasets.

7.1.3 Combining Spatial and Non-Spatial Presentations

A 2D or 3D model of a data is important to a visualization because we can map different representations to it. However, how many simultaneous mappings can we perform? To support ease of understanding, one mapping at a time is usually the maximum that a model can support. However, instances requiring multiple mappings simultaneously are not uncommon. For example, in a reservoir model an engineering may want to learn about the variation of a property along with its effect on the perforation blocks. If we accept this to be a design requirement, it is important to consider how can we support correlations or how can we present two or more mappings together simultaneously. A possible way to approach such design requirements could be to combine concepts of scientific visualization and information visualization.

While some relations are closely tied to the spatial information of the model, others can be presented as more abstract or non-spatial representations. Combining such presentations can assist viewers to gain further insights and also ease understanding. The viewers can take advantage of learning about different relations that influence the decision making process as well as apply another mapping to the model.

7.1.4 Interactivity

Interactivity is perhaps one of the most obvious requirements of any visualization. Interactivity is important to manipulate and analyze the presented information and it is seen to be of particular importance for large datasets and 3D models [20]. Interaction techniques have a wide range. While clicking on a button to get a text message can be an instance of a simple form of interaction and deformation of a 3D model represent a more difficult level of interaction, both are important to learn more about the visuals being presented on the screen. From a reservoir engineering perspective, interactive visualizations are very important. Looking at a static 3D model cannot take the engineer any further with the analysis or decision making process. Interactions such as probing cells to learn about their property values or interactions to select and view different well trajectories are very important. Digital tabletops can further enhance these interactions by allowing users to interact using physical touch and other physical objects.

7.2 Physical Exploration

Chapter 6 presented the exploration of proxemics in the case of a tabletop robot - *Spidey*. In this chapter we present a set of discussion points that emerged from the stages of design, implementation and evaluation of our *Spidey* prototype.

7.2.1 Physical Awareness

The most obvious and first observed characteristic of a physical entity is its physicality. The appearance of a physical entity alerts us of its presence in our environment. When working around a table, if we introduced a robot that can walk around and perform tasks, people are surely going to note its presence. This physical awareness of robotic entities can be advantageous in various scenarios of interaction such as teaching or presentation.

The physicality of the robot allows us to think of it as a representative of another, in other words a physical imprint of another. For instance, a task such as playback (Chapter 8), where the robot can play back a recorded sequence of actions performed by an expert at another time and/or at another place is powerful. We almost think of the robot to be a representative of the expert, bringing the remote persons presence to life.

Level of awareness is also another important factor to consider. The form of the robot allows it to telegraph its intentions via various means. If the robot is appearance constrained [12], it could communicate via movement, orientation, color and sound. However, if the robot has some human features it could communicate via body language [62]. These different ways of communication also impact the kind of awareness we have of the physical entity and can be used in various tabletop involving applications such as games, story building or more exploratory applications.

7.2.2 Social Impact

Robots have been introduced in various environments such as home [29], schools [43] and hospitals [27]. They have been observed to socially impact humans interacting with them [15] to an extend we believe them to be almost alive. We saw similar results from our study (Alive/Dead: mean= 4.0/5.0) and heard a participant explicitly mention that the robot felt more personal and beyond just a robot. The social impact of the robot is often expressed via emotional states such as scared, likeable, acceptable etc. Such emotional states in conjunction with other factors play an important role in measuring how open the users will be to the acceptance of the robot in the interactive environment. The perception of the robot may not always be positive. Users maybe afraid of the presence of the robot, resulting in a distant interaction with the robot or worse a rejection of its presence. Hence it is important to keep in mind the influence of the robot on the participant socially while designing tabletop robot environments.

7.2.3 Potential Roles of the Physical Entity

Physical entities on a tabletop can have sliding roles. Static tangibles have been used to enhance interactions on the tabletop. They help to define a modality, can be associated with elements which can be passed around the table to be viewed by others or they can be used to define some interaction. However, interactive physical entities or interactive tangibles widen the spectrum of roles they can play. The the simple fact that the physical entity can move around and present a reaction for every action, allows us to look at it as a helper, peer, mediator or even a mentor. The non-tiring nature of a robot can be helpful in performing tasks that are cumbersome or repetitive, so that the user can concentrate on performing other tasks of greater importance, improving productivity at workplace. The toy like appearance of robots can be taken advantage of in interactive scenarios involving children. Digital tabletops further promote taking advantage of such physical entities since they are already accepted to present a more engaging and intriguing environment, attracting individuals to work around it. If to such environments we introduce other interactive entities they can further extend the kind of interactive applications that can be explored.

7.2.4 Influence on Interaction

Tabletops have mostly been associated with physical touch and static tangibles. However, robots are perhaps a very different class of physical entities. Their physical presence, ability to be surrogate of another and their potential to invoke emotions in humans interacting with them distinguishes them from regular tangible user interfaces. When such entities are introduced into interactive environments such as tabletops, they can have strong influences on those working at the table. The reactions can be positive or negative, influencing the way of interaction. The influence is perhaps stronger on a tabletop due to the confined space of a tabletop. There is predefined maximum distance that can be maintained between the user and the tabletop robot and such proximity will influence the interaction. The perception of the users regarding the robot and the proximity in interaction are perhaps two major criteria for determining the interaction protocols.

7.3 Implications for Design

The following section attempts to present a set of high level design implications which can perhaps help for future tabletop researches. We believe that this list is open ended and has scope for inclusions and removals based on further research. Some of the heuristics have been previously discussed by Sultanum et al. [73, 75].

7.3.1 Expert Advice

Applied research always revolves around research problems being faced by a particular domain. In this thesis we explored through some open ended problems faced by the domain of oil and gas. From our investigations of different threads connected to exploring 3D reservoir model, we observed that expert advice and suggestion is fundamental to identifying various aspects of what should be presented as the final result. Often the phase of feedback and development is recursive, involving regular updates to the prototypes. Some instances of why and when such advices can be useful are as follows: consider the task of viewing a well. For an expert, there is always a task associated behind every element they investigate. It is important to learn about this task so that a correct and meaningful representation can be presented for further decision making. Such collaborations can also help to identify more specific visualization aspects such as what is the context for visualization and how much context has to be maintained to present more complete information.

7.3.2 Facilitate 3D exploration

"The need to easily access and investigate internal regions of the reservoir must be the primary concern of the tabletop interaction designer. On the other hand, given that reservoir models are 3D entities, external navigation and situational awareness must be supported at all times as well. Since the tabletop environment is not a true 3D environment, the interaction designer should be conscious to the tradeoff between the two, and the need to properly balance between the reservoir's internal interaction mechanisms and its external navigation and manipulation tools. Having a quick and effective mechanism to access and explore hidden data is an invaluable resource in attempting to understand a reservoir's behavior but ideally should not undermine the user's overall awareness of the reservoir and ability to manipulate and navigate it" [73, 75].

7.3.3 Facilitate Correlation

"Designers should provide tools that directly support flexible comparisons and correlation of data within the reservoir environment. The interactive environment should facilitate exploratory and non-restrictive online comparison of its various elements. Throughout the study, for instance, we observed many references to comparison and association, in the most varied renditions. Users wanted to compare properties, looking for possible correlations that might make one affect the other. Supporting such comparison mechanisms is an essential element for experts to gain knowledge about a reservoir, and visualization tools should aim in providing and simplifying these processes" [73, 75].

7.3.4 Providing Control

"Due to the depth and multidimensionality of reservoir data, there are innumerous ways it can be manipulated. Naturally, in the perspective of interface design, particular effort must be put into making these manipulations easy to perform, which often means that a few constraints are applied in order to simplify the interaction; nonetheless, the interface should provide users with enough power to perform more generic, precise operations. An over restraining interface that is easy to use will more likely fail to uncover important aspects of the data" [73, 75].

7.3.5 Challenges of 3D sketching

From our sketching experiments we observed there are several challenges involved in the process of creating entities such 3D wells. Not only are the depth perception problems challenging, to create different well configurations we need to work towards more preciseness and more flexible 3D space navigation. The design critique helped us identify problems such as need for better visual cues for areas of sketching, better management of visual elements etc. From the tabletop viewpoint it is important to consider associating each task to a single physical element or gesture unless its a natural extension to perform another activity. For instance, using single finger for sketching and another element for rotation of planes may serve better than using single finger for sketching and rotation. However, it is important to keep in mind that growth in gesture definitions may not be the most suitable extensions to such problems.

7.3.6 Inclusion of physical entities

Tabletop explorations can benefit from including physical objects. Their inclusion in some way is a straight forward extension to our usual practices of involving physical objects for interaction on a traditional table. Although our exploration was limited to using a tabletop robot for the domain of reservoir engineering, and simple use of tangibles to define modalities and improve the visualization, there are perhaps several scenarios when physical entities can be useful, e.g. robots can be useful for scenarios involving children, since toy robots might work better for attracting a child's attention, it could be used in scenarios of teaching and learning. Physical entities can also facilitate data exchange in a more engaging fashion, perhaps helping in the overall user experience.

7.3.7 Role of proxemics

People and physical entities for enhancing interactions are essential components to interacting on a tabletop. We believe it is important to learn about patterns of interactions among people as well as between people and the physical entities. It helps us learn about design implications of how elements can be arranged in the tabletop virtual space and how the physical medium of the tabletop can be arranged so that the interaction is not intruding and a comfortable experience for those interacting with it.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

In this thesis we presented our research efforts in exploring the benefits of tabletops as an interaction medium applied to the activities involved in discovering further insights about reservoir models. Through the design, implementation and evaluation of four prototypes - *Uncertainty visualization* - a set of visualization techniques combining information visualization and scientific visualization for exploring reservoir models in the context of uncertainty; *Focus and context for wells* - a visualization technique for visualizing well trajectories; set of exploratory prototypes for creating new well trajectories and *Spidey* - a robotic tabletop assistant, we gained further insights about the potential of these exploration concepts and the impact they have in the process of learning more about the reservoirs.

Revisiting our thesis contributions, we presented:

1. **A set of user evaluations reflecting on the user's insights about the validity and usefulness of a set of visualizations for exploring reservoir models** : In Chapters 3 and 4 we presented detailed formal user studies reflecting on the potential of our visualization techniques in terms of usability, usefulness, limitations and ideas for improvement.

2. **Novel interactive 3D visualizations for reservoir simulation post-processing models, using tabletop environment** : In Chapter 3 we presented the design, implementation and evaluation of a set of visualization variations combin-

ing information and scientific visualization concepts to support the investigation of reservoir models in the context of uncertainty. Chapter 4 presented a focus and context approach for visualizing well trajectories in the context of different geological properties.

3. **Other exploratory prototypes investigating ways for creating 3D well trajectories** : Chapter 5 presented three exploratory prototypes for creating well trajectories using the affordances of tabletops. We also present a discussion of each of the three techniques.

4. **User investigations reflecting on the potential of introducing a tabletop robotic assistant in a tabletop interactive environment**: Chapter 6 presents the design, implementation and evaluation of a tabletop robotic assistant - *Spidey*. The evaluation has a two fold contribution, detailing aspects of the tabletop robot and the proxemics in interaction with a tabletop robot.

5. **A tabletop robotic assistant prototype for assisting in a set of valid tabletop reservoir exploration tasks** : Chapter 6 presents *Spidey*, a tabletop robotic assistant designed to collaborate with tabletop users and assist in performing a set of valid engineering tasks in the tabletop interactive environment.

8.2 Future Work

Chapters 3,4, 5 and 6 apart from the design, implementation and results, discussed the immediate future work specific to each of the concepts presented. In this section we present more general research directions for the future.

8.2.1 Collaboration

Tabletops are inherently collaboration supportive. However, collaborative tasks can be classified into the following two categories: (a) Observational: wherein a group of people gather around the table, but only one individual at a time is the active member for interacting with the digital content, while others can only observe [73]. The work presented in this thesis belongs to this category. The second category can be called (b)Active: which presents scenarios where more than one individual can be an active member and all work together simultaneously [69, 66].

Active collaborations is perhaps more relevant to facilitate team work in comparison to observational. Also, in domains like oil and gas, which are multidisciplinary, it is very important to have systems that would allow every individual to be an active member of the interaction. However, the kind of tasks that could really promote such collaborative environments are yet to be explored. To learn about the advantages of such systems and learn about the domain experts expectations, it would be necessary to conduct collaborative task oriented studies.

Another aspect of collaboration is the consideration about which other entities can be involved in the collaboration. While, *Spidey* presented one instance of a non-human entity that could be part of the collaborative environments, we believe the functionality of tabletop robots can reach very different levels. A humanoid working collaboratively at the tabletop with other users would present very different scenarios than working with appearance and capability constrained robots like *Spidey*. In the future, it would be interesting to study coupling more advanced robotic assistants to learn about the collaboration effects between experts and other physical agents.

8.2.2 Coupling Other Interaction Devices

Collaboration with a tabletop can either be co-located or remote. Nevertheless, with the rapid advances in technology and devices, tabletop can not be the only device involved in collaboration. In a co-located interaction, there are only so many people that can gather around a table to discuss the information presented by the digital content. The size of the tabletops could be scaled, however there would still be a limit. In a remote collaboration, this aspect becomes more evident. The remote collaborator could be an individual who has access only to a tablet or other touch devices such as phone. In such scenarios its important to consider how other devices can be coupled to allow for seamless integration of communication between individuals.

An instance which could perhaps take advantage of such coupling is in cases where engineers perform their analysis and can send results to a remote expert. A very common scenario, in most big workplaces. The expert could access the results on his tablet or phone and return back his/her feedback with annotations or modifications for the engineer to continue working.

Some aspects to consider for such scenarios are: can a more generalized gesture set be build for maintaining some consistency in interaction?. What kind of tasks could benefit from coupling various types of devices? and How can we address the technical limitations of the different types of devices?. We believe such coupling can unveil aspects of how communication could foster new ideas and perhaps help productivity at work.

8.3 Final Words

In this thesis we presented the design, implementation and evaluation of two distinct sets of prototypes reflecting on the usage of tabletops as an interaction medium. The need for interactive exploration in the domain of oil and gas made it an apt context for our work. The evaluation results of all these prototypes shed light on the potential of exploring interaction mediums such as tabletops, from different perspectives, for the exploration of rich multi-dimensional and multi-disciplinary data sets. Although there is wide scope for improvement and extensions exploring the spectrum of different interaction styles on the tabletops, we hope that our research would serve to be useful and inspiring for future endeavours leading to new solutions.

Bibliography

[1] Atlantic petroleum. http://www.petroleum.fo/Default.aspx?pageid=8424.

[2] Computer modelling group ltd. http://www.cmggroup.com/software/results.html.

[3] Halliburton. http://www.halliburton.com/ps/default.aspx.

[4] The information store and infusion development. www.istore.com/Surface.html.

[5] International association of oil and gas producers (ogp). http://www.ogp.org.uk/publications/environment-committee/environmental-management-in-oil-and-gas-exploration-and-production.

[6] Schlumberger. http://www.slb.com/services/software/geo/petrel/simulation.aspx.

[7] Peter Aigner and Brenan J. McCarragher. Shared control framework applied to a robotic aid for the blind. In *Proc. of the 1998 IEEE International Conference on Robotics and Automation (ICRA '98)*, pages 717–722, 1998.

[8] Dave Astle and Kevin Hawkins. *Beginning OpenGL Game Programming*. Course Technology, 2004.

[9] Seok-Hyung Bae, Ravin Balakrishnan, and Karan Singh. Ilovesketch: as-natural-as-possible sketching system for creating 3d curve models. In *Proc. of the 21st annual ACM symposium on User interface software and technology (UIST '08)*, pages 151–160, 2008.

[10] Christoph Bartneck, Elizabeth Croft, Dana Kulic, and Susana Zonghbi. Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence and perceived safety of robots. *International Journal of Social Robotics*, 1:71–81, 2009.

[11] Jacques Bertin. *Semiology of Graphics: Diagrams, Networks, Maps.* Esri Press, 2011.

[12] Cindy L. Bethel and Robin R. Murphy. Affective expression in appearance constrained robots. In *Proc. of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction (HRI '06)*, pages 327–328, 2006.

[13] Dale Bowering. Data visualization centers. *Oil & Gas Executive*, 2(2):32–35, 1999.

[14] Scott Brave and Andrew Dahley. intouch: a medium for haptic interpersonal communication. In *Proc. of the extended abstracts on Human factors in computing systems: looking to the future (CHI EA'97)*, pages 363–364, 1997.

[15] Rodney Brooks. *Flesh and Machines: How Robots Will Change Us.* Vintage, 2003.

[16] Stephan Bruckner. *Interactive Illustrative Volume Visualization.* PhD thesis, TU-Vienna, 2008.

[17] Sheelagh T. Carpendale, David J. Cowperthwaite, and F. David Fracchia. Extending distortion viewing from 2d to 3d. *IEEE Computer Graphics and Applications*, 17(4):42–51, 1997.

[18] Sheelagh T. Carpendale and Catherine Montagnese. A framework for unifying presentation space. In *Proc. of the 14th annual ACM symposium on User interface software and technology (UIST '01)*, pages 61–70, 2001.

[19] Laurent Castanie, Bruno Lvy, and Fabien Bosquet. Volumeexplorer: Roaming large volumes to couple visualization and data processing for oil and gas exploration. In *Proc. of the IEEE Visualization (VIS '05)*, pages 247 – 254, 2005.

[20] Mei C. Chuah and Steven F. Roth. On the semantics of interactive visualizations. In *Proc. of the 1996 IEEE Symposium on Information Visualization (INFOVIS '96)*, pages 29–36, 1996.

[21] Jonathan M. Cohen, Lee Markosian, Robert C. Zeleznik, John F. Hughes, and Ronen Barzel. An interface for sketching 3d curves. In *Proc. of the 1999 symposium on Interactive 3D graphics (I3D'99)*, pages 17–21, 1999.

[22] Luca Cosentino. *Intergrated Reservoir Studies*. Technip, 2001.

[23] Rene Cosse. Basics of reservoir engineering. *Technip*, 1993.

[24] Nadine Couture, Guillaume Rivire, and Patrick Reuter. Geotui: a tangible user interface for geoscience. In *Proc. of the 2nd international conference on Tangible and embedded interaction (TEI '08)*, pages 89–96, 2008.

[25] Michael F. Deering. Holosketch: a virtual reality sketching/animation tool. *ACM Transactions on Computer-Human Interaction*, 2(3):220–238, 1995.

[26] Paul H. Dietz and Darren Leigh. Diamondtouch: a multi-user touch technology. In *Proc. of the 14th annual ACM symposium on User interface software and technology (UIST '01)*, pages 219–226, 2001.

[27] John M. Evans. Helpmate: an autonmous mobile robot courier for hospitals. In *Proc. of the 1994 IEEE/ RSJ/ GI International Conference on Intelligent Robots and Systems (IROS '94)*, pages 1695–1700, 1994.

[28] F. J. T. Floris, M. D. Bush, M. Cuypers, F. Roggero, and A-R. Syversveen. Methods for quantifying the uncertainty of production forecasts: a comparative study. *Petroleum Geoscience*, 7:87–96, 2001.

[29] Jodi Forlizzi. How robotic products become social products: an ethnographic study of cleaning in the home. In *Proc. of the ACM/IEEE international conference on Human-robot interaction (HRI '07)*, pages 129–136, 2007.

[30] George W. Furnas. Generalized fisheye views. In *Proc. of the SIGCHI conference on Human factors in computing systems (CHI '86)*, pages 16–23, 1986.

[31] Rocco Gasteiger, Mathias Neugebauer, Oliver Beuing, and Bernhard Preim. The flowlens: A focus-and-context visualization approach for exploration of blood flow in cerebral aneurysms. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2183–2192, 2011.

[32] Jennifer Goetz. Matching robot appearance and behavior to tasks to improve human-robot cooperation. In *Proc. of the Workshop on Robot and Human Interactive Communication*, pages 55–60, 2003.

[33] Michael A. Goodrich and Alan C. Schultz. Human-robot interaction: a survey. *Foundations and Trends in Human-Computer Interaction*, 1(3):203–275, 2007.

[34] Saul Greenberg, Nicolai Marquardt, Till Ballendat, Rob Diaz-Marino, and Miaosen Wang. Proxemic interactions: the new ubicomp? *Interactions*, 18(1):42–50, 2011.

[35] Cheng Guo, James E. Young, and Ehud Sharlin. Touch and toys: new techniques for interaction with a remote group of robots. In *Proc. of the 27th international conference on Human factors in computing systems (CHI '09)*, pages 491–500, 2009.

[36] Edward T. Hall. *The Hidden Dimension*, volume 6. Doubleday, 1966.

[37] John Harris, James Young, Nicole Sultanum, Paul Lapides, Ehud Sharlin, and Mario C. Sousa. Designing snakey: a tangible user interface supporting well path planning. In *Proc. of the 13th IFIP TC 13 international conference on Human-computer interaction (INTERACT '11)*, pages 45–53, 2011.

[38] Michael Hillman, Karen Hagan, Sean Hagan, Jill Jepson, and Roger Orpwood. The weston wheelchair mounted assistive robot - the design story. 20(2):125–132, 2002.

[39] Takeo Igarashi, Satoshi Matsuoka, and Hidehiko Tanaka. Teddy: a sketching interface for 3d freeform design. In *Proc. of the 26th annual conference on Computer graphics and interactive techniques (SIGGRAPH '99)*, pages 409–416, 1999.

[40] Hiroshi Ishii. The tangible user interface and its evolution. *Communications*, 51(6):32–36, 2008.

[41] C. Skourup J. Pretlove and J. Gunnar. Robotics for integrated remote operations. In *Proc. of the Society of Petroleum Engineers Intelligent Energy Conference and Exhibition*, 2010.

[42] M.D. Jackson, G.J. Hampson, J.H. Saunders, A. El-Sheikh, G.H. Graham, and B.Y.G. Massart. Surface-based reservoir modelling for flow simulation. *In Press: Geological Society of London Special Publication*, 2012.

[43] Takayuki Kanda, Takayuki Hirano, Daniel Eaton, and Hiroshi Ishiguro. Interactive robots as social partners and peer tutors for children: a field trial. *Human-Computer Interaction*, 19(1):61–84, 2004.

[44] Aleksander Krzywinski, Haipeng Mi, Weiqin Chen, and Masanori Sugimoto.

Robotable: a tabletop framework for tangible interaction with robots in a mixed reality. In *Proc. of the International Conference on Advances in Computer Enterntainment Technology (ACE '09)*, pages 107–114, 2009.

[45] Ove Daae Lampe, Carlos D. Correa, Kwan-Liu Ma, and Helwig Hauser. Curve-centric volume reformation for comparative visualization. *IEEE Transactions on Visualization and Computer Graphics*, 15(6):1235–1242, 2009.

[46] Paul Lapides, Ehud Sharlin, Mario C. Sousa, and Lisa Streit. The 3d tractus: A three-dimensional drawing board. In *Proc. of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP '06)*, pages 169–176, 2006.

[47] Jakob Leitner, Michael Haller, Kyungdahm Yun, Woontack Woo, Maki Sugimoto, and Masahiko Inami. Incretable, a mixed reality tabletop game experience. In *Proc. of the 2008 International Conference on Advances in Computer Entertainment Technology (ACE '08)*, pages 9–16, 2008.

[48] Simon P. Levine, David A. Bell, Lincoln A. Jaros, Richard C. Simpson, Yoram Koren, and Johann Borenstein. The navchair assistive wheelchair navigation system. *IEEE Transactions on Rehabilitation Engineering*, 7:443–451, 1999.

[49] Gaoming Li and Albert C. Reynolds. Uncertainty quantification of reservoir performance predictions using a stochastic optimization algorithm. *Computational geosciences*, 15:451–462, 2011.

[50] Ulisses T. Mello, M. Lucente, and T. Jackman. Using visualization and parallel computing for interactive reservoir characterization. *Offshore Technology Conference*, 1997.

[51] Tomas Mller and Eric Haines. *Real-Time Rendering.* AK Peters, 1999.

[52] Shahab D. Mohaghegh. Quantifying uncertainities associated with reservoir simulation studies using surrogate reservoir models. In *Proc. of the SPE Annual Technical Conference and Exhibition*, 2006.

[53] Jonathan Mumm and Bilge Mutlu. Human-robot proxemics: physical and psychological distancing in human-robot interaction. In *Proc. of the 6th international conference on Human-robot interaction (HRI '11)*, pages 331–338, 2011.

[54] Robin R. Murphy, Dawn Riddle, and Eric Rasmussen. Robot-assisted medical reachback: a survey of how medical personnel expect to interact with rescue robots. In *Proc. of the 13th IEEE International Symposium on Robot & Human Interactive Communication (RO-MAN '04)*, pages 301–306, 2004.

[55] Alan W. Paeth. *Graphics Gems 5.* Academic Press, 1995.

[56] Esben W. Pedersen and Kasper Hornbk. Tangible bots: interaction with active tangibles in tabletop interfaces. In *Proc. of the conference on Human factors in computing systems (CHI '11)*, pages 2975–2984, 2011.

[57] Catherine Plaisant, Allison Druin, Corinna Lathan, Kapil Dakhane, Kris Edwards, Jack M. Vice, and Jaime Montemayor. A storytelling robot for pediatric rehabilitation. In *Proc. of the fourth international ACM conference on Assistive technologies (Assets '00)*, pages 50–55, 2000.

[58] D. K. Ponting. Corner point geometry in reservoir simulation. In *Proc. of the 1st European Conference on Mathematics of Oil Recovery*, pages 45–65, 1989.

[59] L. A. Rupp. The role of manned underwater vehicles and remote-controlled

robots in deep water oil exploration. In *Proc. of the 8th World Petroleum Congrees*, 1971.

[60] S. I. Sagatun and T. I. Fossen. Computer-controlled underwater robot manipulator. In *Proc. of the Offshore Technology Conference*, 1990.

[61] Malcolm Sambridge, Caroline Beghein, Frederik Simons, and Roel Snieder. How do we understand and visualize uncertainity? *The leading Edge*, 25(5):542–546, 2006.

[62] Mark Scheeff, John Pinto, Kris Rahardja, Scott Snibbe, and Robert Tow. Experiences with sparky, a social robot. In *Proc. of the Workshop on Interactive Robotics and Entertainment (WIRE '00)*, 2000.

[63] Stacey D. Scott and Sheelagh Carpendale. Guest editor's introduction: Interacting with digital tabletops. pages 24–27, 2006.

[64] Stacey D. Scott and Sheelagh Carpendale. *Theory of Tabletop Territoriality*, pages 375–406. Springer, 2010.

[65] Stacey D. Scott, Sheelagh T. Carpendale, and Kori M. Inkpen. Territoriality in collaborative tabletop workspaces. In *Proc. of the ACM Conference on Computer-Supported Cooperative Work (CSCW '04)*, pages 294–303, 2004.

[66] Stacey D. Scott, Karen D. Grant, and Regan L. Mandryk. System guidelines for co-located, collaborative work on a tabletop display. In *Proc. of the eighth conference on European Conference on Computer Supported Cooperative Work (ECSCW '03)*, pages 159–178, 2003.

[67] Noel Sharkey and Amanda Sharkey. Artificial intelligence and natural magic. *Artificial Intelligence Review*, 25(1-2):9–19, 2006.

[68] H.L. Shatto. Rov dilling support for deep water. In *Proc. of the Offshore Technology Conference*, 1984.

[69] Chia Shen, Frdric Vernier, Clifton Forlines, and Meredith Ringel. Diamondspin: an extensible toolkit for around-the-table interaction. In *Proc. of the SIGCHI conference on Human factors in computing systems (CHI '04)*, pages 167–174, 2004.

[70] M. C. Sousa. Slide notes, university of calgary. http://pages.cpsc.ucalgary.ca/ mario/courses/591-691-W11/.

[71] R.M. Srivastava. The interactive visualization of spatial uncertainity. In *Proc. of the Society of petroleum engineers (SPE '94)*, pages 87–95, 1994.

[72] Anselm L. Strauss and Juliet Corbin. *Basics of Qualitative Research : Techniques and Procedures for Developing Grounded Theory.* SAGE Publications, September 1998.

[73] Nicole Sultanum. Exploring novel interfaces for 3d visualization of reservoir simulation post-processing data. Master's thesis, University of Calgary, 2011.

[74] Nicole Sultanum, Ehud Sharlin, Mario C. Sousa, Daniel N. Miranda-Filho, and Rob Eastick. Touching the depths: introducing tabletop interaction to reservoir engineering. In *Proc. of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*, pages 105–108, 2010.

[75] Nicole Sultanum, Sowmya Somanath, Ehud Sharlin, and Mario C. Sousa. "point it, split it, peel it, view it": techniques for interactive reservoir visualization on tabletops. In *Proc. of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '11)*, pages 192–201, 2011.

[76] Dag Sverre Syrdal, Kheng Lee Koay, Mick L. Walters, and Kerstin Dautenhahn. A personalized robot companion? - the role of individual differences on spatial preferences in hri scenarios. In *Proc. of the 16th IEEE International Symposium on Robot & Human Interactive Communication (RO-MAN '07)*, pages 1143–1148, 2007.

[77] T. Taerum, Mario C. Sousa, Faramarz F. Samavati, S. Chan, and Joseph R. Mitchell. Real-time super resolution contextual close-up of clinical volumetric data. In *Proc. of the Eurographics/IEEE - VGTC Symposium on Visualization (EuroVis '06)*, pages 347–354, 2006.

[78] Leila Takayama and Caroline Pantofaru. Influences on proxemic behaviors in human-robot interaction. In *Proc. of the 2009 IEEE/RSJ international conference on Intelligent robots and systems (IROS '09)*, pages 5495–5502, 2009.

[79] Laura Tateosian, Helena Mitsov, Brendan Harmon, Brent Fogleman, Katherine Weaver, and Russel S. Harmon. Tangeoms: Tangible geospatial modeling system. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):1605–1612, 2010.

[80] Lucia Terrenghi, David Kirk, Abigail Sellen, and Shahram Izadi. Affordances for manipulation of physical versus digital media on interactive surfaces. In *Proc. of the SIGCHI conference on Human factors in computing systems (CHI '07)*, pages 1157–1166, 2007.

[81] Marco R. Thiele, Rod P. Batycky, and Darryl H. Fenwick. Streamline simulation for modern reservoir engineering workflows. *Journal of Petroleum Technology*, 2010.

[82] James J. Thomas and Kristin A. Cook. A visual analytics agenda. *IEEE Computer Graphics and Applications*, 26(1):10–13, 2006.

[83] John Underkoffler and Hiroshi Ishii. Urp: a luminous-tangible workbench for urban planning and design. In *Proc. of the SIGCHI conference on Human factors in computing systems (CHI'99)*, pages 386–393, 1999.

[84] Ivan Viola, Armin Kanitsar, and Eduard Grller. Importance-driven volume rendering. In *Proc. of the conference on Visualization (VIS '04)*, pages 139–146, 2004.

[85] Daniel Vogel and Ravin Balakrishnan. Interactive public ambient displays: transitioning from implicit to explicit, public to personal, interaction with multiple users. In *Proc. of the 17th annual ACM symposium on User interface software and technology (UIST '04)*, pages 137–146, 2004.

[86] Kazuyoshi Wada, Takanori Shibata, Tomoko Saito, and Kazuo Tanie. Analysis of factors that bring mental effects to elderly people in robot assisted activity. In *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '02)*, pages 1152–1157, 2002.

[87] Michael L. Walters, Kerstin Dautenhahn, Rene te Boekhorst, Kheng L. Koay, Dag S. Syrdal, and Chrystopher L. Nehaniv. An empirical framework for human-robot proxemics. In *Proc. of the New Frontiers in Human Robot Interaction*, pages 144–149.

[88] Colin Ware and Marlon Lewis. The dragmag image magnifier. In *Proc. of the conference companion on Human factors in computing systems (CHI '95)*, pages 407–408, 1995.

[89] Craig M. Wittenbrink, Alex T. Pang, and Suresh K. Lodha. Glyphs for visualizing uncertainity in vector fields. *IEEE transactions on visualization and computer graphics*, 2(3):266–279, 1996.

[90] Min Xin, Ehud Sharlin, and Mario C. Sousa. Napkin sketch: handheld mixed reality 3d sketching. In *Proc. of the 2008 ACM symposium on Virtual reality software and technology (VRST '08)*, pages 223–226, 2008.

[91] James Everett Young, Richard Hawkins, Ehud Sharlin, and Takeo Igarashi. Toward acceptable domestic robots: Applying insights from social psychology. *International Journal of Social Robotics*, 1(1):95–108, 2009.

[92] N.M. Zamel, J.A. Pita, and A.H. Dogru. Next-generartion visualization technologies for exploration and production. In *SPE Middle East Oil Show*, 2001.

[93] Bjorn Zehner, Norihiro Watanabe, and Olaf Kolditz. Visualization of gridded scalar data with uncertainity in geosciences. *Computers & Geosciences*, 36(10):1268–1275, 2010.

[94] Torre Zuk. *Visualizing Uncertainity*. PhD thesis, University of Calgary, 2008.

Appendix A

Uncertainty Visualization Study Material

This appendix contains the related components used for conducting user evaluations described in Chapter 3.

- recruitment letters used for the study.
- description of the procedures of the study.

UNIVERSITY OF CALGARY

Exploration and Visualization of Uncertainty in reservoir models

Study Recruitment Email Letter - Visualization group

Dear colleague,

*I'm a master's student from the Scalable Illustrative & Scientific Visualization Group (SISV) located at the University of Calgary (**6th floor, Math Sciences building, room 625A**). I'm currently developing a reservoir 3D post-processing tool for Uncertainty visualization on digital tabletops, an emerging technology that leverages interaction and collaboration to new levels in computational applications, and only recently has been finding its way into oil reservoir systems.*

We would like to invite you to take part in the design and evaluation of our developing prototype, and share your thoughts, critics and suggestions on how we could make our tools better. We are ideally looking for participants who have some experience with visualizations of any kind. No prior knowledge about reservoirs is required.

Sessions will begin by a demo of one tool at a time, followed by an open discussion. The whole process will take no more than 1.5 hour. With your consent, we might record or videotape the sessions, for later analysis.

*Please reply to **Sowmya Somanath** letting us know whether you are interested in volunteering to participate on this research.*
*The study is scheduled to run starting from **next week (Feb 21st) till March 12th**. We will do our best to accommodate for the timeframes you are available. We will be paying the participants $15 as a token of appreciation for your time.*

Thank you for your time!

UNIVERSITY OF CALGARY

Exploration and Visualization of Uncertainty in reservoir models

Study Recruitment Email Letter - Domain experts

Dear colleague,

*I'm a master's student from the Scalable Illustrative & Scientific Visualization Group (SISV) located at the University of Calgary (**6th floor, Math Sciences building, room 625A**). I'm currently developing a reservoir 3D post-processing tool for Uncertainty visualization on digital tabletops, an emerging technology that leverages interaction and collaboration to new levels in computational applications, and only recently has been finding its way into oil reservoir systems.*

We would like to invite you to take part in the design and evaluation of our developing prototype, and share your thoughts, critics and suggestions on how we could make our tools better. <u>We are looking for candidates who have at least some experience working with visualization and analysis of reservoir flow simulation models.</u>

Sessions will begin by a demo of one tool at a time, followed by an open discussion. The whole process will take no more than 1.5 hour. With your consent, we might record or videotape the sessions, for later analysis.

*Please reply to **Sowmya Somanath** [redacted] letting us know whether you are interested in volunteering to participate on this research.*

*The study is scheduled to run starting from **next week (Feb 21st) till March 12th**. We will do our best to accommodate for the timeframes you are available. We will be paying the participants $15 as a token of appreciation for your time.*

Thank you for your time!

UNIVERSITY OF CALGARY

Exploration and Visualization of Uncertainty in reservoir models

Study Recruitment Email Letter - Others group

Dear colleague,

*I'm a master's student from the Scalable Illustrative & Scientific Visualization Group (SISV) located at the University of Calgary (**6th floor, Math Sciences building, room 625A**). I'm currently developing a reservoir 3D post-processing tool for Uncertainty visualization on digital tabletops, an emerging technology that leverages interaction and collaboration to new levels in computational applications, and only recently has been finding its way into oil reservoir systems.*

We would like to invite you to take part in the design and evaluation of our developing prototype, and share your thoughts, critics and suggestions on how we could make our tools better. <u>No prior knowledge about reservoirs is required. Be a part of the study to know if the visualizations work for you, and let us know how you perceive it!</u>

Sessions will begin by a demo of one tool at a time, followed by an open discussion. The whole process will take no more than 1.5 hour. With your consent, we might record or videotape the sessions, for later analysis.

*Please reply to **Sowmya Somanath** [redacted] letting us know whether you are interested in volunteering to participate on this research.*

*The study is scheduled to run starting from **next week (Feb 21st) till March 12th**. We will do our best to accommodate for the timeframes you are available. We will be paying the participants $15 as a token of appreciation for your time.*

Thank you for your time!

Introduction

Hello! My name is Sowmya. Thank you for being part of the study today. The study that I am doing today is to evaluate 3 concepts we developed in the context of reservoir engineering for exploring and visualizing uncertainty.

Before I get into the details of the three techniques I am evaluating today, I would like to know if you're familiar with reservoir models. <For non-domain participants> Reservoirs are basically entities hidden several feet below the surface of the earth. In order to make any kind of analysis about them, reservoir engineers depend on indirect methods such as sensors, or collection of samples to make an estimate about the reservoir model. Using this data and human inputs, models are created. These models are then used by visualisation applications at the post processing stage. Since, 3D models are almost the closest representation you can get for the actual reservoir, they are used in visualization applications, and tools are developed to allow exploration of these 3d models to make some kind of analysis or important decisions- such as well placement decisions. These 3D reservoir models are irregularly shaped, grid structures, consisting of several cells. Each cell is associated to a set of time steps and static and dynamic properties, such as pressure, porosity etc. We cannot change any simulation parameters for these models at the post processing stage, to generate new ones. The main advantage of these models is that we can map different techniques to them and create tools that can help to explore them, and gain insight.

Now, like I mentioned a little while ago, <Common point for all participants> all the information that engineers have about reservoirs, comes through indirect methods, and to construct models, they use the information they obtained, and make further estimates. Due to these estimates, there is uncertainty associated with these models. Now let us assume that we had some way to measure this uncertainty, and we had these uncertainty measures at the post processing stage for some particular model. Then we could map these values to the model to visualize uncertainty in reservoirs. The main aim of the 3 techniques that I am going to demonstrate to you today is to be able to allow an engineer to explore such uncertainty values and perhaps do some analysis using the information he obtained. From the little I know about reservoir engineering, low uncertainty can be used as a measure for determining possible locations for drilling an oil well. In which case, what we are really looking for is tools that would let us identify regions of low and high uncertainty, or in the case of analysis, possibly studying what kind of uncertainty region, an existing well is situated in.

The validity of how uncertainty is defined or measured is beyond the scope of this evaluation. What I would like you to do is to think about these visualization techniques and share your thoughts, suggestions and feedback about them. Your criticism is equally important, so please feel free to express yourself. These techniques are not solutions for any kind of commercial package, and they do not represent a complete working tool. They are exploratory concepts, and we would like to know your opinions about them.

How we are going to go about things today is:

1. I would first like you to please fill out a consent form for me,

2. Then answer a very simple questionnaire, detailing your current academic title and area of research

3. And then, I will demo each of the 3 techniques, let you try them out, and ask you a couple of questions about them. There are no right or wrong answers, so please express you freely. Your suggestions, opinions and criticism are all very important to me.

Pre- session Questionnaire

Name:

Current academic title:

Area of specialization:

Demo:

(A) Res < prop>

Here is a reservoir model, color coded according to some geological property, pressure in this case. You can see that this model has 2 oil wells, represented by the 2 red lines. You can explore the model by rotating it, zooming it and translating it like this.
<Allow user to try it out>.

(B) Res <Uncertainty>, color scale, wells

Now to the same model, we have mapped uncertainty values, using the color scale you see here. As you can see, the range of uncertainty for this model is from 1% to 60%. The two wells that you see here have some uncertainty associated to them. What I mean by that is, each of these well points, are contained in some particular cell and that cell has some uncertainty value associated to it. You can explore this model, like I previously mentioned, by rotating it, zooming and translating. Please feel free to explore it and let me know if you have any questions.
<Allow user to try it out>.

Questions:

1. Do you think well B has been placed in a relatively low uncertainty area?
2. Can you tell me roughly what kind of uncertainty range could well B possibly have?
3. How do you think or what do you think we could do to make answering these questions easier or with more confidence?
4. <If they talk about deformations>, do you think <deformation> could perhaps be an acceptable compromise between the amount of context you can see and the information to be gained?

-------------------------------------- CANDY VISUALIZATION --

(C) Res <Uncertainty>, single candy visualization

To answer these questions that I just asked you, we developed our 1st technique – Candy Visualization and that is what I am going to show you now. <step 1> These things that just popped up are what we call Candies. Candy visualization is based on the metaphor of reflections. They have 2 components, just like a lollipop, the candies, which are these cubes on the top and the candy stick. The candies are clones of the blocks through which these well points pass. They are the same size, and same color as the original block hidden below .The candy sticks are lines connecting the original blocks to the clones. The height of these sticks depends on the layer to which the actual point belongs. So the shorter length means the point is somewhere higher up in the layers, and the longer the length means, its coming from somewhere far below. Is there any question you would like to ask me regarding this candy visualization? Did the explanation make sense?

Questions:
1. Do you think, candy visualization is useful for commenting about the uncertainty associated with a well, in comparison to when you couldn't see them?
2. What is the kind of information you can tell about the uncertainty of this well, using this visualization?
3. Can you think of any other data sets where such a technique could be used? And how it could be used?
4. What are the advantages of this technique according to you?
5. Disadvantages?
6. Suggestions for improvement?

(D) Res <property>, single candy

Now I would like to show you, another way, Candy Vis can be used: Now the reservoir model is color coded according to some geological property – say pressure and the candies are color coded according to the uncertainty color scale. So now, you can explore the uncertainty associated with a well, while keeping the rest of the reservoir mapped to another property or any other mapping function. Is there any question you would like to ask me regarding this candy visualization? Did the explanation make sense?

Questions:
1. Do you think this is useful? If yes, for what is it useful?
2. What are the potential advantages of this?
3. Disadvantages?
4. Suggestions for improvement?

(E) Res <Uncertainty>, 2 Candies

Till now you saw, the candy vis for a single well. But as you can see this model has 2 wells, with very different shapes. Now, we'll see, how candy vis looks, when the shape of the wells are not so spread out as well B. These 2 triangles that appeared, are going to let you select the well, for which you want to see the candy vis. You can do the selection, by simply tapping twice on the triangle, like this. Is there any question you would like to ask me regarding this candy visualization? Did the explanation make sense?

Questions:
1. Do you think candy vis is useful however the shape of the well maybe?
2. Do you think, it's easy to read from this kind of vis, whatever maybe the shape of the wells?
3. Does this way of selection work for you?
4. Do you think, candy vis should be represented differently when well configurations are not very spread out? If yes, how do you think, we could do this?

-- HISTORY CIRCLES ---

(A) History circles <with no interaction >

Now from the Candy Vis you saw the kind of uncertainty distribution associated with the well. But if you had to tell me what are the exact values in this uncertainty range associated with this well, then it would be difficult. To make answering such a question possible, we devised our 2nd technique – history circles. These circles that you see here show you the unique uncertainty values that this well has. The radius hints at the number of blocks which belong to the particular %. So from this rep, you can see, that quiet some blocks of this well, have 1% uncertainty. Is there any question you would like to ask me regarding this technique? Did the explanation make sense?

Questions:
1. Is this technique useful?
2. Potential advantages?
3. Disadvantages?
4. Suggestions for improvement?

(B) History Circles < with interaction >

Now these circles are a static rep of some numerical values. Now what if you wanted to know, which are those blocks, that have 1%, 42% etc? Basically, which are those blocks that are responsible for this circle to exist? To know this, we devised a simple interaction, which connects the Candy vis and history circles together. You can simply tap on these circles and see the corresponding blocks, get highlighted in yellow. Is there any question you would like to ask me regarding this technique? Did the explanation make sense?

Questions:
1. Useful?
2. Advantages?
3. Disadvantages?
4. Suggestions for improvement?

(C) History Circles (multiple history circles)

Now you saw the history circles for 1 well, and how to interact with it. Now I am going to show you, how we can bring up the history circles for multiple wells and compare their total uncertainty. Here you see the history circles of well A to F hanged on a rod. The scale is the uncertainty % scale. The circles are placed according to their uncertainty %. The circle at the end represents the total uncertainty. Is there any question you would like to ask me regarding this technique? Did the explanation make sense?

Questions:
1. Useful?
2. Advantages?
3. Disadvantages?
4. Suggestions for improvement?

Appendix B

Focus and Context Study Material

This appendix contains the related components used for conducting user evaluations described in Chapter 4.

- recruitment letter used for the study.
- description of the procedures of the study.

UNIVERSITY OF
CALGARY

Exploring Novel Interfaces
and Visualization techniques
applied to Reservoir

Study Recruitment Letter

Dear colleague,

We are part of Illustrare*, the Scalable Illustrative & Scientific Visualization Group (SISV) located at the* Graphics Lab *and* Interactions Lab *at the University of Calgary (6th floor, Math Sciences building, room 625A). We are currently developing a reservoir 3D post-processing visualization tool on digital tabletops, an emerging technology that leverages interaction and collaboration to new levels in computational applications, and only recently has been finding its way into oil reservoir systems.*

We are looking for volunteers to take part in the design and evaluation of our developing prototype, and share your thoughts, critics and suggestions on how we could better attend the needs of potential users. We are looking for candidates who have experience working with visualization and analysis of reservoir flow simulation models.

Sessions will begin by a quick demo on the tabletop device and our application, followed by an open discussion. The whole process should take no more than 1 hour. With your consent, we might record or videotape the sessions, for later analysis. Additionally, if possible, we would also like to have another separate follow up meeting. We will be offering $15 per session for the participants, as a token of appreciation for your time.

Please reply to ***Nicole Sultanum or Sowmya Somanath*** *letting us know whether you are interest in volunteering to participate on this research. We will do our best to accommodate for the timeframes you are available, within the 1-week period of the study, approximately from* ***June 20 to June 24****.*

Thank you for your time!

01 – Introduction: Presentation and Structure

Thank you for your participation. We invite you to take part in the evaluation of this tabletop visualization prototype for reservoir post-processing data. We have been working in collaboration with reservoir engineers in trying to shape this new experience as a very meaningful one for the users.

Imagine a world in which you could have your reservoir model, at hands reach... and you could easily, and intuitively, manipulate it freely, directly, and you could feel it, tear it apart, see the tiny bits and the big picture, remodel wells... anything you can imagine. Technologically, it is still very challenging to have such a thing happening, but we are going to present you some of our current efforts towards this vision, with this tabletop prototype. It is a very different way to see reservoir models, for a very different experience, and (hopefully) a positive one. So we would invite you to 'think out of the box' as well... "go crazy, let your imagination go wild", and always reflecting on the possible implications for the domain. There is no right and wrong, so express yourself freely. Tell us what you think about it. Your opinion is very valuable to us, and criticism is very welcome too. We are also seeking constructive ideas on how to improve and evolve our ideas.

We developed a few tools for the exploration of reservoir flow simulation models on tabletop, and we would like to hear your subjective insight on them. This is not a commercial tool, it is an evolving prototype, so it might crash and behave unexpectedly. But we believe it brings across the concepts we are trying to propose – our main goal – while also reflecting on the specifics and the mechanics of the 'how to's.

This study is not task or goal oriented. You will not be asked to perform a specific task but rather to use a set of tools, and to brainstorm with us about them. This section will be divided as follows:

1) *First, we would like you to fill out this consent form (explain about the consent form);*
2) *We have also prepared a simple questionnaire, to know a bit more about you and your experience.*
3) *Then, we will present the tabletop environment, and explain the features of our prototype. Meanwhile, we invite you to use the system. We will ask you to "think aloud" while doing so, which is basically constantly verbalizing your thoughts. Your ideas will be recorded for later evaluation and consideration, and provide us with further insights... and, there is no right and wrong, so please express yourself freely, whatever you are thinking. What might seem a trivial thought to you might be insightful to us. We will also ask you a series of questions about your vision and opinion on the presented system.*
4) *Finally, we conclude, while welcoming any additional comments if there are any.*

02: Questionnaire

---

1) Name:

2) Age:

3) Current professional/academic title:

4) Professional background/education and experience (include no. years):
    a. Academic training (degrees, specializations):

    b. Professional training (w/professional positions):

5) Res. engineering software tools used in the past, for how long and for which role.

6) Previous experience/use of reservoir simulation models?

03: Demo and Discussion: Procedure

1) Demonstrate a feature:
   Focus and Context for wells
   Show and explain well selection and visualization; show rotation of tangible

2) Ask the user to repeat the action until they confirm they understood it. Allow the users considerable time with the interface. Address any questions they may have.

3) Questions:

   - Can you tell us how and when you think this feature might be useful?
   - Do you see any potential problems with the way it currently works?
   - Would you have any ideas on how this could be made better?
   - What do you think about this function?
     (a) Intuitive / not intuitive? To what degree?
     (b) Easy to use / cumbersome? To what degree?
     (c) Useful / useless? To what degree?
     (d) Relevant / disposable? To what degree?

04: After the demo: < this study evaluated three other techniques along with the `focus and context' technique for wells>

1. Of all visualization functions presented here, which do you, see as having more potential and why?
2. Which do you think is weaker and why?
3. Can you think of features that you think would be important to offer in terms of reservoir visualization and manipulation?
4. Any additional comments that you think have not been addressed yet?

Appendix C

Spidey Study Material

This appendix contains the related components used for conducting user evaluations described in Chapter 7.

- recruitment letter used for the study.
- description of the procedures of the study.
- Questionnaires.

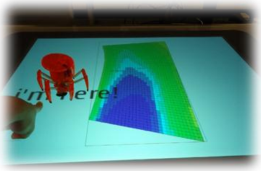
UNIVERSITY OF CALGARY

Designing Spidey: A Tabletop Robotic Assistant for Reservoir Engineering tasks

Study Recruitment Letter

Dear colleague,

I am a master's student from the Scalable Illustrative & Scientific Visualization Group (SISV), located at the University of Calgary (6th Floor, Math Sciences, room number: 625A). I am currently developing a prototype for a small tabletop assistive robot – Spidey.



Spidey can perform a few tasks in the context of reservoir engineering (It can trace paths, reach out to different regions on the reservoir, highlight specific regions etc.).

Come meet Spidey and help us improve our prototype!

Where: Math Science, 6th floor, 625A

Remuneration: **$15** for the precious time you spend with us for helping us out.

Duration of the study: 50-60 mins.

We would like to invite you to take part in the design and evaluation of our developing prototype and share your thoughts, critics and suggestions on how we could make our prototype better. The evaluation sessions, will begin by a demo of each of the task that Spidey can perform, followed by an open discussion. The duration of the session would be approximately 1 hour.

*Please reply to **Sowmya Somanath** letting us know whether you are interested in volunteering to Participate on this research.*

Thank you for your time!

Introduction

Hello! My name is Sowmya . Thank you for being a part of this study today. The study that we are conducting today is to explore the possible benefits and limitations of a digital tabletop robotic assistant.

Microsoft surface is a digital multi-touch tabletop that you can interact with using physical touch and tangibles of this sort.

Imagine the following scenario, let's say at your workspace you have this big digital tabletop on which you can interact using physical touch and examine and analyse your dataset. Let's say, your boss has asked you to perform 2 specific tasks and report the results from your analysis. However you were supposed to work with your colleague on this, since he was going to help you with the basics of it. Due to some reason, on that day your colleague could not join you. He is sorry about it, but informs you, that instead he has trained his robotic assistant who would help you today. This robotic assistant is going to be your companion today and guide you through your tasks using the expertise he learned from your colleague. He will talk to you via virtual messages, will take you step by step through the various processes that need to be performed, demonstrate to you how a particular task can be accomplished and so on.

Such an effective assistant is the big goal of this project. For this study, we have spider robotic assistant, who we call *Spidey*. *Spidey* can perform some simple tasks in the context of reservoir engineering dataset and interact with you to allow you to explore the reservoir models.

Reservoirs are basically a piece of the sub-surface earth and a pool of hydrocarbons. The 3D reservoir models are virtual representations of the original reservoirs. These models are gridded structures consisting of several cells. Each cell is associated to a set of static and dynamic properties and time steps. A reservoir also has other entities such as wells, traps, faults etc.

Spidey is very light, and interaction with it wouldn't cause any physical harm.

How we are going to go about the study today is:

1. We will first start with the consent forms
2. Then I will ask you to answer a simple questionnaire for me, detailing your current academic title, if you have any previous experience of interacting with robots of any kind etc.
3. Finally, we will get into the demos. I will first demo the tasks that spidey can perform 1 by 1, and then allow you to try it out. During this interaction session I will ask you a couple of questions about your experience with *Spidey*.
4. End of the study we have another questionnaire that we would like you to fill out for us.

As a participant, I would like you to interact with Spidey, and as you interact, I would request you to think aloud and express your opinions, suggestions or any thoughts you have about Spidey. Please express yourself freely. The questions I ask you are going to be very subjective, so there is no right or wrong answers. So please let me know your opinions freely. Your criticism is equally important to us. Before we get into the demo I would like you to know that this is an evolving prototype, so it may behave unexpectedly at time, or may sometimes crash while you're interacting with it. In which case it is surely not your fault, and we are sorry for any such problems that may come up.

DEMO

Stage 1: Come to the destination

The most common requirement that a user may have for his robotic assistant would be an ability to have it "come and go" to locations specified by the user. And this is what I am going to demonstrate to you now.

Touch a point on your screen, and see Spidey come to you !

<Ask them to try>

Questions:

1. Was this method for "calling" you're assistant intuitive?
2. Can you think of any other way that you would like to employ to call your assistant?
3. Any problems that you see with how Spidey responded to your call?
4. Suggestions for improvement?

Stage 2: Follow the path

Now you saw how Spidey can come to locations pointed out by you, let's say you had a scenario where you wanted Spidey to follow a particular path to reach the destination. So how you can make spidey trace your paths is like this: Use a single finger and draw a path. Release your hand, and see Spidey trace your path. One possible idea for the need for such a path trace could be, that as Spidey walks the path, he could collect data of the cells below, or adjacent cells and present them to you.

<Ask them to try>

Questions:

1. Did you find this path tracing effective?
2. Any problems?
3. Possible usage scenarios?
4. Suggestions for improvement?

Stage 3: Highlight:

Now Spidey can do a couple of other interesting things for you to allow you to learn more about the reservoir. The first thing spidey is going to do for you is, highlight regions of the reservoirs. For a reservoir engineer, correlation is important. They usually have the need to be able to see 2 geological properties at the same time. So now Spidey is going to do exactly this. Lead him on to some region you want to explore, and see what he can do.

1. Was it easy to do this?
2. Was this highlighting action by Spidey easy to understand?
3. Any problems?
4. Suggestions for improvement?

Stage 4: Highlight and Rotate:

The second thing that Spidey can do is, highlight and rotate the model for you. By now, you probably know what to do. Just lead him on and see him perform for you.

1. Was it easy to do this?
2. Was this action by Spidey easy to understand?
3. Any problems?
4. Are there any words that you would like to associate Spidey to, after your interaction with Spidey?
5. Suggestions for improvement?

Stage 5: Playback

Till now, you saw how Spidey did things according to you. If you wanted to highlight some region, he would walk up there and highlight that particular region for you and so on.

Now consider a slightly different scenario: Yesterday when you hadn’t been able to attend a meeting, your colleague had done a few explorations with the model. He would like to share those results with you. So he tells you that Spidey recorded his actions yesterday, and can playback those actions for you today. And after you have a look at it, you can meet him to discuss your opinions about it. So this ability of playing back recorded interactions, or sharing the expertise of one colleague with another when everyone cannot meet at the same time, is the scenario that I am going to demonstrate to you now. There are a couple of things an engineer did yesterday, and Spidey is going to play back those actions for you now.

1. Was this task easy for you to understand?
2. Is it meaningful?
3. Was the action performed by Spidey easy to understand?
4. Any problems?
5. Suggestions for improvement?

Pre-session questionnaire:

1. Name :
2. Current academic title :
3. Area of research :
4. Any previous experience with robots? If yes, can you please name the robots you have interacted with :
5. Three words or short sentences that describe an assistant according to you :
6. How comfortable are you when using new interaction mediums/ new software’s? – (Scale 1-5; 1: Not at all comfortable, 5: Very comfortable)

Post-session questionnaire:

1. Please rate your **impression of the robot** on these scales:

Fake	1	2	3	4	5	Natural
Machinelike	1	2	3	4	5	Animal like
Unconscious	1	2	3	4	5	Conscious
Artificial	1	2	3	4	5	Lifelike
Moving rigidly	1	2	3	4	5	Moving elegantly
Dead	1	2	3	4	5	Alive
Stagnant	1	2	3	4	5	Lively
Mechanical	1	2	3	4	5	Organic
Inert	1	2	3	4	5	Interactive
Apathetic	1	2	3	4	5	Responsive
Dislike	1	2	3	4	5	Like
Unfriendly	1	2	3	4	5	Friendly
Unkind	1	2	3	4	5	Kind
Unpleasant	1	2	3	4	5	Pleasant

Awful	1	2	3	4	5	Nice
Incompetent	1	2	3	4	5	Competent
Ignorant	1	2	3	4	5	Knowledgeable
Irresponsible	1	2	3	4	5	Responsible
Unintelligent	1	2	3	4	5	Intelligent
Foolish	1	2	3	4	5	Sensible

2. Please rate **your emotional state when interacting with the robot** on these scales:

Anxious	1	2	3	4	5	Relaxed
Expected	1	2	3	4	5	Surprised

3. Generated behaviour felt like working with a companion? (1-5)

4. In the beginning of the study you associated Assistants with three words/sentences; do you think you would associate them to Spidey?
   - All three?
   - Two? (reason)
   - One? (reason)
   - None? (reason)