PLANWELL: Spatial User Interface for Collaborative Petroleum Well-Planning

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Figure 1: (a) 3D printout, stylus and ipad used as the *overseer* interface (b) *overseer* operating on the 3D printout (c) visualizations on *overseer* interface(d) visualizations on *explorer* interface (f) *explorer* with an AR device

Abstract

We present our prototype of *PlanWell*, a spatial augmented reality interface that facilitates collaborative field operations. *PlanWell* allows a central *overseer* (in a command and control center) and a remote *explorer* (an outdoor user in the field) to explore and collaborate within a geographical area. *PlanWell* provides the *overseer* with a tangible user interface (TUI) based on a 3D printout of surface geography which acts as a physical representation of the region to be explored. Augmented reality is used to dynamically overlay properties of the region as well as the presence of the remote *explorer* and their actions on to the 3D representation of the terrain. The *overseer* is able to perform the actions directly on the TUI and then the *overseer's* actions are presented as dynamic AR visualizations superimposed on the *explorer's* view in the field. Although our interface could applied to many domains, the PlanWell prototype was developed to facilitate petroleum engineering tasks such as well planning and coordination of drilling operations. Our paper describes the details of the design and implementation of the current *PlanWell* prototype in the context of petroleum well planning and drilling, and discusses some of the preliminary reflections of two focus group sessions with domain experts.

CR Categories: H.5.1 [**Information Interfaces And Presentation**]: Artificial, augmented, and virtual realities; H.5.3 [**Group and Organization Interfaces**]: Computer-supported cooperative work

Keywords: Augmented Reality, Spatial User Interaction, Computer Supported Cooperative Work, Tangible User Interfaces

1 INTRODUCTION

Many collaborative field tasks involve a centralized control center overseeing multiple teams in the field. Collaboration between this central control and the remote teams requires pertinent information to be presented to each individual involved according to their role in a timely and effective manner. Furthermore, it is necessary to provide clear presentation of this information within different contexts so that central control may effectively monitor and advise individuals in the field and allow them to apply the appropriate context to central control's requests. Failure to accomplish this compromises situational awareness as well as communication and thus the ability to complete the tasks efficiently. Such failures could have a very high impact in critical applications such as search and rescue, remote emergency response and military operations. Even in less critical applications these failures could lead to wasted time and money. We design spatial tangible mobile interfaces that help alleviate some of these challenges and apply it in the context of collaborative petroleum well-planning workflow. Though *PlanWell* can be applied to various collaborative terrain exploration scenarios and tasks such as military operations and rescue missions, in this paper we use a specific petroleum engineering scenario as the context and design the system to address practical problems relating to remote collaboration in such activities. We also conducted two focus

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group discussions with domain experts to gather qualitative feedback of our prototype and design approach.

Our work makes three main contributions:

1) A tangible 3D augmented reality technique providing clear and intuitive spatial and structural awareness to a central overseer in a command center, while providing immediate and relevant information to a user in the field.

2) Application of the technique to a realistic engineering scenario, based on feedback and suggestions gathered during interviews with domain experts. The qualitative analysis of the [i]focus group discussions which have brought about interesting insights on our design approach.

3) Details of our implementation so that others may build similar applications as well as a technical evaluation which presents the technical strengths and limitations of our system.

2 RELATED WORK

Our work falls under the intersection of the following themes in HCI research:

1) Augmented Reality and Applications
2) Collaborative Augmented Reality
3) Tangible Interfaces for Collaboration

In this section we will be discussing the previous literature that relates to our work and falls under the above mentioned themes.

2.1 Augmented Reality and Applications

Augmented reality has been used in a wide variety of domains including civil engineering [Schall et al., 2008], tabletop reservoir engineering interaction [Lapides et al., 2012], human-robot interaction [Li et al., 2015], geographic visualization [Hedley et al., 2002], and topographical terrain exploration [Li et al., 2014] and for spatially aligning virtual objects with the real-world objects [Bimber and Raskar,2005],[Raskar et al., 1998].

2.2 Collaborative Augmented Reality

The use of augmented reality for collaborative tasks has been explored extensively [Barakonyi et al., 2004], [Billinghurst and Kato, 2002]. With respect to remote collaboration, previous research explored collaboration between an indoor and outdoor user for managing and accessing spatial information [Hollerer et al., 1999], [Robert et al., 2013],[Stafford et al., 2006]. Previous research also explored the use of 3D spatiality in remote collaboration [Gauglitz et al., 2014], [Sodhi et al., 2013].

2.3 Physical Interfaces For Collaboration

Attempts have been made to merge the physical environment with remote collaboration and tangible user interfaces have also been explored to support collaboration [Follmer et al., 2013], [Gauglitz et al., 2012], [Leibe et al., 2000]. Physicality has been explored in remote collaboration with spatial and physical cues in distributed collaborative environments and tabletop collaboration [Leithinger et al., 2014], [Robinson and Tuddenham, 2007], [Sakong and Nam, 2006]. However, to the best of our knowledge, the use of 3D printed scaled model of the environment for enhancing spatial awareness during remote collaboration has not been explored in general, and especially not in realistic scenarios such as the applied domain of reservoir engineering.

3 PLANWELL

3.1 Design Considerations

Since our design and system has to be used by experts from various domains who may not be experts in using computing systems and environments, we had the following set of design considerations and their respective implications on the design.

3D Printed Terrain as a TUI : Previous TUI research has provided evidence that physical representations help in understanding complex spatial environments and relationships [Gillet et al., 2005], [Harris et al., 2011], [Jansen et al., 2013]. Geologists and Urban planners have already explored the effectiveness of 3D printing to print physical models of GIS data [Rase, 2009].The conclusions developed from this research indicate that physical printed models enhance the spatial situational awareness during collaboration.

Implications on Design: This previous positive research inspired us to use physical 3D printed representation of the oil reservoir as an interactive medium for collaboration.

Maintaining The Local Physical Context: One of the requirements of our system is that it should preserve the actual physical context of the surroundings in which the users are present.

Implications on Design: We could have used map based navigation system or pure virtual environments for the collaborative tasks. Though these techniques are efficient and provide various essential features such as zooming and panning, they disconnect the user from the actual physical environment. We used Augmented Reality to ensure that the users (both the *overseer* and the *explorer*) can perceive the physical context of their local environment.

Interaction Design: Based on our discussions with domain experts, we determined that the Surface Team is responsible for coordinating and planning the drilling operations and the on-site drilling team performs the required tasks. Based upon this setting, we envision the *overseer* as the person or group who drives the entire task, while the *explorer* is the user who typically \executes" tasks based on the directions from the *overseer*. This corresponds with how a surface team would work with the workers on-site.

Implications on Design: We empower the *overseer* to a wider set of stylus-based interaction which enables him to annotate, and sketch on the 3D printout, while the *explorer* can only visualize or select some important features for analyzing them in-situ and relaying the same information to the *overseer*.

Simple and Commercially available Apparatus: Another requirement is that the system should be small and easily setup so that it may be used in various application domains and situations. The domain experts whom we envision to be our system users might not be well-versed with setting up the environment; hence our system needs to be easy and simple to be setup by novice users without much training.

Implications on Design: There are multiple approaches such as a shape/surface-changing display [Follmer et al.,2013] with AR, or using a projector for overlaying content on the 3D printout [Bimber and Raskar, 2005]. However these solutions are difficult and complex to setup for non-experts and could limit the flexibility of the system. For this reason, we use the mobile Augmented Reality approach of using off the shelf mobile and tablet devices as our AR displays.

3.2 Design

The primary design goal was to enable two parties to share a spatial awareness via an interface designed to provide clear and intuitive understanding of each other's situation, despite differences in scale and perspective. To help us achieve this goal we used 3D printing to generate a terrain model with realistic spatial representation, as well as augmented reality techniques. The *explorer* in the field uses the actual physical environment as an interactive medium, and the *overseer* uses a 3D printed model of the same environment as an interactive medium.

By designing for a specific petroleum engineering workflow, our approach may be deployed and tested in a real world application. In our scenario, a petroleum energy company would have a surface team who would be responsible for all surface operations. The surface team would collaborate with an on-field drilling team (often a contractor) in order to plan and implement an oil or gas well.

PlanWell contains two major components:

1) The *overseer* interface used by the surface team. In our scenario, this would reside at the energy company office. (Figure 1b, 1c and 1e).
2) The explorer interface used by the drilling team in the field (Figure 1a and 1d.).

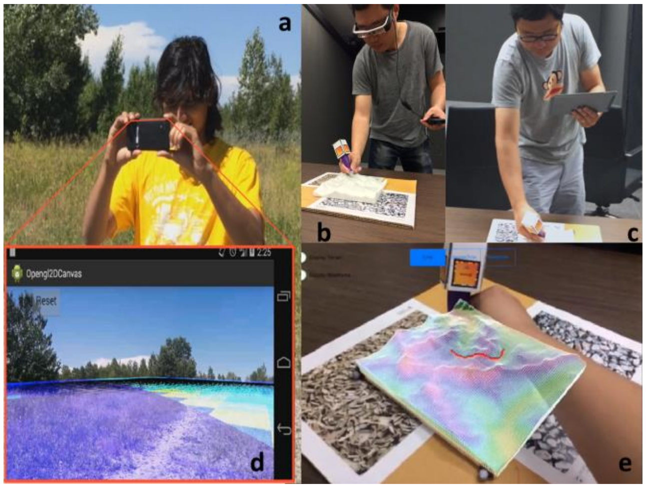

Figure 2: (a) Outdoor *explorer* with the AR device (b) *overseer* using the tangible user interface with AR glasses (c) *overseer* using an iPad as the AR device (d) Screenshot of *explorer* interface (e) Screenshot of *overseer* interface

The *overseer PlanWell* interface uses a 3D printout as the physical representation geographical area. This model was based on real geographical data and produced using 3D printing, a process that is fast becoming ubiquitous. Augmented reality is used to superimpose the application-specific information onto the 3D printout. The combination of visual illustration as well as the realistic spatial representation and tangible nature of the model allows the *overseer* to understand the topographical properties of the terrain intuitively and clearly. The goal of this arrangement is to offer the *overseer* direct physical representation of the topographical spatial properties enabling unambiguous interpretation of spatial properties, and allowing access to the 3D printed TUI both visually or by touch. The AR visual feedback enables awareness of the activities in the field in real time, and facilitates interactive access to the application-specific visualization, superimposed on its scaled-down 3D physical representation.

PlanWell also provides interactions that allow the *overseer* to annotate and modify the existing data with a stylus (Figure 1c and Figure 1e). The stylus enables the *overseer* to draw a relatively precise path or select an area on the surface of the 3D model and send it to the *explorer* to provide instruction or guidance. Also, the *overseer* may drag and move an existing point-of-interest (POI) to a new location, in order to allow the *explorer* to examine it in the field. Apple iPad Air tablet was used as the handheld AR device. The *PlanWell explorer* interface (Figure 1d) uses augmented reality to superimpose the application-specific data such as reservoir data or drilling locations onto the terrain around the *explorer*, presenting static information such as petroleum-reservoir properties, as well as dynamic information from the *overseer* such as paths, selected areas and suggested locations of wells. The communication is bi-directional.

4 IMPLEMENTATION

Both the headset (Epson Moverio[1]) and the handheld screen (iPad Air) were used as the AR device. The 3D printout of the terrain model was provided by a 3D printing service vendor (Shapeways Inc.[2]) based on the digital model of the terrain. *PlanWell* uses an intermediate server to exchange information, including geo-references marked by the *explorer* and point-of-interests (POIs) marked by the *overseer* or *explorer*. The *overseer* and *explorer* clients are implemented on different devices and runtime environments. The *overseer* interface was implemented on an iPad Air running iOS and the *explorer* interface was implemented on a Google Nexus 5 running Android.

Both clients display content via augmented reality. However, the *explorer* interface provides a geo-reference based in-situ experience by placing visualizations over the surrounding environment, while the *overseer* interface creates an exocentric visual experience and superimposes visualizations over the 3D printout with pen based interactions implemented using the Qualcomm Vuforia[3] library. To achieve alignment between the perspective and the physicality, the *explorer* interface uses the built-in functions on the *explorer's* device such as the accelerometer, step detector, magnetic and GPS sensors. The *overseer* maintains alignment by tracking fiducial markers placed around the 3D printout.

To tailor our design for the petroleum engineering domain, we overlaid information, such as petrol-reservoir data and production wells on the 3D printout as well as on actual physical terrain as shown in figure 1(e) and figure 1(d). Both interfaces use OpenGL ES to provide the visual elements.

5 APPLICATION SCENARIO

Petroleum well planning and drilling is the application that we have targeted for this project. To test the effectiveness of our prototype, we consider a scenario that contains tasks commonly carried out during well planning and drilling operations.

Prior to the implementation of an oil or gas well, an interdisciplinary surface team consisting of petroleum engineers, geologists, civil engineers and planners meticulously plan the logistics of the resource extraction including locations of the drilling wells. The desired well locations are based on data provided from reservoir engineers, although in practice there is flexibility with regards to the actual location of the well due to directional drilling. The surface team determines potential locations for the wells based on the recommendations of the reservoir engineers as well as the economics and logistics determined by the surface team.

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[1] Epson Moveiro: http://www.epson.com/moverio

[2] Shapeways Inc:http://www.shapeways.com/

[3] Vuforia: https://www.qualcomm.com/products/vuforia

This plan is then sent over to the drilling team (often a contractor), which is responsible for the drilling and operations of the physical wells on the field. The drilling team must then build a more detailed plan of how to implement the well, and suggest any necessary changes to the surface team's plan. During the course of the drilling team's planning, the potential well locations will typically require site surveys and there may be back-and-forth dialogue between the surface team and the drilling team based on information uncovered during the site surveys. Potential well locations may have environmental or archeological significance, or have features that impact the economics or safety of the well.

After many potential iterations of planning, the drilling plan may be executed. This entire turn-around time could take days or weeks based on the complexity of the terrain and the drilling plan. Our interface hopes to expedite this process and reduce the time of this collaboration as well as improve communication of information and therefore reduce the probability of errors.

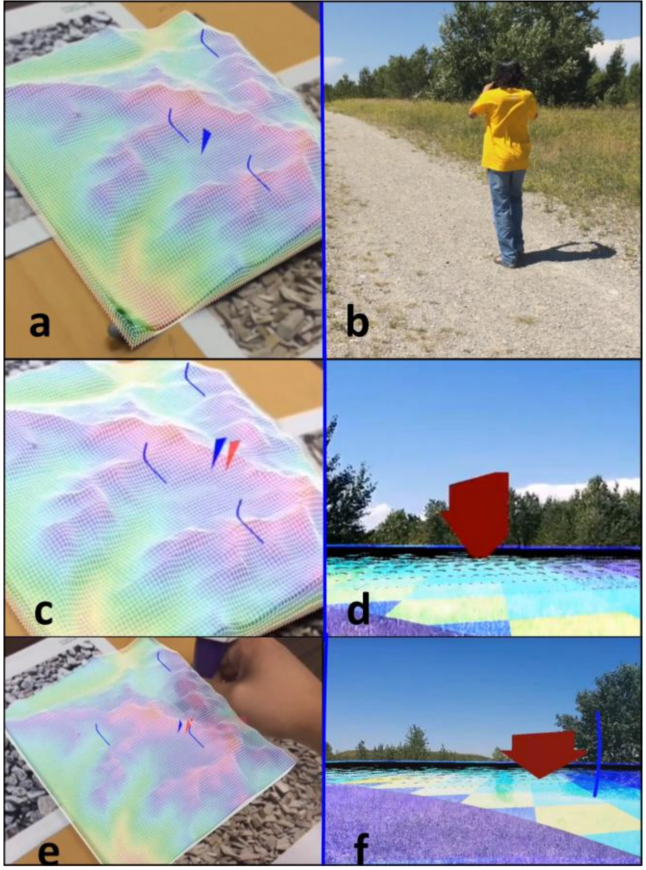

Figure 3 : (a) *explorer* position on 3D printout (b) *explorer* marches to another position (c) POI selected by *explorer* updated on 3D printout (d) the *explorer* marks a POI (e) *overseer* updating a POI on the 3D printout (f) POI updated by *overseer* shown on *explorer* interface

We designed three primary interaction scenarios to facilitate such remote collaboration for well-planning. In the first scenario the *explorer's* location is dynamically updated on the 3D printout of the *overseer*. While navigating the field (Figure 2b), the *explorer's* geo-reference is continuously sent to the *overseer*, allowing the overseer to maintain the spatial awareness of the *explorer* (Figure 2a).

In the second scenario, the *explorer* may select a particular POI on the field by tapping on the touchscreen of the device (Figure 2d), and then the selection will be translated into world coordinates and rendered as a red arrow on both the overseer and *explorer* screens, pointing at the corresponding location. This POI could be a certain terrain feature such as an environmental or safety concern or it could be a potential well location (Figure 2c). In the third scenario, in the case of a location determined to be suitable for a well based on the site survey, the overseer then could drag the representation of the well from an unsuitable place, to this POI (Figure 2e). Meanwhile, the *explorer* could also see the well representation appear on his AR interface (Figure 2f) at the proper location as it is moved by the overseer.

The above scenario demonstrates the bidirectional information exchange triggered by user interactions, and the corresponding visual representations on both interfaces.

6 TECHNICAL EVALUATION

In this section we reflect on the potential of our system and discuss our technical evaluation of the accuracy and latency of the prototype.

Accuracy: The GPS accuracy of the Nexus5 smartphone which was used as the *explorer* AR device is 10 meters. In our case, we have mapped an area of 6km x 6km to a 20cm x 20cm 3D printout, which means 1cm on the 3D printout represents 300m on the actual terrain. This means that the *explorer* has to walk for 150m for the *overseer* to observe a change of 0.5mm in the location of the *explorer* on the 3D printout. This scale issue may negatively impact the application design. Depending on the required accuracy and exploration styles, (e.g. rough exploration by a car vs a detailed exploration by walking) the impact of this metric varies. A potential solution include the use of dynamic multi-scale visualization on the 3D printout where the detailed information could be presented with a magnification lens [Looser et al., 2007] while enabling the user to switch back to the overview view with correct spatial scale and texture. Also, the acceptable scale could be determined based upon the application and the interface could implemented with the appropriate scale for the application, if feasible.

Latency: The data latency between the overseer and the *explorer* depends on the transmission infrastructure. In this prototype, we measured the latency of both sent and received JSON packets to be on average 2.4 seconds measured over a one hour duration between remote sites using a commercial cellular (3G) service. This should be acceptable performance, since the distance covered by the overseer in such a small time is should not be significant for this application.

7 USER STUDY

We conducted two focus group sessions with domain experts to gain further insights into our design. In this section, we will be describing the major themes that emerged out of our discussions. The results of both the focus groups were consistent and back up our claims.

7.1 Focus Group

We conducted two focus groups with different set of domain experts in each group. The first group had three experts who were from the petroleum and reservoir engineering departments at the University of Calgary. Though all of these experts are from the academia, they have worked in or alongside different teams and disciplines within the oil-and-gas- production cycle. They had several years' of experience in the industry as well. The second group had three experts who were from the industry. They are part of the surface team and perform the well-planning and analysis. Based on this, we believe our participants were qualified to comment about the validity of our prototype. The aim of the focus group was to gather qualitative feedback about the validity of our prototype and its perceived benefit to the oil-and-gas production cycle. We also sought to find the specific workflows for which our prototype could provide value and gain feedback and comments regarding improvements to the visual representation of data and interaction techniques.

The focus group was conducted in a controlled setting with the authors driving the entire session. The domain experts were first instructed on the technology and concepts involved, such as augmented reality. The instruction included both conceptual discussions as well as demonstrations of the AR devices showing some sample AR applications. The 3D printed model of the terrain was then explained and the AR overlay on the 3D printout was demonstrated. The participants had the opportunity to try our demo with both the iPad and the Epson headset. The participants were then introduced to the pen-based interactions and encouraged to try them on the 3D printout. The participants were also shown the *explorer* interface. For simplicity, we mocked up the *explorer* interface to show the *explorer* AR overlay and visualizations in the focus group session. The experts were given the opportunity to try our entire system with mock scenarios and the participants also had the opportunity to take the role of both the *overseer* and the *explorer*.

Once the experts seemed to fully understand the functionality and interaction techniques of the prototype, we conducted the focus group. The entire conversation was audio-recorded and the sessions lasted for 60 minutes each. Using the audio recordings we transcribed the audio for both the focus group discussions. We performed open coding of the transcribed data in order to group broad themes and identify interesting observations [Strauss et al., 1990]. For the discussion of the results we refer to the academic experts from the first focus group discussion as A1, A2 and A3, while the experts from the industry are referred as I1, I2, and I3.

8 RESULTS AND DISCUSSION

The domain experts were quite excited and interested by the prototype. They claimed to have not seen anything similar and provided valuable feedback about how *PlanWell* could be useful in the oil and gas industry. During our focus group study, the following major themes emerged.

8.1 The Role of 3D Printout for Better Spatial Understanding

Previous TUI research has confirmed that physical representations help in understanding complex spatial representations and relationships [Gillet et al., 2005], [Harris et al., 2011], [Jansen et al., 2013]. Our focus group affirmed these claims. The domain experts felt that the 3D printed models could be useful in clearly and intuitively understanding the nuances of the terrain. For example one of the domain experts explained that with a 3D printout of the terrain, it would be easier to know the appropriate pad sites for well construction which ultimately helps in reducing the time and cost and reduces errors. One of the domain experts from the first group also expressed similar views saying that 3D printed models could help in understanding the regularities and irregularities on the surface based on which well platforms can be constructed. However, with respect to quantitative measures such as task efficiency and productivity, the expert was unsure how 2D map would compare against a 3D printed model. We believe that a quantitative task based evaluation would help us in answering this question.

"*With the 2D map, it is tougher. For example, we decide a pad on the edge of the hill and then the scout guys takes two weeks, and analyses the location and says, that its not going to work, then we choose a new pad and then again scout again takes 15 days, goes to the new place and then maybe if it works then we start with the drilling, otherwise the cycle continues. So with the 3D printout, its easier to get to know the appropriate pad sites. Having a better idea about what's there on the ground and the features help in reducing the time and cost*." - I1.

"Based on the regularity or irregularities of the surface, well platforms can be constructed. These regularities and irregularities can be easily visible on a 3D printout. But I am not sure how this can be compared to 2D maps" - A2.

8.2 Enhanced Collaboration between The Two Remote Teams

With current practices in the petroleum engineering domain, the planning of a well can take a very long time and there is a need for collaboration throughout this time period. Our experts claimed that this application could be best for facilitating real-time coordination and communication between remote teams and planners and could significantly reduce both the time spent planning and the potential for miscommunication and error. "*Communication breaks between the field scout and the office planning team. The coordination misses and results in lot of time and money. There is a lot of break between the guys on field trying to find the location and the office team tries to plan the location. It takes a lot longer for us to get these pads approved. By the time they get the crown approved, it takes 6-8 months' time. And the from the time we plan the pad to the time we start drilling there sometimes we miss the timing and coordination and then we have to go somewhere else. Having a tool like this allows you to be able to in the office and see right up front, what is happening, what is looks like, the issues encountered and shorten the time, so that the locations can be approved, and get them on production and follow the yearly production forecast cycle.*"- I1

"*This application could be best for the coordination between the surface team and the on-field drilling team." - A1.*

"When there is change in the location of the well, then it has to go back to the drilling engineer because they have to correspondingly change the plan according to the new location. With this tool, the information exchange between the remote sites enables the teams to dynamically change the plans." - A3.

Based on the comments of the experts, it is evident that the collaboration facilitated by *PlanWell* can help the remote teams to dynamically plan, change and edit well locations and other operations and thus reduce time and cost of the collaborative work we have described.

8.3 The power of Spatial Augmented Reality

Our experts were very much impressed with the AR interface and the ability to overlay information over the physical environment. They suggested that such spatially augmented reality could save them time and money as they can test the well locations and well types by overlaying virtual wells while in direct communication with the planners. They also suggested other information that could be overlaid on both the *explorer's* surroundings and the 3D printout. This includes information such as details regarding well locations and well types, locations of archaeological sites, environmentally sensitive areas, flood plains and watersheds.

"*There could be constraints such as a particular site could be archaeological site, or there could be lot of underground water,* *or there could be lakes and rivers. All this information can also be overlaid.*" - A2.

8.4 3D printout as a Collocated Collaborative Interface

The current PCs and desktop computers which are widely used are designed for single-user applications and don't support comfortable and effective collocated collaboration. Tabletop systems have been developed that support collocated collaboration between users [Buisine et al., 2012], [Rogers and Lindley, 2004]. Extending upon these tabletop interfaces, tangible user interfaces have also been built that supported collocated collaboration. Based on this previous literature we envision that our 3D printed terrain model could be an effective tangible user interface that supports collocated collaboration. The domain experts' views from our focus group discussion also supported our vision. The experts claimed that the 3D printed physical terrain model in the *PlanWell* interface could be a collaboration tool which would be useful in bringing multiple experts from various domains to collaborate on well planning tasks. Such a collaborative medium could facilitate common spatial awareness between all the users and hence could significantly reduce the time for decision-making process.

"*The 3D printed terrain model could be very useful collaboration tool. This could be leveraged as a useful collaboration tool to get multiple people.*" - I3.

"*The overseer rather than one person per explorer trip could be an entire team that could collaborate over the 3d printout and finalize it in a single trip and reduce the cycle time and cost.*" - I2.

8.5 Physicality and the 3D stylus-Based Interaction on the 3D printout

One of the important features that our *PlanWell* prototype offers is the physicality provided by the 3D printout. Physical interfaces add value as they allow the user to touch, feel and manipulate the interface. This is particularly useful in domains such as geology, archaeology, and reservoir engineering as the experts generally prefer to touch and "feel" the surface for analysis.

"*Physicality adds value. I always prefer the physical models, touching it and feeling it. We use 2D maps which are so old fashioned and we miss so many things. Now this 3D model acts as a decision space where I can now everything in 3D. Now I see the value in physical level in addition because with software 3D models there always some issues with respect to perception and there are always some errors and spatial data errors and these would easily be corrected with the physical model. You can measure it to fair extent and look at the 3D digital models, but it doesn't much relate to the real world.*" - I1.

Although computer generated models provide 3D visualization, these visualizations are often complex and there could be perception issues [Johnson, 2004] ,[Ware, 2012]. The physicality provided by the 3D printed model resolves this perception issue as the visualization now is physical and relates to the real-world. During the focus group discussion the various perception issues the experts experienced in the commercial 3D software packages were described. Sometimes these perception issues make it very difficult for the older staff to grasp the interaction with the 3D virtual models in relation to their physical real-world interaction. Also the modes of interaction with the 3D spatial data in the commercial software packages are with 2D interfaces such as mouse and keypads. This makes the interaction with 3D terrain non-intuitive and often leaves the user clueless about the orientation of the model. These issues were explained in detail by the experts in our focus group discussions.

"*For older staff, sometimes it's very difficult to orient and visualize the 3D visualization. Not even operating the tool, just visualizing the model, spinning and orienting themselves to the view is very difficult to get and understand what they are seeing. It does happen quite often. Physicality helps in conveying certain spatial concepts to people.*" - I2.

One of the other important features the *PlanWell* interface is the natural 3D stylus interactions which allow the *overseer* to sketch and draw on the 3D printout. This is in particular useful as it provides a natural 3D interaction with the physical world, compared to the 2D visualizations of 3D data as offered by the current commercial software packages. Many times, experts interact with high resolution data and sketching of paths is one of the most common modes of interaction. However the current 3D software packages make it very non-intuitive for this mode of interaction and make sketching a path a multi-step process. The users have to make 2D sketches and these need to be converted into 3D shape file by another specialized software and this file is fed as input to the 3D visualization software to visualize the final output. Our stylus-based interaction approach eliminates this multi-step approach and enables the user to directly interact with the data without any perception issues.

"*Sometimes we work on smaller area and higher resolution. The process we do now are with commercial map-based software, we make 2D sketches, and go through a rather multiple-step process, like make that into a shape file, load it into a 3D software. The pen-based interactions are very intuitive because they can sketch it onto the actual 3D printout and there are no perception issues. More over direct input on the 3D printout is very intuitive and presents natural interaction, rather than 2d sketches on 3d data using software. The current sketching and planning process is multiple-step approach. They use 2d map-based software which allows them make some sketches for planning. In order to visualize and plan them in 3D, these 2d sketches involve a multiple step process to convert to 3D, i.e. they need to create shape file and then input this into another commercial 3D viz software and then visualize it. And again when they have to make a new sketch or change the existing sketch, they have to go back to the previous 2D maps-based software, make a new sketch and convert and then see it 3D using the 3D software. So this sketching and planning operations are very time consuming and non-intuitive*." - I1.

8.6 Applicability beyond Well Planning

Our experts commented that our prototype had the potential to be useful for other workflows within the petroleum engineering domain. These include monitoring remote oil rigs, reservoir planning and facilitating collaboration between reservoir engineers and geologists for tasks such as extrapolating sub-surface models from the surface terrain. There may also be applications to geomatics and civil engineering.

"*This could be very useful for the geomatics guys, especially the ones who do mapping and surveying*." - A3.

"*This 3D model could help in estimating the sub-surface model that lies beneath the earth. The terrain pattern could be used to extrapolate the subsurface which could also be useful in reservoir engineering studies*." - A1.

"*The application could be useful in monitoring rig movements. For example if there are a number of rigs place on the field, the overseer can monitor the rig movements and plan for the upcoming strategies, for production.*" - A2.

"*Civil engineers could also use PlanWell, for construction of roads, structures etc*" - A3.
Based on this feedback, we envision that our *PlanWell* concept could be useful and applicable across a various domains for a variety of tasks

9 LIMITATIONS AND FUTURE WORK

PlanWell is functional and was designed according to input from domain experts and reservoir engineers. However, though our focus groups and interviews affirm the applicability and usability of our prototype, it is still a preliminary prototype. We have not validated its usability "in-the-wild" with domain users performing actual tasks. One current limitation of our design is the procurement of high quality 3D printed models. A geographical region may be very detailed and complex and it is still an effort to print a high quality 3D version of it. However with the progression of the current 3D printing technologies, it is likely that this barrier will eventually be reduced if not completely eliminated. Another limitation is the AR devices of the *overseer* interface. It could be tiresome for the users to hold the hand-held device and operate on the TUI. Though this ergonomic issue could be solved by the AR headset, the headset suffered from a limited field-of view and low resolution display which might not be suitable for visualizing high resolution data. Although *PlanWell* provides a novel interaction and collaboration mechanism for remote users, its comparison with traditional maps or desktop tools must be further investigated to determine if there are clear advantages to conventional 2d maps. With respect to the collaborative features, we would like to extend the design to multiple (non-collocated) *explorers* and also to multiple (non-collocated) *overseers*, all analyzing the same reservoir model.

10 CONCLUSION

We presented our *PlanWell* prototype which facilitates collaborative well planning and drilling operations using AR and 3D printing technologies. This system allows a central *overseer* and an in the field *explorer* to dynamically exchange information within a shared spatial medium. The *overseer* uses a scaled 3D printed model of the petroleum reservoir surface terrain, which acts as an aid to understand the spatial nuances of the terrain and also as a tangible user interface (TUI). The seamless integration of AR with the TUI provides visual as well as tactile sensation about the petroleum-reservoir surface terrain and supports collaboration between the *overseer* and the *explorer*. The *explorer* interacts with the surface environment directly via an AR interface. Our contributions include the use of an AR interface using a 3D printed terrain model to support interactive techniques that provide spatial and structural awareness during collaborative navigational tasks. We apply this interface to a realistic petroleum engineering scenario and discuss our design and prototype implementation with domain experts. Based on these discussions, *PlanWell* could prove to be a practical tool which would provide value to collaborative petroleum engineering workflows.

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