UNIVERSITY OF CALGARY

SHVIL, PLANWELL, & FLYING FRUSTUM : Spatial Interaction With 3D Physical Maps

by

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Abstract

Spatial representations are crucial when people interact with the physical environment. For example, geographic maps are one of the primary sources for way-finding, spatial planning and navigational activities. Spatial representations of the environment, such as geographic maps, have evolved from the age-old physical paper maps to current maps on GPS navigation systems and mobile devices. Recent technological advancements enable further evolution of current 2D interactive spatial representations of the environment to physical 3D interactive representations using techniques such as 3D printing and mixed reality interaction. We believe that novel interactive technologies which leverage the physicality and spatiality offered by physical 3D spatial representations could be useful for a variety of applications such as collaborative terrain navigation, rescue missions, petroleum-well planning tasks, and human-UAV (Unmanned Aerial Vehicle) awareness. Our exploratory research presented in this thesis aims to design and implement applications across various domains where 3D spatial awareness of the terrain could be a crucial factor for the success of the task.

In this thesis, we undertake the task of designing collaborative spatial interaction techniques for physical representation of maps. We designed interfaces for the following application scenarios: collaborative terrain navigation, petroleum-well planning, and remote unmanned aerial vehicle (UAV) control. We present our research, encompassing three prototypes we designed and implemented: *Shvil*, an augmented reality interface for collaborative terrain navigation; *PlanWell*, a spatial user interface for collaborative petroleum well planning; and *Flying Frustum*, a spatial interface for enhancing human-UAV awareness. We conclude by presenting some of the design lessons we learned and describe future directions for our work.

Preface

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

- **Nico Li, Aditya Shekhar Nittala, Ehud Sharlin, and Mario Costa Sousa. "Shvil: collaborative augmented reality land navigation." In CHI'14 Extended Abstracts on Human Factors in Computing Systems, pp. 1291-1296. ACM, 2014.**

- **Aditya Shekhar Nittala,Nico Li, Stephen Cartwright, Kazuki Takashima, Ehud Sharlin, Mario Costa Sousa. "PlanWell: Spatial User Interface for Collaborative Petroleum Well Planning." In SIGGRAPH ASIA 2015 Symposium on Mobile Graphics and Interactive Applications. ACM,2015.**

- **Nico Li, Stephen Cartwright, Aditya Shekhar Nittala, Ehud Sharlin, and Mario Costa Sousa. "Flying Frustum: A Spatial Interface for Enhancing Human-UAV Awareness." In Proceedings of the Third international conference on Human-agent interaction(ACM HAI'15). ACM, 2015.**

Video Figures

This thesis contains two video figures that illustrate the interfaces described in chapters 4 and chapter 5.

- ***PlanWell* : Spatial Interface for collaborative well-planning**

  This video is available at the University of Calgary Prism Online Repository with report number : 2016-1083-02. Publication Date : 2016/1/19

- ***Flying Frustum*: A Spatial Interface for Enhancing Human-UAV Awareness**

  This video is available at the University of Calgary Prism Online Repository with report number: 2016-1082-01. Publication Date : 2016/1/18

Acknowledgements

Indian tradition equates the teacher/Guru/Advisor to God, as the Sanskrit hymn goes “acharya devo bhava” (In Devanagari/Sanskrit script: आचर्यदेवोभव). Deeply influenced by this ancient Hindu tradition I revere my advisors Prof. Ehud Sharlin and Prof. Mario Costa Sousa with highest regard.

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I would like to thank my collaborators Nico and Stephen without whom none of the prototypes in this thesis would have been possible. Thank you very much for all the help.

I would like to thank all my lab mates Allan, Reza, Bita, Felipe, Sowmya, Xiaoyang, Ahmed, for bearing with me for two years. For a grad student, lab is your first home, and you guys have made the lab a home. I will always cherish and miss those beautiful "coffee times" and the random discussions we had.

I would like to thank the members of the iLab and Graphics jungle labs for being bright and friendly communities, creating a dynamic environment for exchange of ideas.

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Last but not the least, a big thank you to my family who stood by me for all my decisions and providing constant support and encouragement during this journey. Without this truly wonderful family I would not have been here.

Thank you everyone! :-)

Dedication

To my Parents
RamaKrishna Nittala and Lakshmi Nittala
and my brother
Krishna Chaitanya Nittala

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Chapter 1

INTRODUCTION

1.1 Background

Spatial representations are crucial when humans interact with physical environments. For example, geographical maps are a primary resource for way-finding, spatial planning and navigation activities, and people have been creating such maps ever since the beginning of human civilization. One of the oldest maps that survives today is the representation of northern Mesopotamia scratched into an earthenware plate, dating from about BC 2400-2200 [Imhof, 2007]. Already this map shows mountains; portrayed from the side, as they would be seen when looking up from a valley. This shows that efforts and new techniques were devised to depict and represent the topography in an intuitive way since the advent of maps. The study of map-making and the practice of crafting representations of earth upon a flat surface is called Cartography. This thesis is a contemporary reflection on the age-old art of map representation through a technological lens involving 3D printing, mixed reality, UAVs and other modern techniques and tasks.

This thesis deals with the design of spatial interaction techniques or physical representation of maps. The evolution of maps has come a long way from physical paper maps to digital maps available on mobile devices and GPS navigation systems. Topography and elevation are among the most important pieces of information on many maps. Traditionally, cartographers attempted to make the terrain more accessible by using relief representations such as contour lines, shaded relief and elevation colour-

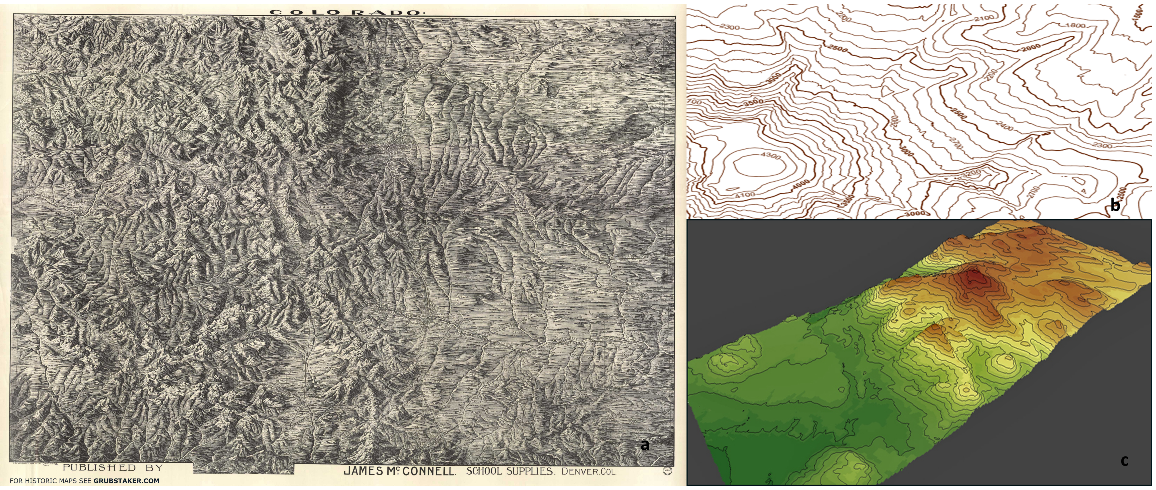

Figure 1.1: Various representations of elevations in maps (a) shaded relief map of Colorado in 1894 (b) Elevation represented as contour lines in a contour map (c) Elevation colored map with contour lines

ing [Imhof, 2007]. A contour line in a contour map joins points of equal elevation above a given level such as mean sea-level. Hence contour maps are used in many applications to represent the elevations of a terrain (Figure 1(b)). Though still widely used in many domains such as military and defense applications, contour lines are difficult to read compared to other techniques [Phillips et al., 1975] [Rapp et al., 2007] but with training it is possible to extract absolute elevations by interpolating between the contour lines. Another method cartographers use for relief representation is through shaded relief maps. Shaded relief or “hill-shading” is a technique in which the terrain is shaded to simulate the highlights and shadows produced by a light source (Figure 1(a)). It is widely used in modern maps including many digital mapping services. This approach was pioneered by Swiss cartographers in the late 19th century and was further refined and documented by cartographers like Eduard Imhof [Imhof, 2007] and uses natural visual cues to suggest the shape of the terrain. The use of illumination and shadows in “hill-shading” produce an appearance of the three-dimensional space.

Elevation coloring or “hypsometric tinting” is another technique which uses color gradients to visualize terrain elevation. Colors may be modulated with illumination to more clearly illustrate shaded and illuminated terrain slopes. Relief shading and elevation colouring provide only relative elevation, but are easier and faster to read than contour lines and portray the terrain as a continuous surface(shown in Figure 1(c)) [Castner and Wheate, 1979] [Phillips et al., 1975] [Potash et al., 1978].

Intuitive spatial representation of the topographical maps has been of particular interest to Cartographers, geographers and computer scientists. Over the past few years, new visualization techniques have been developed to better represent and enhance perception of the maps. For example, [Willett et al., 2015] developed a set of non-intrusive, direct manipulation interactions that expose depth and shape information in terrain maps using ephemeral animations. This interactive relief shearing on interactive digital maps reveals depth information via shearing animations on 2D maps and can be paired with existing interactions such as pan and zoom.

Recently, the GeoViz and cartography community has also explored the use of physical models of landscapes, and city models for better spatial perception [Rase, 2009].

Traditionally, the Cartography community has only focused on novel representations of height and altitude, and to the best of our knowledge, no previous work studied the performance of 3D physical maps with the 2D maps with standard tests such Line-of-Sight(LOS) comparisons, relative elevation comparisons and absolute elevation comparisons.Physical models have the advantage over 2D drawings that slight movements of the head or body suffice to compare heights, to solve viewing ambiguities or to reveal parts of the model that might be obscured in a fixed view. The estimation of distance and height within the model is easier with a physical model

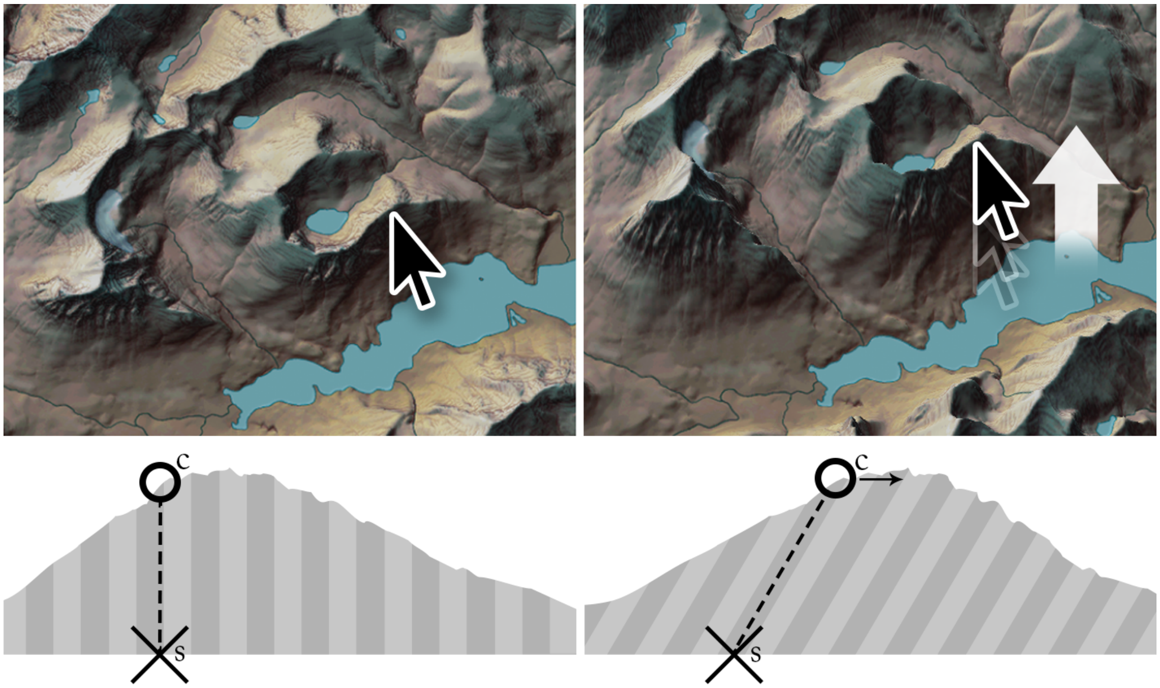

Figure 1.2: Lightweight relief shearing for Interactive maps by [Willett et al., 2015]. Using explicit interactive relief shearing, the user grabs a point on the map (left) and drags it upward (right). The base of the terrain model stays in place, but the model is sheared so that the selected point remains under the cursor, revealing the shape of the terrain. When released, the map animates back to the original un-sheared position.

due to the lifelong experience with 3D views. Physical models have an advantage over Virtual Reality (VR) methods when a group of people are trying to grasp spatial situation.

3D Physical representation of the maps offer the advantages of physicality and spatiality, and to the best of our knowledge, few interfaces have been designed or built that leverage the advantages offered by the 3D physical maps. This thesis aims to explore the design of collaborative spatial interfaces for physical maps and to provide a set of application instances where such interfaces could be beneficial.

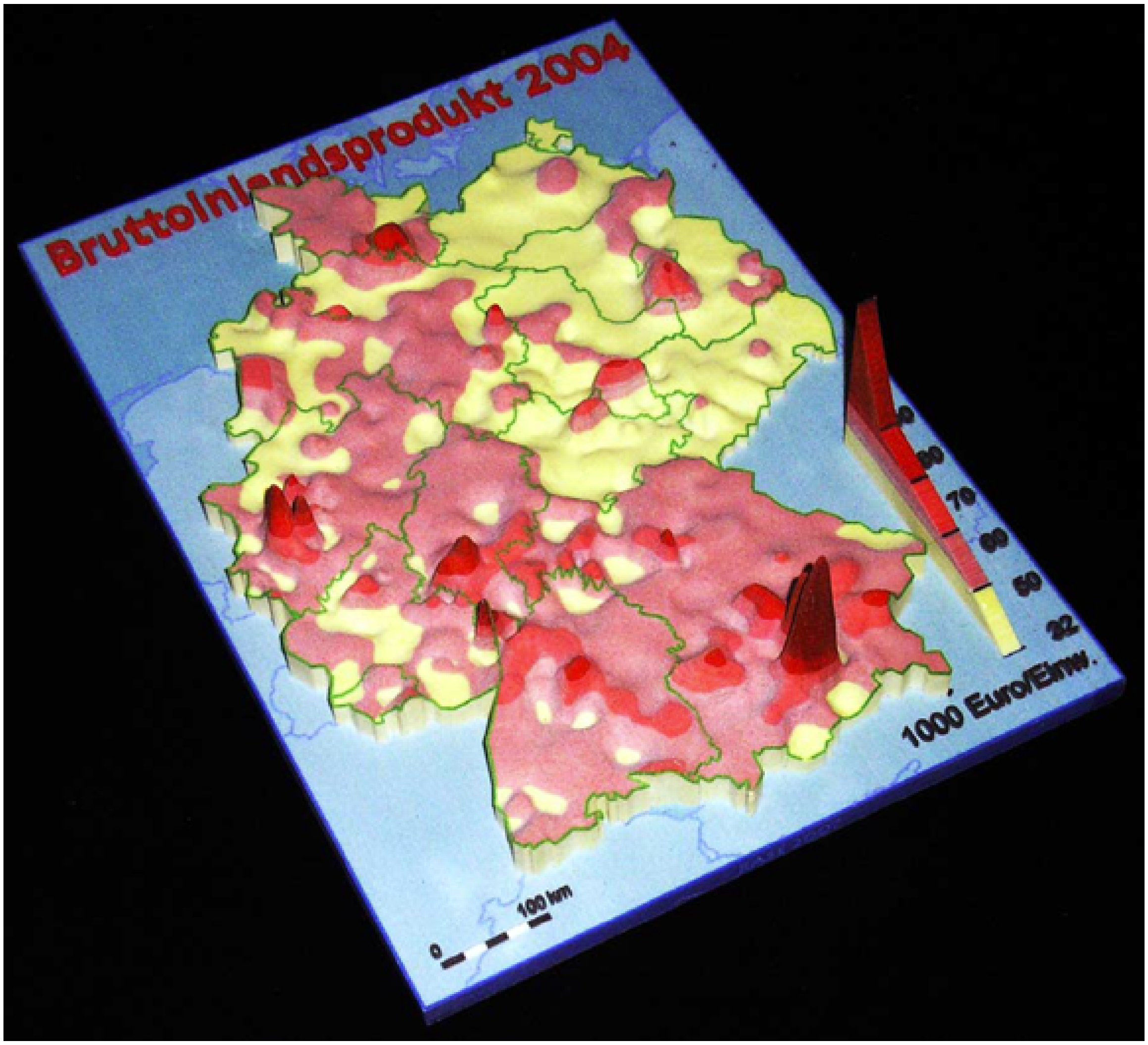

Figure 1.3: 3D printed physical representation by [Rase, 2009]

1.2 Motivation: Why Spatial Interfaces for Physical Maps

The goal of this thesis is to explore the design, and to build spatial collaborative interfaces which take advantage of the spatiality and physicality offered by the 3D physical maps.

Many collaborative field tasks involve centralized remote mission control overseeing multiple in-field teams. Oftentimes the collaboration between the remote mission control and the in-field teams requires real-time information sharing where data needs to be dynamically communicated, processed, and represented to each stakeholder according to their different roles in the task. The need to continuously and properly represent data, adapting it to each participant's perspective, situational awareness and role in the task is an inherent challenge that can hinder collaboration. Failing to provide a clear representation of the shared data within the different task contexts and scales can prevent the remote mission control from effectively advising the in-field teams, or limit the teams from situating the mission control's requests within the context of the task. Such failures could be very expensive in critical applications such as Remote rescue missions, remote defence monitoring systems etc. Our motivation for this thesis comes from various application tasks in the following domains: Land navigation, petroleum engineering, human-UAV tele-operation, military expeditions, search and rescue operations where spatial awareness of the terrain is essential for the two remote teams to make swift and effective decisions.

Users at of both the remote mission control and the on-field explorers explorations tasks rely heavily on the 2D maps and navigation aids. The use of 2D maps (including the contour ones) requires extensive training and even after extensive training, they impose a certain amount of cognitive load onto the users. They also have certain issues such as the inversion of depth impression (which leads to ambiguity in recognizing a mountain or a valley). The military research labs have already started experimenting with the user of outdoor-based augmented reality for military operations (Livingston et al. 2002). The advantage of such augmented-reality based systems is that it keeps the user immersed in to the local physical environment while adding appropriate points of interest (POIs) such as landmarks, routes etc into the user's surroundings. The users in the remote mission control need to have access to spatial information which cannot be provided by 2D maps and displays. There is a need for another layer of abstraction which can enhance the spatial awareness. 3D maps, city and surface models have been explored by the Urban Planning and GeoViz community (Rase, Wolf-Deiter, 2009) and they state that such 3D spatial representations are advantageous over flat 2D surface maps.

Therefore, this thesis aims to explore the design and implementation of novel spatial interfaces for physical representation of maps facilitating collaboration between remote teams.

1.3 Research Questions

The overall objective of this thesis is to explore and answer the following research questions:

- What are some of the technical limitations and strengths of a novel spatial interface for physical representations of maps?
- What are the possible application scenarios of such novel physical representations of maps?

To investigate these research questions we follow a multi-disciplinary approach and draw upon the theories and concepts from various disciplines such as interaction design, human-computer interaction, petroleum engineering, UAV-tele operation, tangible user interfaces, and computer-supported co-operative work. Therefore in this thesis, the reader will find elements from all these domains.

To address our research questions we set the following practical goals for our research:

- To design and realize a spatial interface that can leverage the spatiality and physicality offered by physical maps.

- To explore individual application instances of 3D spatial maps and then design and build spatial interfaces tailored for these instances.

1.4 Contributions

Following the research questions previously described, this thesis documents the following contributions:

- Design and implementation of *Shvil* - an augmented reality interface for collaborative terrain navigation. We also present some of the lessons learned while realizing the prototype.
- Design, Implementation and Preliminary Evaluation of *PlanWell*- a spatial interface for collaborative petroleum-well planning.
- Design and implementation of *Flying Frustum* - a spatial interface for enhancing the user spatial awareness during a remote UAV (Unmanned Aerial Vehicle) interaction task.
- We contribute lessons learned from our research on 3D interactive spatial representations which can aid future efforts in this area of research.

1.5 Approach

3D physical representation of maps can be used for a wide variety of applications such as military expeditions, gaming applications, collaborative field navigation, geological field-trips, petroleum well-planning, theatre and performing arts. However, in this thesis we designed and built three prototypes: *Shvil*, *PlanWell* and *Flying Frustum* for the specific tasks of collaborative land navigation, collaborative petroleum-well planning and enhancing human-UAV awareness respectively. Our prototypes are meant to augment and support the existing methods and tools but not to replace them.

For our first prototype *Shvil* we explored the design of a system that provides real-time information exchange between the outdoor explorer (outdoor user) and an indoor *overseer* by using the same topographical representation of the terrain at difference scales. In case of the *explorer* geo-location based augmented reality is used and related Points of Interest (POIs) are overlaid onto the physical terrain surrounding the *explorer*. We provide a scaled-down 3D representation of the same topography to the *overseer* (indoor user). Hence both the users are interacting over the same spatial representation at different scales.

Our second and third prototypes are application scenarios which aim to address our second research question. These applications have been designed for the petroleum engineering and remote-UAV tele-operation domains respectively.

In our second prototype, we use a petroleum-engineering task as our application scenario. We designed and implemented our prototype of *PlanWell* which enables an *overseer* and an *explorer* to collaboratively plan the location of petroleum wells on the physical terrain. Since the *overseer* and *explorer* interact with the same terrain at different scales, we believe that they share the same spatial awareness which is required for well-placement and planning. We conducted a preliminary evaluation of our prototype by conducting two focus group sessions with the domain experts and present the results in chapter 4.

In the third prototype, we explore the design of a spatial interface that we believe can enhance the spatial awareness during a remote UAV (Unmanned Aerial Vehicle) tele-operation task. Tele-operating a drone over a remote terrain is a very complex task and often requires the operator to have significant level of spatial awareness of the terrain to safely operate the drone. We believe that the physical representation of the terrain models help in enhancing the spatial awareness which might reduce the cognitive load for tele-operating the UAV.

1.6 Thesis Overview

The remainder of this thesis proceeds as follows:

- In Chapter Two, we provide an overview of the key related work regarding different elements of this thesis. We discuss a number of relevant efforts in the realm of Augmented Reality, Computer Supported Cooperative Work (CSCW), Tangible User Interfaces (TUIs), human-robot interaction and terrain exploration.

- In Chapter Three, we present in details, the design and implementation of *Shvil* : an augmented reality interface for collaborative terrain navigation. We report the results of the technical evaluation and the lessons we learnt while realizing the prototype.

- In Chapter Four, we present *PlanWell* the petroleum-engineering application scenario for 3D printed terrain models which enables petroleum engineers to collaboratively plan the location of petroleum wells. We briefly present an overview of the oil and gas domain to setup the context for the design, implementation and preliminary evaluation of the *PlanWell* prototype.

- In Chapter Five we introduce *Flying Frustum* which is a prototype designed and developed for enhancing the human-UAV awareness during a UAV tele-operation task. We provide a brief overview of situational and human-UAV awareness and describe in details the design and implementation of the *Flying Frustum* prototype.

- In Chapter Six, we present the lessons learned from our research and discuss our reflections which can help facilitate further research in this area.
- In Chapter Seven, we present some of the avenues for future work and conclude this thesis by revisiting and highlighting our contributions.

Chapter 2

BACKGROUND AND RELATED WORK

This thesis is concerned with the design of novel spatial user interfaces for 3D physical maps. We designed, and developed spatial interfaces for 3D physical maps across various domains. All the prototypes and application instances detailed in this thesis encompass the following major themes in HCI research:

- Navigation and Collaborative Way-finding
- Tangible User Interfaces for Remote Collaboration
- Collaborative Augmented Reality
- Computer Supported Co-Operative Work
- Human-Robot Interaction

This section presents brief overview of the five themes of the research and discusses the prior related work pertaining to all these themes.

2.1 Navigation and Collaborative Way-Finding

Land Navigation is a military term for the study of traversing through unfamiliar terrain by foot or by a land vehicle. Such land navigation exercises are very common in many domains such as military and defense, geology, petroleum engineering and also in sports such as orienteering. Land navigation typically requires the ability to read maps, use compass and other navigational skills, and hence the geographical information presentation plays an important role in the success of the task. Way-finding is another term which closely relates to land navigation. Way finding refers to various ways in which people orient themselves in physical space and navigate from place to place. Recent advances in technology have provided for better interfaces and interaction techniques to accomplish these tasks and various scientific studies have also been conducted to examine how people performed collaborative way-finding and navigation tasks.

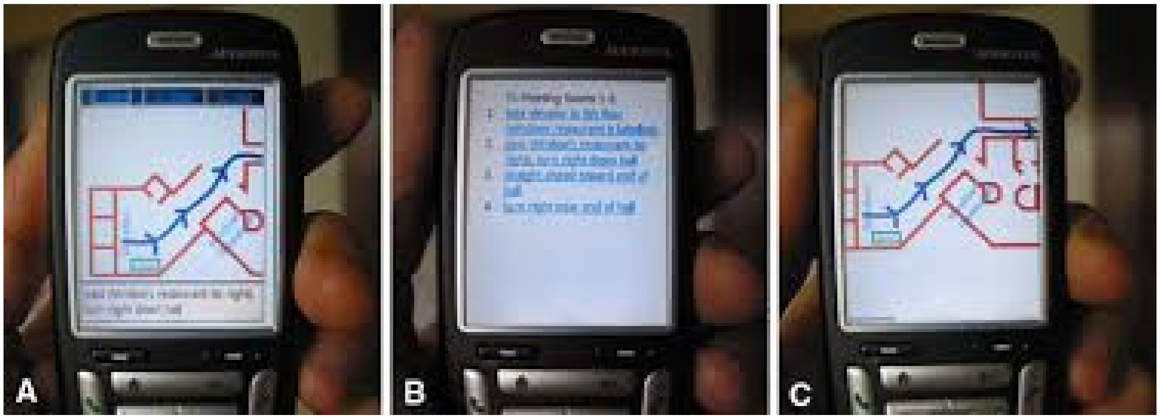

Figure 2.1: The two route interfaces and the scroll map used by [Reilly et al., 2008]. (a) The paged interface, providing a map section and textual description for each phase in a route. (b) The textual interface, providing the entire route as a numbered list. (c) The scroll map, traversed using the jog dial

[Bidwell et al., 2005] proposed design guidelines for designing navigational aids for way-finding and navigational applications. Mobile map interfaces were augmented with other tools such as kiosk maps for way-finding and navigation inside buildings. The studies showed that using kiosk maps alongside a mobile way-finding application promoted acquisition of spatial knowledge [Reilly et al., 2008]. [Reilly et al., 2009] (figure 2.1)conducted studies to examine how pairs share a single mobile phone during a collaborative way-finding activity. The authors provide a classification of strategies, role relationships and phone interactions employed to conduct the way-finding activities.

[Bouwer et al., 2011] presented a number of requirements for mobile indoor navigation systems that support collaborative destination and path finding tasks based on observation studies of visitors at a large public fair.

In our first prototype *Shvil* [Li et al., 2014](explained in chapter 3), we draw inspiration from this existing work on navigational and way-finding interfaces and realized an augmented reality interface for collaborative land navigation.

2.2 Tangible User Interfaces For Remote Collaboration

Tangible user interface is a user interface which allows an user to interact with digital information through physical form. Interactions with digital information are largely confined to Graphical User Interfaces (GUIs). The Graphical User Interface (GUI) has been in extensive use since 1970s and has first appeared commercially in the Xerox 8010 Star System in 1981 [Smith et al., 2001]. With the commercial success of the Apple Macintosh and Microsoft Windows, the GUI has become the standard paradigm for human computer interaction (HCI). GUIs represent information with pixels on a display. These graphical representations of information can then be manipulated with remote controllers such as mice and keyboards. Though such graphical representation of information made a significant improvement over its predecessor Command User Interface (CUI), interaction with the pixels on the display is inconsistent with our interactions with the rest of the physical environment in which we live. When interacting with the GUI world, we cannot take advantage of our dexterity or utilize our skills for manipulating various physical objects such as our ability to shape models of clay or building blocks. Tangible user interfaces (TUIs) aim to take advantage of these haptic interaction skills, which is a different approach from GUI. The key concept behind TUIs is to give physical form to digital information [Ishii, 2007] [Dourish, 2004].

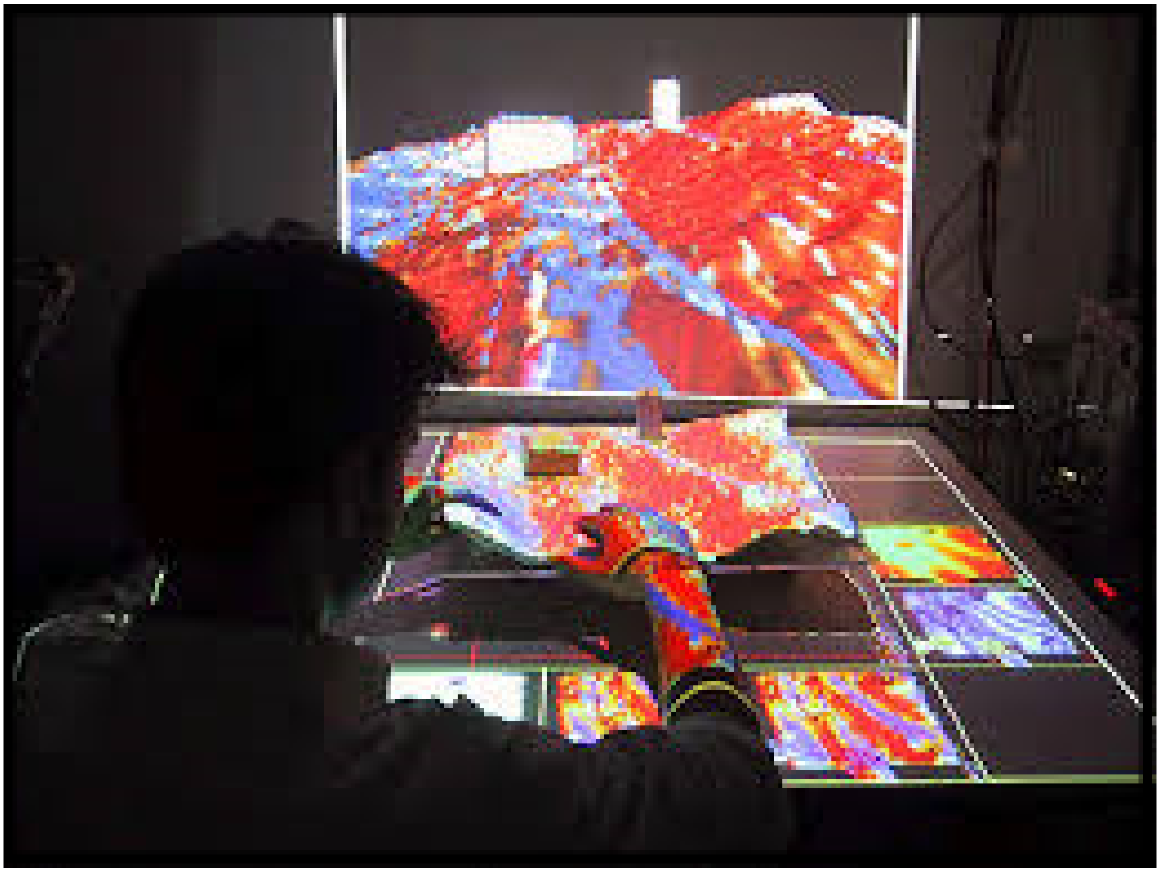

Figure 2.2: Illuminating Clay developed by [Piper et al., 2002]. for Landscape analysis.

Urp [Underkoffler and Ishii, 1999] was the first tangible user interface developed that facilitated collaborative urban planning and design. Since, then tangible user interfaces (TUIs) have been developed for various domains and applications such as Reservoir engineering, Landscape planning and molecular biology. *Illuminating clay* is a 3-D tangible interface that was designed for landscape analysis [Piper et al., 2002](figure 2.2). Users of the system could alter the topography of a clay landscape model while the changing geometry is captured in real-time by a ceiling-mounted laser scanner. A depth image of the model served as an input for landscape analysis functions and the result of the analyses were projected back in to the workspace and registered with the surface of the model. *Snakey* is another tangible user interface that was designed to support well path planning in reservoir engineering domain [Harris et al., 2011]. The design of *Snakey*(figure 2.3(a)) emphasized intuitive manipulation and interaction with 3D curves, common to underground well path exploration and planning in reservoir engineering. It facilitated tangible and collaborative interaction and spatial exploration during the multi-stage planning processes involved in well path design. Structural molecular biologists have also explored the use of tangible interfaces [Gillet et al., 2005]. Augmented reality was used to overlay 3D representations onto the tangible molecular models (figure 2.3(c) and 2.3(d)). The overlaid information could easily be changed by users switching between different representations of the molecule. In addition to providing powerful, intuitive interface, this also facilitates better understanding of the spatial relationships between molecules [Sharlin et al., 2004]. GeoTUI [Couture et al., 2008] is another system designed for geophysicists that provides props as tangible user interface on a tabletop vision-projection system for the selection of cutting planes on a geographical map of a subsoil model.

TanGeoMS [Tateosian et al., 2010] is a tangible geo-spatial modelling visualization system that couples a laser scanner, projector, and a flexible physical three-dimensional model with a standard geospatial information system (GIS) to create a tangible user interface for terrain data (figure 2.3(b)). TanGeoMS projected real-world data onto a physical terrain model and allowed the users to alter the topography of the model by modifying the clay surface or placing additional objects on the surface.

[Brave et al., 1998] proposed the use of tangible user interfaces for collabora-

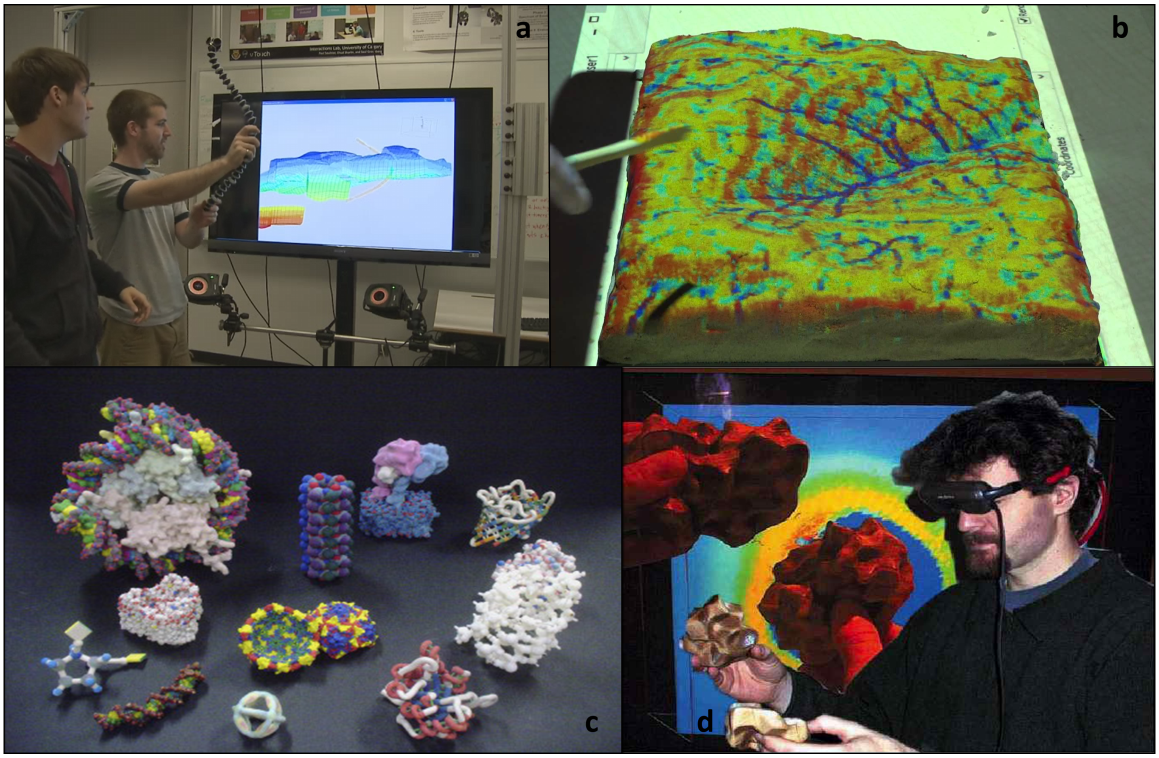

Figure 2.3: Applications of Tangible user interfaces across various domains (a) *Snakey*: A tangible user interface for supporting reservoir well planning [Harris et al., 2011].(b) *TanGeoMS* is a tangible geo-spatial modeling system [Tateosian et al., 2010]. (c) Physical models of molecular structure. (d) Augmented reality overlaid onto the physical molecular structures for analysis [Gillet et al., 2005]

tion and communication. Unlike the traditional visual and auditory media, tangible interfaces place greater emphasis on physicality and touch and hence enhance the remote collaboration and communication. They demonstrated this with two prototypes: Physically Synchronized Bench (PSyBench) and inTouch. PsyBench employed the concept of Synchronized Distributed Physical Objects to provide a generic shared physical workspace across distance.It allowed distributed users to cooperate in tangible interface application such as Illuminating Light which are heavily based around physical objects. Each physical interface object was turned into a Synchronized Distributed physical object so that it can be shared by distant users. *inTouch* [Brave

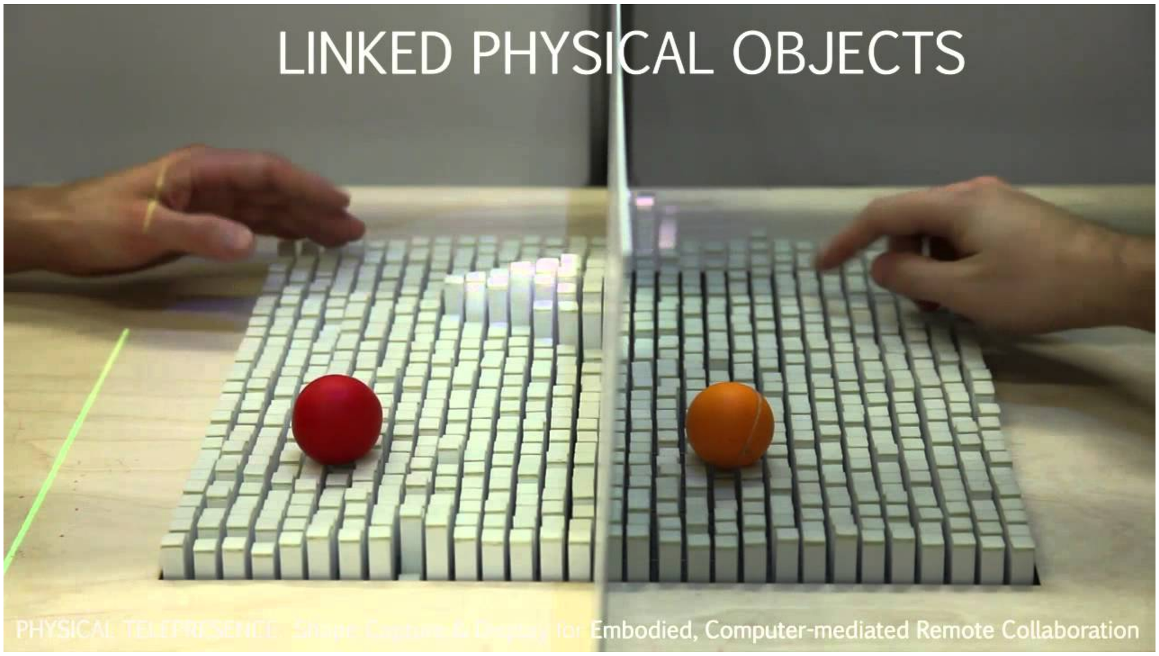

Figure 2.4: Physical Telepresence with shape transmission through actuated tables. [Leithinger et al., 2014].

and Dahley, 1997] is another tangible interface that provides interpersonal communication. *inTouch* used haptic feedback technology to create a physical link between people separated by distance. [Richter et al., 2007] built a display-based measurement system to support remote active tangible interactions. [Riedenklau et al., 2012] showcased an integrative approach to actuated Tangible Active Objects (TAOs), that demonstrated distributed collaboration support. Physical actuation, visual projection in 2D and 3D and vibro-tactile feedback were incorporated to provide multi-modal feedback.

[Leithinger et al., 2014] proposed a novel approach to physical telepresence based on shared workspaces. They described the concept of shape transmission, and proposed interaction techniques to manipulate physical objects and physical rendering of shared digital content(figure 2.4).

[Kurata et al., 2005] presented a tabgible tableTop(TTT) interface to support remote collaborative works between an expert and multiple field workers in a direct and intuitive way. The TTT interface consisted of a large touchscreen LCD as a tabletop display and small ultrasonic transmitters that act as physical tags on the display. The physical tags represent either each worker or each tool and since they are equipped with ultrasonic transmitters, the orientation of the tags is easily known. The TTT interface offered several remarkable features including affordances of physical tags, tag gesture and bi-manual manipulation with tags and touchscreen.

We build upon this existing work on tangible user interfaces. In chapters 3 (*Shvil* [Li et al., 2014], 4 (*PlanWell* [Nittala et al., 2015a]) and 5 (*Flying Frustum* [Li et al., 2015]), a 3D physical map acts a tangible user interface enabling the user to perform operations such as sketching and annotation. In chapters 3 and 4, we show how physical map can facilitate collaboration between two remote users.

2.3 Collaborative Augmented Reality

Augmented Reality refers to the technology where a physical,real-world environment area is augmented by computer-generated sensory input such as sound,video, graphics or GPS data. Hence, the Augmented Reality(AR) technology enhances the user's perception of reality [Azuma et al., 1997] [Alem and Huang, 2011].

Unlike virtual environments, in which a virtual world replaces the real world, in augmented reality a virtual world *supplements* the real world with additional information. This concept was first pioneered by [Sutherland, 1968] (figure 2.5).

Spatially augmented reality introduced by [Raskar et al., 1998] is a new paradigm of augmented reality where virtual objects are rendered directly

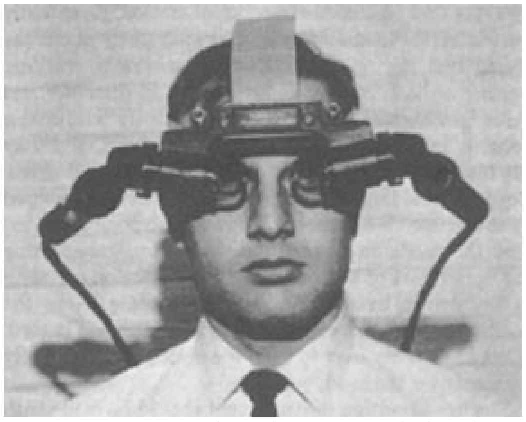

Figure 2.5: First head-mounted display realized by [Sutherland, 1968]

within or on the user's physical space. The key benefit of such spatially augmented reality is that the user does not need to wear a head-mounted display. Instead, the images of virtual objects can be integrated directly into the environment with the use of spatial displays. For example, the virtual objects can be realized by using digital light projectors to "paint" 2D/3D imagery onto real surfaces or flat panel displays and current mobile displays could also be user to provide AR experience to the users (figure 2.6).

Since its introduction, Augmented Reality has been used in a variety of applications. Touring Machine is a 3D mobile augmented reality system that was designed for exploring the urban environment [Feiner et al., 1997]. The application was designed to provide the user with information about their surroundings, creating a personal "Touring Machine". The prototype assists users who are interested in the authors' university campus overlaying information about items of interest in their vicinity. The user's position is tracked with GPS and the content is updated dynamically and presented to the user (figure 2.8).

The domain of civil engineering has also experimented with the use of Augmented reality for Virtual redlining and annotations on underground infrastructure such as gas pipes or power lines [Schall et al., 2008] (figure 2.7(a)). Similarly, Landscape and Urban planning community has also explored the use of augmented reality techniques in combination with geographic information systems (GIS) to dynamically augment a landscape view with weed (blackberries) data [Ghadirian and Bishop, 2008](figure

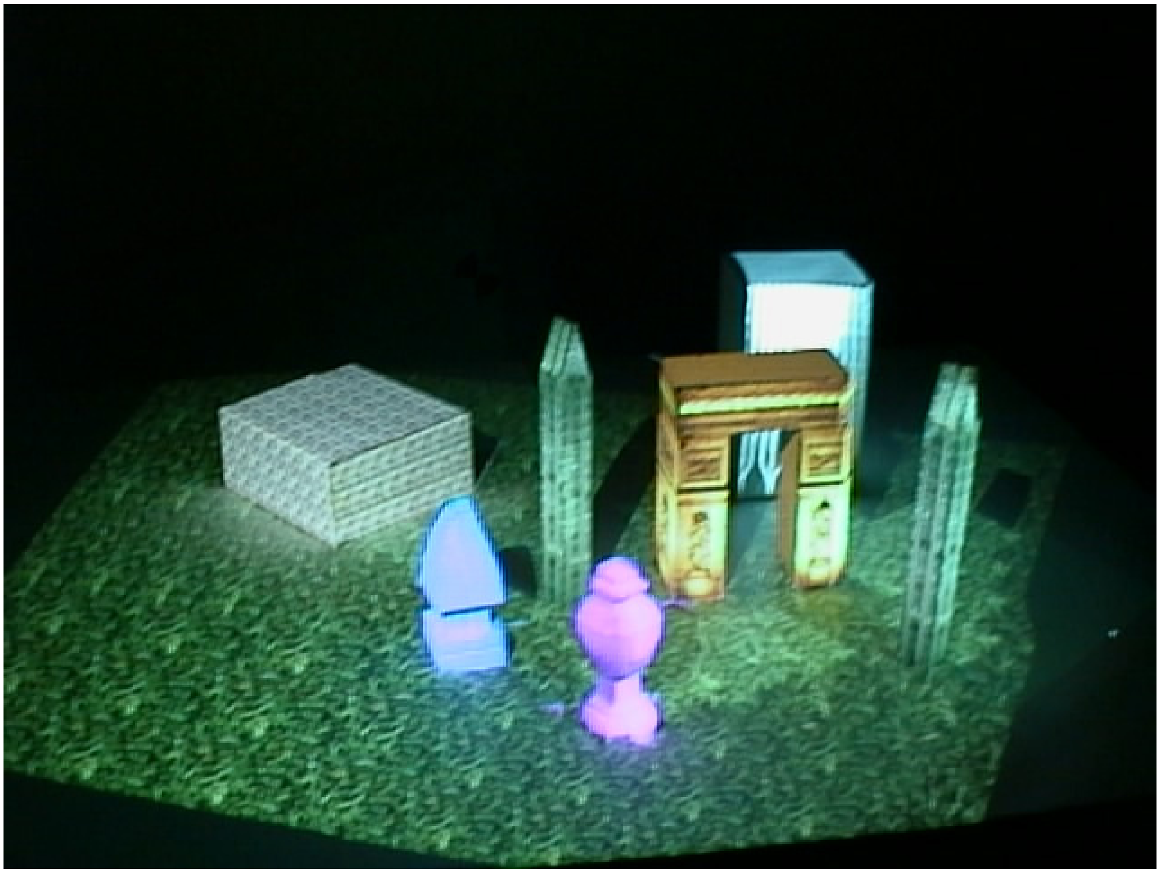

Figure 2.6: Spatially augmented reality by [Raskar et al., 1998]

2.7(c)).

[Lapides et al., 2012] implemented a seamless augmented reality tracking system for tabletop reservoir engineering which enables the reservoir engineers to interact with the petroleum reservoir data-sets. The users can use the mixed reality tracking system(figure 2.7(d)) as a private work-space while the tabletop provides the collaborative public access to the experts. Augmented reality has also been used for collaborative crime scene investigation. [Poelman et al., 2012] designed and realized a novel mediated reality system that supports collaboration between crime scene investigators during a first analysis on a crime scene, remotely supported by expert colleagues (figure 2.7(b)).

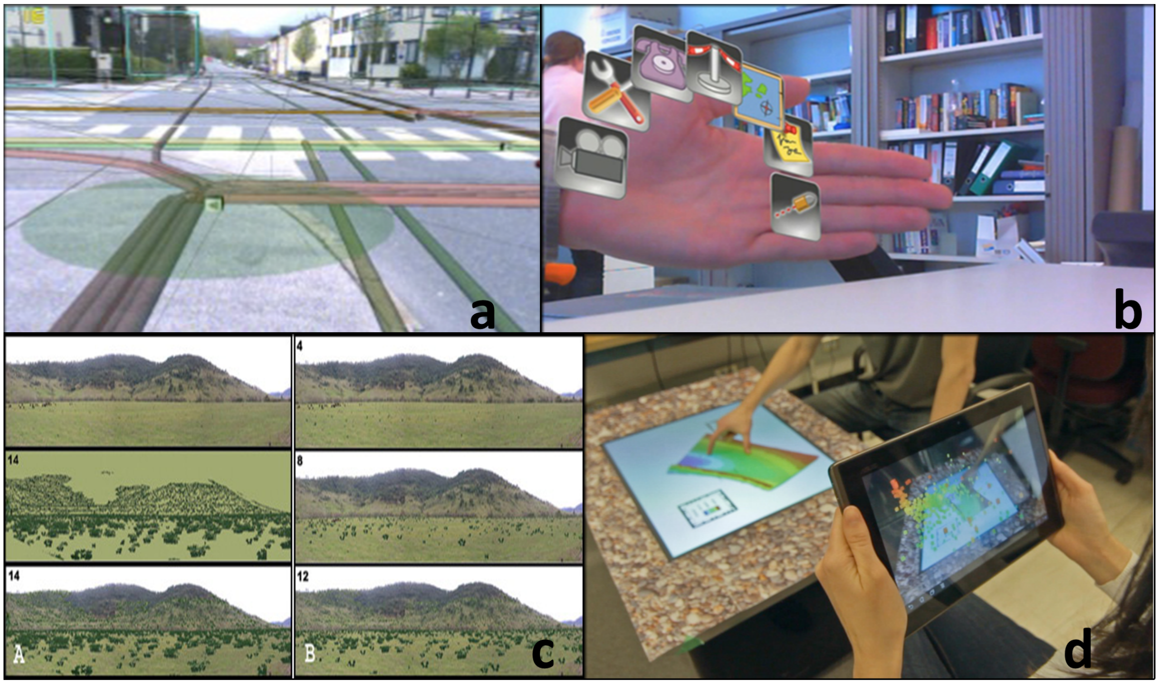

Figure 2.7: Applications of Augmented Reality across various Domains (a) Augmented reality for civil engineering in real environments [Schall et al., 2008](b) Mediated Reality for collaborative crime scene investigation [Poelman et al., 2012] (c) Augmented Reality to dynamically augment a landscape view with weed data [Ghadirian and Bishop, 2008] (d) Seamless augmented reality tracking system for tabletop reservoir engineering [Lapides et al., 2012]

Collaborative Augmented reality refers to systems that support collaboration between two users through the means of augmented reality [Alem and Huang, 2011] [Billinghurst and Kato, 2002]. One of the first real world teleconferencing system using augmented reality was developed by Billinghurst and Kato. [Billinghurst and Kato, 2000]. Augmented reality can be used for enhancing the shared physical workspace and create a three-dimensional interface for computer supported cooperative work(CSCW). One of the first interfaces that showed the potential for face-to-face collaboration was the StudierStube project of Schmalsteig et. al [Szalavári et al., 1998]. They report the users finding the interface very intuitive and conducive to the real world collaboration. The StudierStube researchers identify five key features of collaborative AR environments:

- Virtuality: Objects that do not exist in the real world can be viewed and examined.
- Augmentation: Real objects can be augmented by virtual annotations.
- Cooperation: Multiple users can see each other and cooperate in a natural way.
- Independence: Each user controls his own independent viewpoint.
- Individuality: Displayed data can be different to each viewer.

Figure 2.8: Mobile Augmented Reality System developed by [Höllerer et al., 1999]. (left) indoor user interface showing the overview of the outdoor scene and (right) an outdoor user exploring the spatially registered information with the real-world.

reality system (MARS) in 1999 that employs different user interfaces to allow outdoor and indoor users to access and manage information that is spatially registered with the world. Outdoor users can experience spatialized multimedia presentations that are presented on a head-tracked, see-through, head-worn display used in conjunction with a hand-held pen-based computer. Indoor users can get an overview

Figure 2.9: God-Like Interactions by [Stafford et al., 2006]. (a) indoor user pointing at a location on the table-top surface, which contains the representation of the outdoor world. (b) Outdoor AR view showing the indoor user's hand appearing form the sky and pointing toward a location in the distance.(c) Physical objects used as props to convey extra meaningful information about the environment.

of the outdoor scene and communicate with the outdoor users through a desktop interface or a head and hand-tracked immersive augmented reality interface. Human Pacman [Cheok et al., 2004] is a novel interactive entertainment system that ventures to embed the natural physical world seamlessly with a fantasy virtual playground by capitalizing on mobile computing, wireless LAN, ubiquitous computing and motion-tracking technologies. It facilitates collaboration and competition between players in a wide outdoor physical area which allows natural wide-area human-physical movements. [Stafford et al., 2006] presented new interaction metaphor of "god-like interaction" for improved communication of situational and navigational information between outdoor users equipped with mobile augmented reality systems and indoor users equipped with tabletop projector display systems(figure 2.9). Perceptive Workbench developed by [Leibe et al., 2000] enabled spontaneous and unimpeded interface between physical and virtual worlds. It uses vision-based methods for interaction that eliminate the need for wired input devices and wired tracking. 3D hand position, pointing direction, and sweeping arm gestures are also integrated into the system and such gestures enhance selection and manipulation in navigation tasks.

Figure 2.10: World-Stabilized annotations for live mobile remote collaboration [Gauglitz et al., 2014]. (a) Screenshot of the remote helper interface. (b) Screenshot of the local user with live annotations made by the remote user.

More recently, the ubiquity of mobile devices has led to the widespread use of mobile augmented reality systems for remote collaborative tasks. [Henrysson et al., 2005] developed a system that supports collaborative AR gaming. [Gauglitz et al., 2014] developed a system that supports an augmented shared visual space for live mobile remote collaboration on physical tasks. The remote user can explore the scene independently of the local user's current camera position and can communicate via spatial annotations that are immediately visible to the local user in augmented reality(figure 2.10). Mobile Helper [Robert et al., 2013] is another remote guiding prototype that is developed on a tablet device with the feature of allowing helpers to use hand gestures to guide the remote worker for various physical tasks.The worker side interface integrates a near eye display to support mobility and real time representations of the helper's hand gestures using augmented reality technologies. TeleAdvisor [Gurevich et al., 2012] is another novel solution that was designed to support remote assistance for real-world scenarios. It consists of a video camera and a small projector mounted at the end of a tele-operated robotic arm. This enables a remote helper to view and interact with workers' workspace, while controlling the point of view.

Our work draws inspiration from systems such as MARS [Höllerer et al., 1999] and the above mentioned existing work to enable spatial interaction with the terrain through augmented reality.

2.4 Computer Supported Co-Operative Work

Computer Supported Co-operative Work (CSCW) is a generic term that combines the understanding of the way people work in groups with the enabling technologies of computer networking and associated hardware, software, services and techniques [Wilson, 1991]. It was first coined by Irene Greif and Paul M.Cashman in 1984, at a workshop attended by individuals interested in technology to support people in their work [Grudin, 1994].

The advances in CSCW research has led to the development of real-time communication systems that support effective collaboration between physically dispersed teams. CSCW researchers are developing many novel video mediated communication (VMC) systems that allow distant colleagues to accomplish tasks with same or better efficiency and satisfaction than when collocated [Hollan and Stornetta, 1992]. Although the traditional VMC systems are commonly used and are able to meet the needs of the users, they may not be suitable for communicating the same level of spatial awareness between the remote users [Gaver, 1992].

Spatiality in Computer Supported Co-operative work(CSCW) has been an active research area since a long time. [Kuzuoka, 1992] introduced “spatial workspace collaboration” and developed a SharedView system having the capability to support spatial workspace collaboration. One of the attempts in supporting spatialiy for collaboration was FreeWalk [Nakanishi et al., 1998]which is an application that supports casual meetings among many people. It provides a three-dimensional(3D) community where participants can behave just as they do in real life(figure 2.11(a)). [Regenbrecht et al., 2004] presented the concept of Augmented Virtuality for remote collaboration. Their system allows three participants at different locations to communicate over a network in an Augmented virutality environment. Integrated into the AV(Augmented Virtuality) environment are live video streams of participants spatially arranged around a table, a large virtual presentation screen for 2D display and application sharing, and 3D geometry(models) within the room and on top of the table. [Barakonyi et al., 2004] developed a novel Augmented Reality(AR) videoconferencing system combining a desktop-based AR system and a videoconferencing module(figure 2.11(b)).

Figure 2.11: (a) Freewalk interface from [Nakanishi et al., 1998] and (b) Augmented Reality Video conferencing interface from [Barakonyi et al., 2004]

[Sakong and Nam, 2006] presented new interaction techniques for supporting telepresence in distributed 3D collaborative design environments. Synchronized turntables were employed which enhanced physicality in manipulation of virtual 3D objects and provided physical cues for awareness of others. Virtual shadows, visualization of hand movements of remote partners were also designed which implied not only location and activities of others but also indicated pointing and gestures towards 3D objects(figure 2.12). [Robinson and Tuddenham, 2007] derived design guidelines for

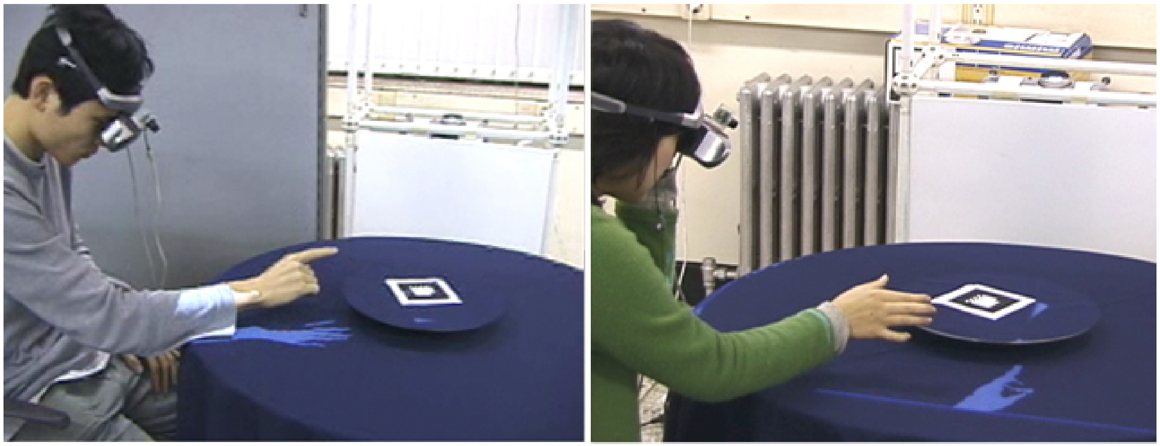

Figure 2.12: Supporting Telepresencein distributed 3D collaborative design environments. Virtual shadows, visualization of hand movements of remote partners were designed to indicated location and activities of collaborators and also facilitated pointing and gestures towards 3D objects.

mixed-presence and remote collaboration for tabletop systems.They also presented Distributed Tabletops, a novel system that can be customized to investigate various mixed-presence tasks. Previous research also explored collaborative navigation, though in CVE(Collaborative Virtual Environments). [Yang and Olson, 2002] explored collaborative navigation task in CVE and investigated the effect of the dimension of egocentric-exocentric perspectives on collaborative navigation performance. Based on the results of the study they proposed a set of design guidelines to design interaction techniques that support collaborative navigation and awareness in CVE.

[Hauber et al., 2006] compared a variety of social and performance measures of collaboration when using two approaches of adding spatial cues to video-conferencing:

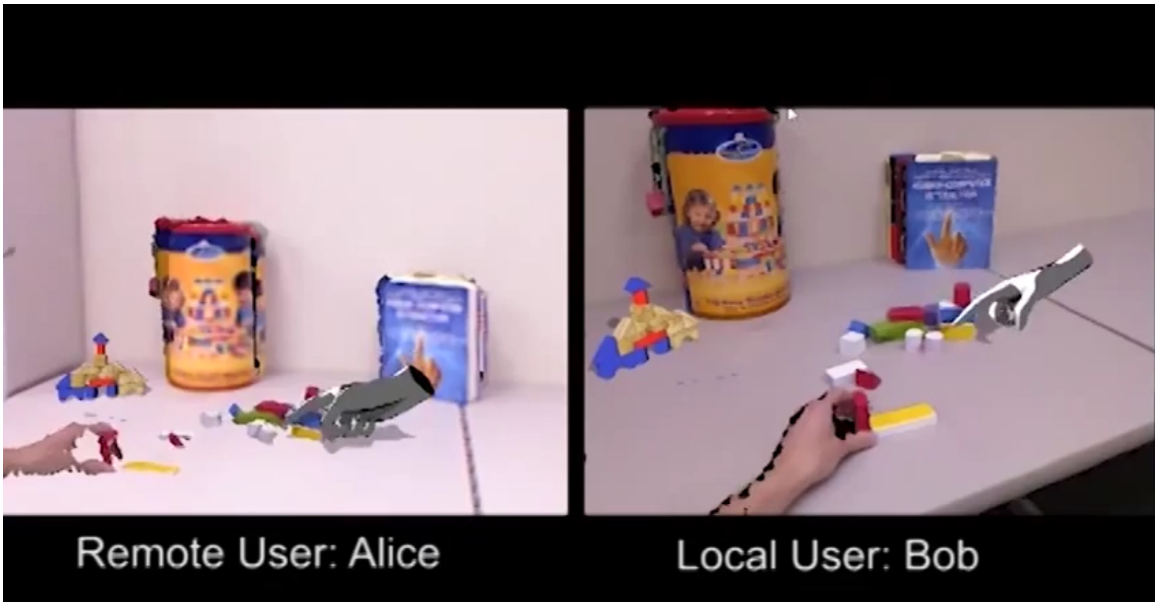

Figure 2.13: Screenshot of the BeThere collaborative interface. For the remote user "Alice" the scene is reconstructed using depth and rgb cameras and the local user's actions are represented through a 3D virtual hand. Similarly, the local user "Bob" can see Alice's interactions represented by the 3D virtual hand.

once based on immersive 3D, the other based on traditional 2D video-planes. Their studies showed that the 3D interface positively influenced social-and-co-presence measure in comparison to 2D but the task measures favored the two-dimensional interfaces.

3D helping hands was a gesture based Mixed Reality system for remote collaboration [Tecchia et al., 2012]. It enabled a remote helper to assist a physically distant worker to perform manual tasks through hand gestures.

BeThere was a proof-of-concept system designed to explore 3D input for mobile collaborative interactions [Sodhi et al., 2013]. 3D gestures and spatial input allowed remote users to perform a variety of virtual interactions in a local user's physical environment.The system used depth sensors to track the location of user's fingers,as well as to capture the 3D shape of objects in front of the sensor(figure 2.13).

JackIn is another new human-human communication framework for connecting two or more people. With first-person view video streaming from a person(called *Body*) wearing a transparent head-mounted display and a head-mounted camera, the other person (called *Ghost*) participates in shared first-person view [Kasahara and Rekimoto, 2014].With

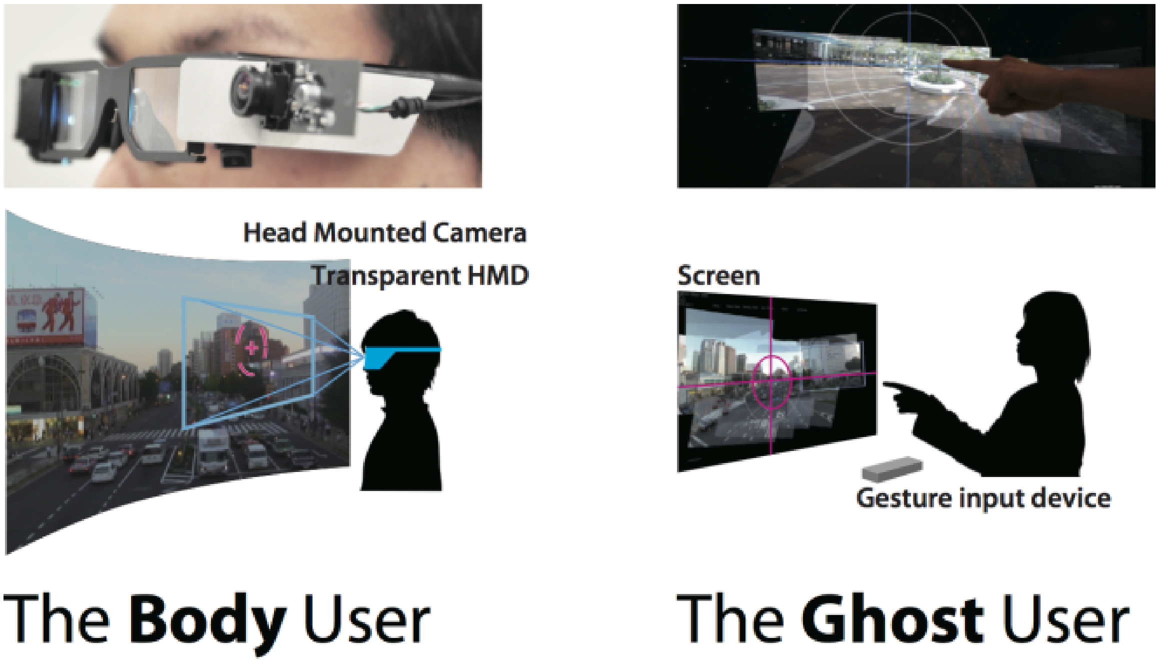

Figure 2.14: JackIn interface (left) First-person video streaming from *Body* user and (right) the *Ghost* user can view the first-person video from *Body user, understand spatialiy and interact with scene*

JackIn, people's activities can be shared and assisted or guidance can be given through other's expertise. User evaluation of JackIn revealed that *Ghosts* could easily understand the spatial situation of *Body* (figure 2.14).

2.5 Human-Robot Interaction

Human robot interaction is the study of interactions between the robots and humans and is commonly referred as HRI. UAV(Unmanned Aerial Vehicle) and semi-autonomous UAV control and interaction is an area within HRI which deals with the studying, designing, implementing and evaluating interfaces which aid in operating the UAVs. A number of remote teleoperation interfaces have been developed to operate these UAVs remotely [Quigley et al., 2004], and as these UAVs are increasingly becoming common for a variety of tasks such as search and rescue operations, military expeditions, and geological explorations, the need to design and develop novel human-UAV interfaces is becoming even more essential.

Maintaining situational awareness has a crucial impact on the design of remote teleoperation interfaces [Endsley et al., 2000] [Drury et al., 2006a]. While the original situational awareness theory evolved around pilots, air traffic controllers and other critical interaction settings, it soon emerged as a more general CSCW theory, which can be applied to various workplace scenarios (for example [Gutwin and Greenberg, 2002]). The domain of Human-Robot Interaction (HRI) adapted situational awareness onto its own unique collaborative settings and tasks, using the term HRI Awareness, and recognizing the inherently different and asymmetrical roles humans and robots play within the HRI collaborative settings [Yanco et al., 2004] [Drury et al., 2003]. Work was also done on applying HRI awareness to UAVs related settings and tasks, for example by studying Desert Hawk UAVs and their operators [Drury et al., 2006b]. These efforts resulted in a discussion of a subset of HRI-awareness called Human-UAV awareness [Drury and Scott, 2008], which addresses the specified interaction space of UAV and their remote operators.

As previously mentioned, communicating directionality and human-UAV aware-

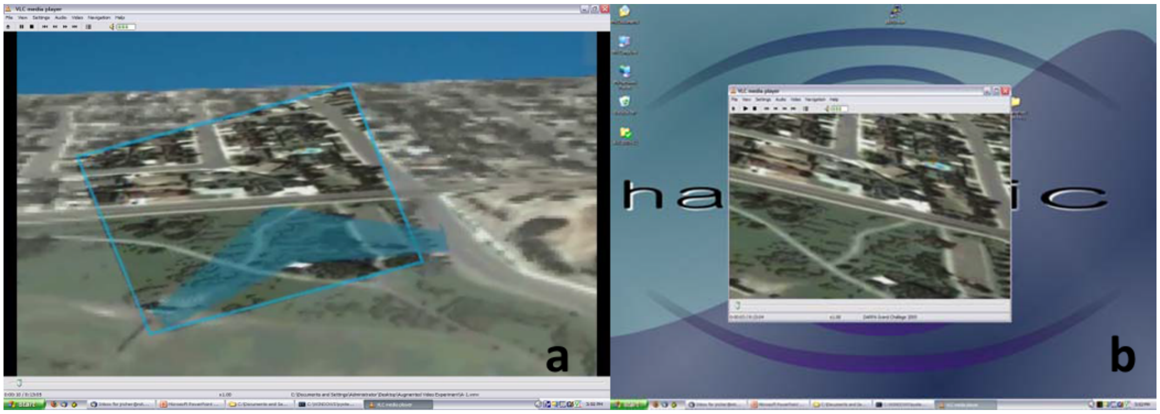

Figure 2.15: UAV interaction design approach developed by [Drury et al., 2006a] to improve the situation awareness of the conditions pertaining to the UAVs. (a) The center of the screen shows a transparent silhouette of the UAV from behind that changes attitude in real time as the aircraft flies through the virtual environment. The video display is in the inset box. The video is geo-referenced to the pre-loaded map data, meaning that it appears on top of the map area to which it refers.(b)The video is shown in a stationery window of the same size as the video presentation in the augmented display.

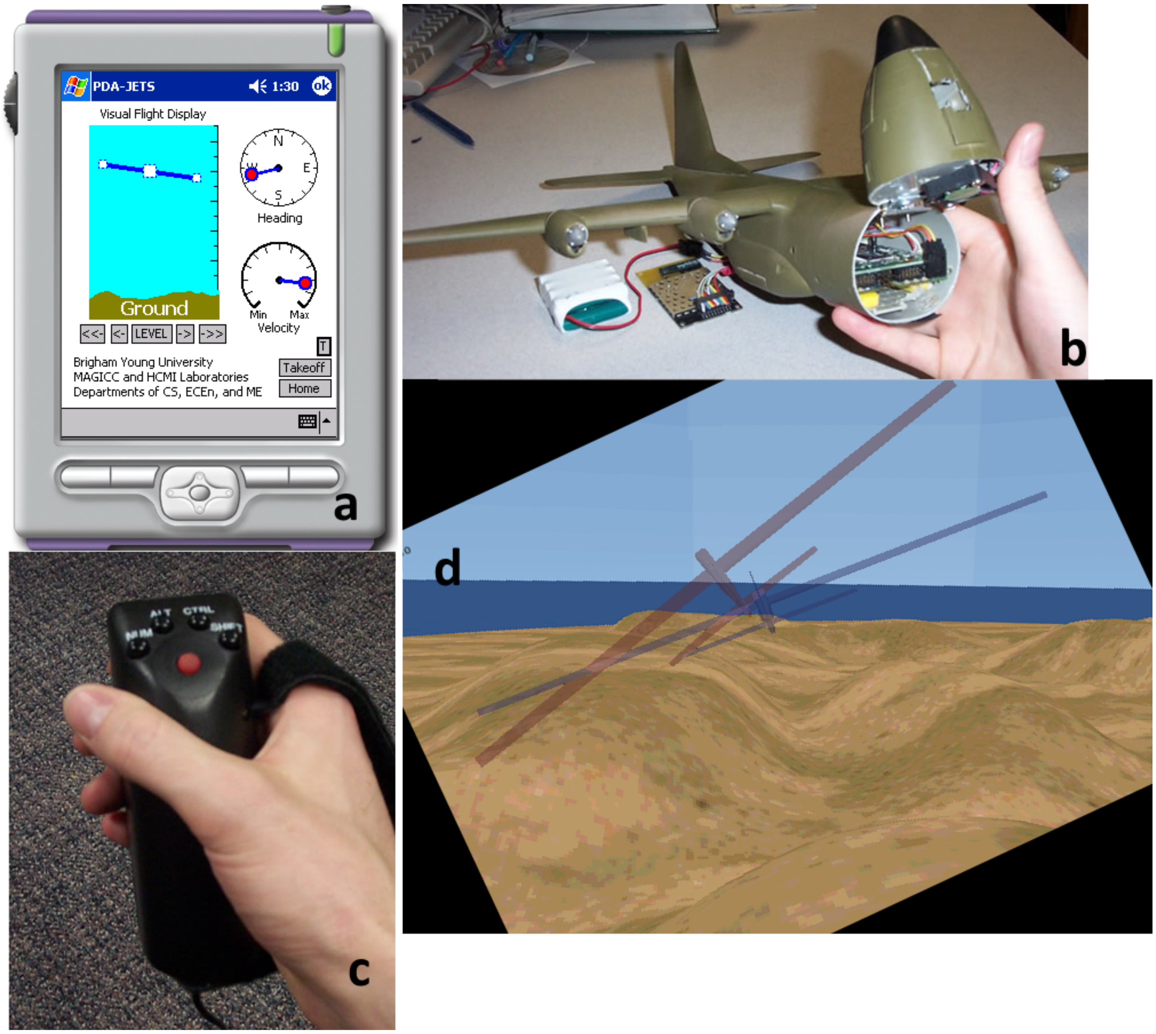

Figure 2.16: Various human-robot interfaces developed by [Quigley et al., 2004] that support real-time control of small semi-autonomous Unmanned Aerial Vehicle(UAV).(a) A PDA interface to control the heading and ”wing-view” display (b) Tangible the physical icon interface which is opened to show the placement of its on-board autopilot (c) A Twiddler controller to facilitate single-handed operation (d) Mixed-Reality Physical Icon interface. The actual telemetry,plotted as a transparent blue OpenGL model, is shown slightly rolling to the left. The user has requested a climb and a sharper left roll, as shown in the second OpenGL model, which is transparent red when seen in color. The simulated video image has been rolled so as to level the horizon.

ness has emerged as a significant research area in the realm of HRI. Szafir et al., [Szafir et al., 2014] explored the design of natural and intuitive flight motions that improved the ability of Assistive Free-Flyers(AFFs) to communicate intent while simultaneously accomplishing task goals. The flight paths were represented as a series of motion primitives based on natural motion principles to indicate movement intent.

Building upon their previous work, Szafir et al., [Szafir et al., 2015] explored the design space of flight intentions of robots to nearby users by using an LED ring under the drone. They applied design constraints to robot flight behaviours, using biological and air-plane flight as inspiration, and developed a set of signalling mechanisms for visually communicating directionality while operating under such constraints.

Figure 2.17: [szafir et al.2015] explored the design of visual signalling mechanisms for flying robots to support the expression of robot intent and increase usability in collocated interactions.

Drury et al., [Drury et al., 2006a] developed a UAV interaction design approach to improve the design of human-UAV interaction so that operators can have better situation awareness (SA) of the conditions pertaining to the UAVs. Their design approach uses pre-loaded terrain data to augment real-time video data sensed by the UAVs. Their hypothesis was that such augmentation of the video would improve the overall situational awareness of the operators and a counterbalanced within-subjects experiment showed that the technique helped the operators to have better comprehension of the spatial relationships between the UAV and the terrain. One of our prototypes in this thesis *Flying Frustum* (chapter 5) [Li et al., 2015] extends upon this work of Drury et al., [Drury et al., 2006a].

Flying Frustum builds on this past effort by extending the interface into 3D using a physical printout of the terrain, a situated pen-based interface that is used to draw the UAV's commands on the terrain, and 3D situated streaming video from the UAV.

2.6 Commercial Applications

There are some commercial applications that allow users to track the location of their friends and other people of interest. Though these applications such as *Apple find my Friends* [Fin, 2016] , *Glympse* [Gly, 2016], *Google Location History* [Goo, 2016] superimpose the locations on traditional 2D maps. However these applications have some major drawbacks. Firstly, though they provide information about the remote users, they do not support collaboration between the remote users. Secondly, traditional 2D maps are used which might not provide any idea about the spatiality of the users.

Our work builds upon the previous research though with notable differences. From the standpoint of spatial perception of 3D physical maps, we use 3D printed models

Figure 2.18: Commercial applications such Glympse(left) and Apple Find My Friends(right) allows users to track the locations of their friends on tradtional 2D maps.

of terrain as a spatial interactive medium which facilitates spatial awareness of the terrain. From the collaboration stance, our work focuses on using the terrain itself as the spatial interactive medium. For the indoor user, it is represented as a scaled-down 3D printed model while for the remote field explorer, the actual physical terrain becomes an interactive medium and we use augmented reality to provide collaborative immersive experience to both the users.

2.7 Summary

In this chapter, we reviewed related research and background for this thesis by reviewing the past work in Navigation and Collaborative way-finding, Tangible User Interfaces, Collaborative Augmented Reality, and Computer Supported Cooperative

Work (CSCW).

In the first section , we introduced the concept of land navigation and collaborative way-finding. We reviewed the previous scientific literature that focused on the specific problems related to collaboration and spatial knowledge for collaborative way-finding tasks. We also presented previous research that presented and informed us about the various design guidelines that need to be followed for designing systems that support collaborative way-finding.

In the second section we introduced tangible user interfaces and their applications for remote collaboration. We presented the various domains and applications such molecular biology, geo-spatial modeling, reservoir engineering and GIS (Geographical information Systems) simulations where tangible user interfaces enhanced spatial perception. We then presented the past research that explored remote collaboration with tangible user interfaces and discussed how tangible user interfaces can facilitate engaging remote collaboration for performing shared physical tasks.

In the third section we introduced the Augmented Reality(AR) technology and presented the results of the very first research and inventions in the area. We described the various applications of augmented reality in a variety of domains such as tabletop reservoir engineering, civil engineering, landscape visualization. We then presented the concept of collaborative augmented reality and the research that introduced AR for collaborative tasks. We also presented some of the conceptual ideas that emanated from the past research in collaborative augmented reality.

In the fourth section we introduced Computer Supported Co-Operative work(CSCW) and presented the first initial research in the area. We then focused on the role and importance of spatiality in computer supported co-operative work(CSCW). We presented the previous research which explored spatiality for collaboration and presented previous research which used the Reailty-Virtuality continuum for facilitating collaboration. We discussed the previous research that used spatial cues for performing collaborative tasks and the research that explored the role of spatiality in collaborative virtual environments(CVE).We then concluded by presenting the most recent research that used 3D gestures and spatial inputs for collaborative tasks.

In the fifth section we introduced human-robot interaction. We then presented the sub-discipline of human-UAV interaction and human-UAV awareness. We then discussed the previous research work in the area of human-UAV awareness and concluded by mentioning how our work draws inspiration from the previous work.

We described earlier research works in navigation, Tangible UIs, Augmented Reality, CSCW, Human-Robot Interaction and a few commercial applications. Though these works inspired us and have some similarities to our work, we also mentioned how our own work differs from them and the contributions we make building on the previous work.

Chapter 3

Shvil : Augmented Reality Interface For Collaborative Land Navigation

In this chapter we present our first exploration into the design of spatial user interfaces for 3D physical maps. We present our prototype of *Shvil*, an Augmented Reality (AR) system for collaborative land navigation. *Shvil* facilitates path planning and execution by creating a collaborative medium between an *overseer* (indoor user) and an *explorer* (outdoor user) using AR and 3D printing techniques. *Shvil* provides a remote *overseer* with a physical representation of the topography of the mission via a 3D printout of the terrain, and merges the physical presence of the *explorer* and the actions of the *overseer* via dynamic AR visualization. The system supports collaboration by both overlaying visual information related to the *explorer* on top of the *overseer*'s scaled-down physical representation, and overlaying visual information for the *explorer* in-situ as it emerges from the *overseer*. In the remainder of this chapter we describe in detail the design, and implementation efforts of our prototype. We then present some of the preliminary reflections of our prototype and conclude the chapter by presenting avenues for future work for our *Shvil* prototype.

3.1 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. Such collaborative land navigation tasks are common in many domains including archaeology, geology, reservoir engineering, petroleum engineering, military operations, and mountaineering. We design spatial tangible mobile interfaces that help alleviate some of these challenges and apply it in the context of collaborative land navigation.

Shvil (Hebrew for path or trail) attempts to address tasks where a remote *overseer* (indoor user) and an insitu *explorer* (outdoor user) are performing land navigations collaboratively. *Shvil* also attempts to provide better situational awareness [Endsley, 1995] and task awareness to *overseer* and *explorer* by allowing both of them to experience the task representation physically through a tangible medium, as well as visually via AR techniques.

3.2 Design

"*We now use the country itself as its own map, and I assure you it does nearly as well*"

- Lewis Carroll's Sylvie and Bruno, 1893

Shvil aspires to convey the spatiality of the area being navigated into an interactive medium. For the *overseer*, this spatiality is embedded in the physical 3D printout(figure 3.1), and for the *explorer*, the spatiality is expressed via the actual physical terrain that becomes an active, one-to-one-scale map .

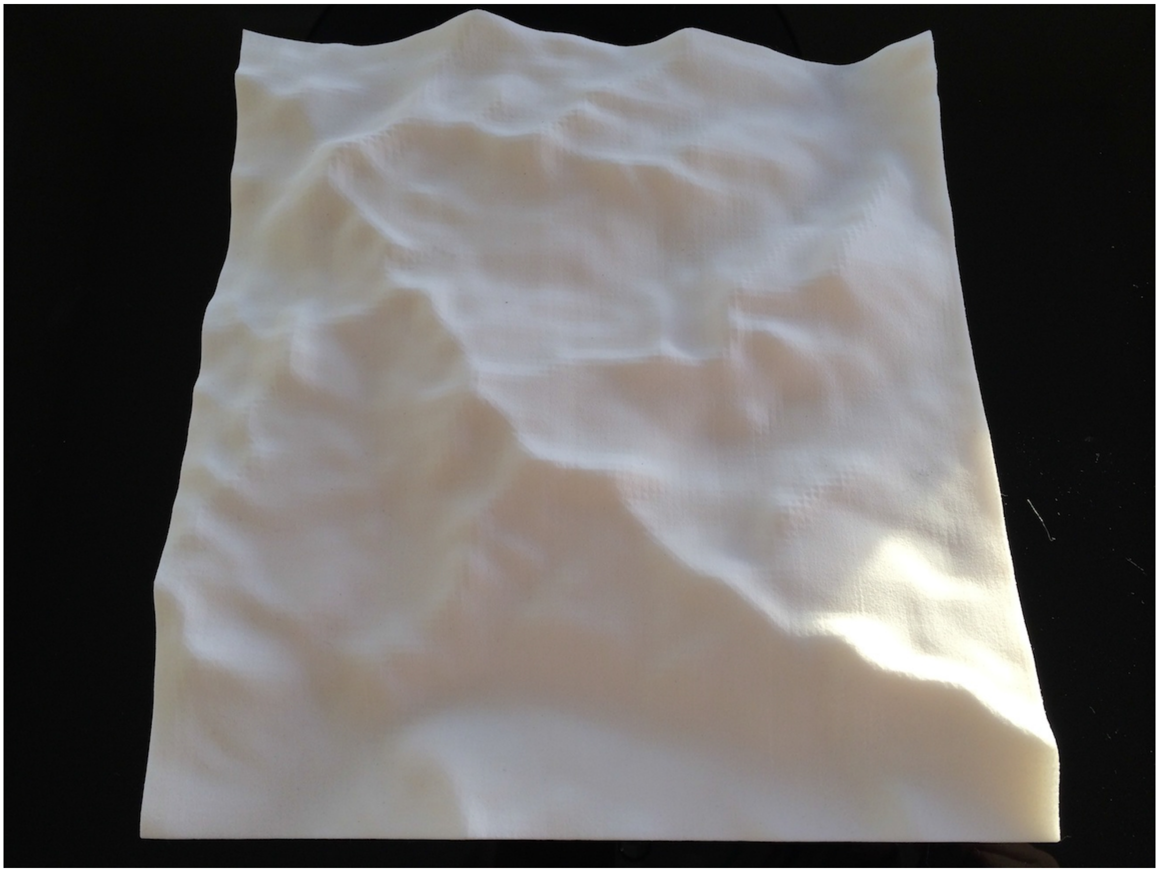

Figure 3.1: 3D printout of the terrain.

The component of *Shvil* used by the *overseer* handles the data visualization technique in an offsite (indoor) facility, while the *explorer* component deals with the data visualization in the field. In addition, each component also takes care of the presentation of the shared data, which allows *Shvil* to facilitate the collaboration between the *explorer* and the *overseer*. Both the *overseer* and *explorer* components of *Shvil* use AR to enhance the interactive environment and to access the 3D spatial navigational data in real-time. The *explorer* interacts with the physical terrain using AR directly in the field; however, the *overseer* benefits from accessing the 3D printout of the terrain, not only as a realistic illusion enhanced by the superimposed AR visualization, but also the tangible provides additional perceptional advantage and understanding of the terrain as experienced by the *explorer*. *Shvil* is based on a 3D printout model of the terrain data (figure 3.1). With the current advances and accessibility of 3D printing technology, such printouts are easy to generate and becoming less costly. We expect that, similar to how conventional 2D maps are commonly printed and distributed, 3D printouts of terrains could be easily produced and distributed in the near future. *Shvil*'s *overseer* interface combines the 3D printout with AR tracking (see the bottom left image of figure 3.2).

The route information is rendered via mobile devices running the AR library with the virtual representations overlaid and correctly aligned on the physical 3D printout. Changes in the virtual content (such as position updates of the *explorer*) are instantly applied upon the physical 3D printout enabling the *overseer* to visualize these changes. The experience is enhanced when the *overseer* moves around the physical model, since the AR device automatically detects the location and orientation of the model in real-time and adjusts the virtual image along with it. Various routes and related points of interest from the *explorer* are rendered in the AR environment in real time. Since the virtual image presented to the *overseer* is aligned with the physical model, it feels like those routes and points of interest are marked on the physical presentation of the terrain directly (see Figure 3.2).

The *explorer* component of the system is used as an aid for an in-the-field *explorer* to identify the routes and various points of interest on the terrain. It is essentially a geo-location based AR system that helps to identify aforementioned information in the scene, based on the *explorer*'s location and direction. The system overlays this

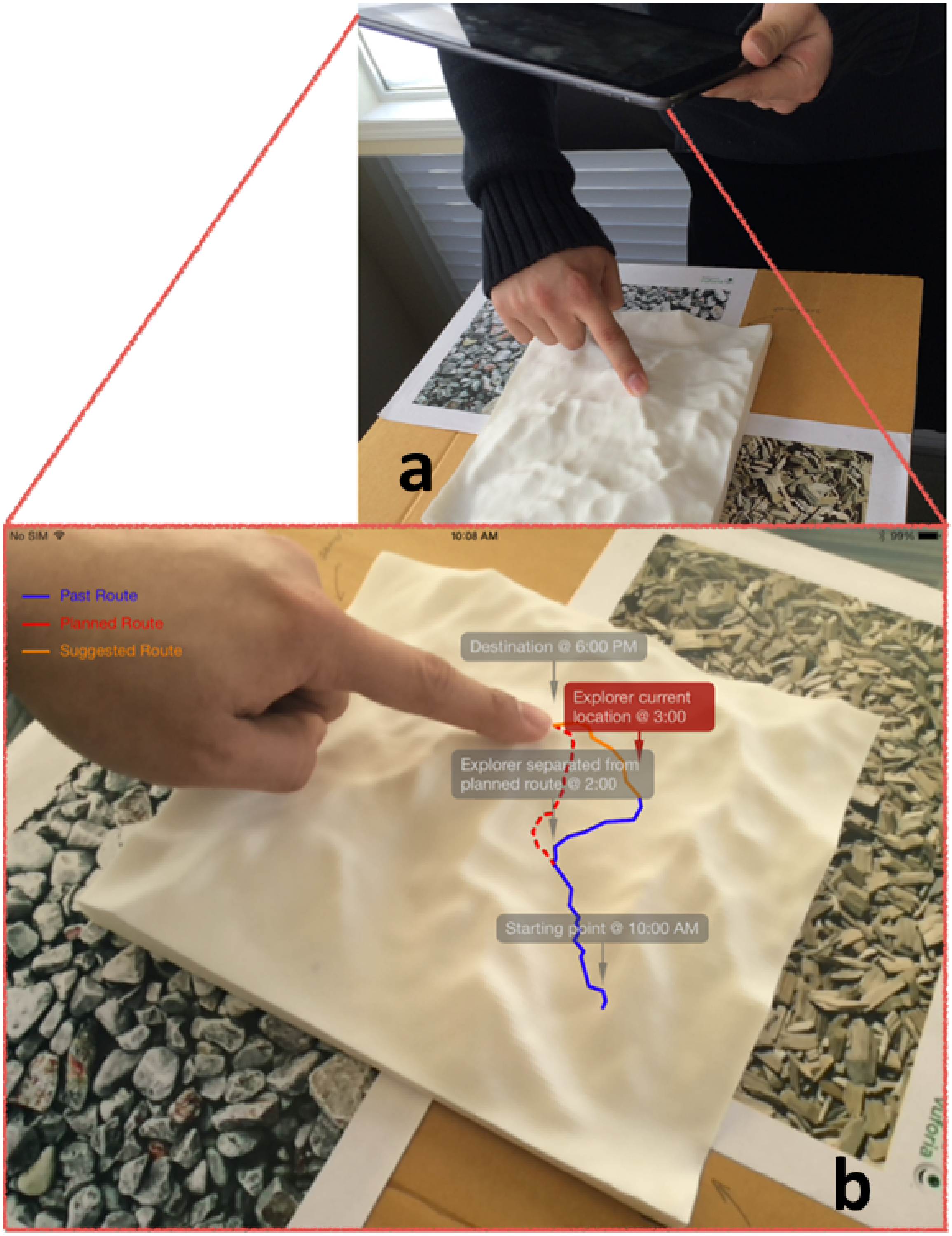

Figure 3.2: The *overseer* interface of *Shvil*. (a)An *overseer* (indoor user)is examining the 3D printout of the topological terrain data through an AR interface (b)Screenshot of *Shvil*'s *overseer* visualization, including the terrain model,route information, and corresponding points of interest (i.e. timestamps)

information onto the live camera feed in order to create the in-situ experience. The *explorer* interface demonstrates an egocentric system, while the *overseer* component presents an exocentric view of the terrain (see figure 3.3). Since the goal of this system is to facilitate the collaboration between the *overseer* and the *explorer* in real-time, both people in different locations are de facto examining the same set of data. However, rather than a birds-eye view as experienced by the *overseer*, the *explorer* observes the information in-situ. Also, information will be updated dynamically to either part of the system simultaneously.

3.3 Implementation

Shvil is designed with loose coupling as a goal, so any component may be changed without impacting other parts of the system. There is an intermediate server to handle the information sharing, and standard REST APIs are used for data transmission in between.The *overseer* and *explorer* clients are implemented on different devices and runtime environments (iOS vs Android). The *overseer* interface was implemented on an iPad Air running iOS and the *explorer* interface was implemented on a Google Nexus 5 running Android.

3.3.1 *Overseer* Interface

In the *overseer* interface, the AR and the 3D printout of the terrain are used for creating the exocentric visual experience. Markers are placed around the 3D printout, and Qualcomm Vuforia[1] [vuf, 2016] is used as the image recognition library for obtaining the location and orientation of these markers. Based on the spatial information, the mobile device adjusts the virtual image correspondingly when the viewer walks

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[1] Vuforia. www.qualcomm.com/products/vuforia

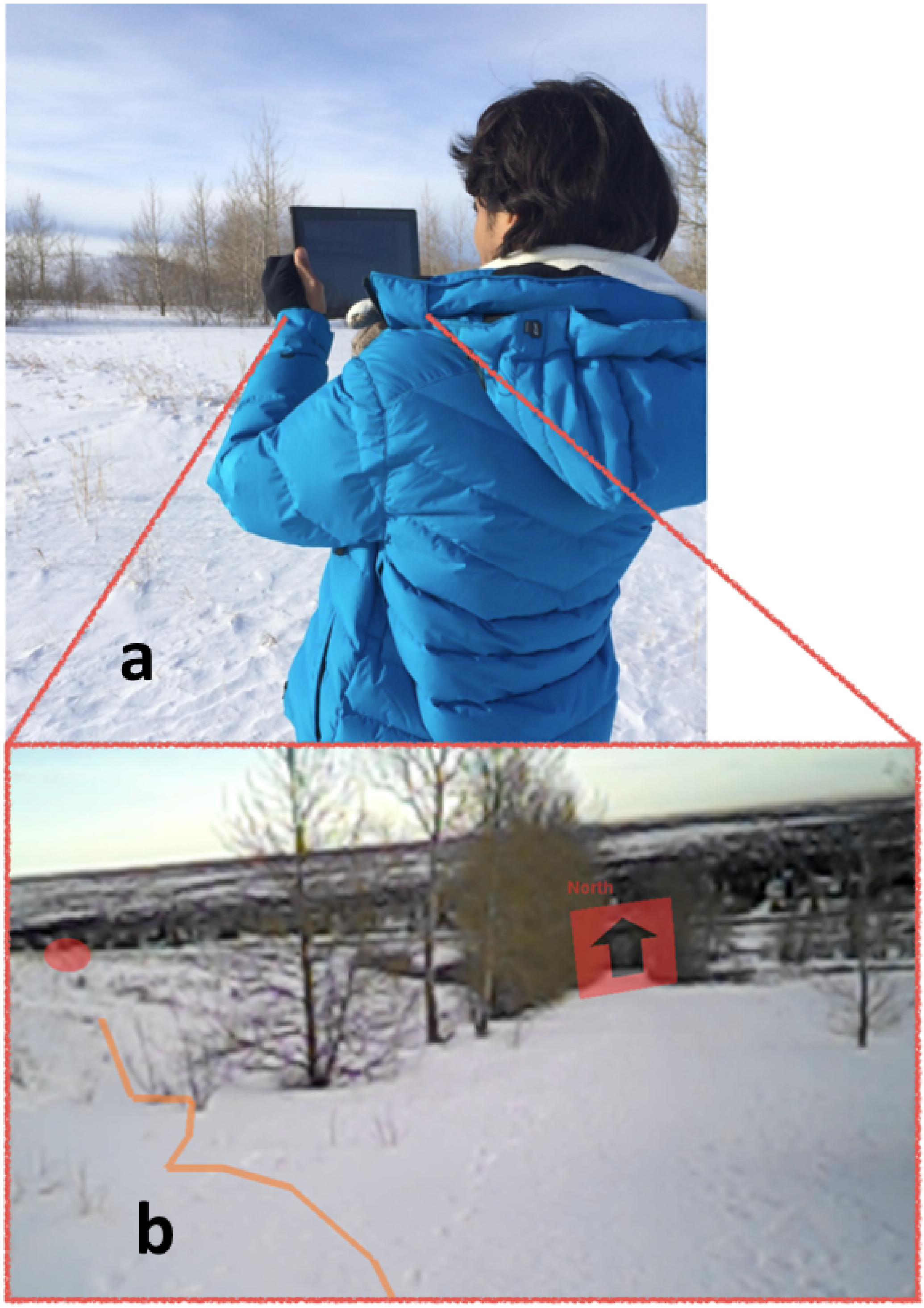

Figure 3.3: The *explorer* interface of *Shvil*. (a)An *explorer* (outdoor user) is walking on the terrain viewing his surroundings via *Shvil*'s AR visualizations (b)Screenshot of *Shvil*'s *explorer* visualization, which demonstrates the route and timestamps in their spatial locations from the *explorer*'s perspective

around the physical model. Navigational information, including the route of the field *explorer* and other points of interest, are visually mapped onto the physical model to give the impression that they are indicated and labeled on the model directly (see figure 3.2(b)).

3.3.2 *Explorer* Interface

The *explorer* interface is a geo-location based augmented reality system [Schmalstieg et al., 2011]. Location and orientation of the *explorer* are collected from the built-in GPS sensor, compass, and inclinometer sensors. Low-pass filtering algorithms were implemented to smoothen and filter out the noise in sensor readings(see Appendix B.2 for the Low-pass filtering used to smoothen the compass values). Based on this data, routes and points of interest are mapped to the physical position so that it looks like they are painted "on the ground" from the *explorer*'s perspective (see the figure 3.3(b)). For the GPS triangulation on the 3D printout, we initially, map the four corners of the 3D printout with the corresponding GPS coordinates and triangulate each and every point within the 3D printout by simple linear interpolation. The *explorer*'s interface, queries the current GPS location of the *explorer*, normalizes it into the [0 -1] range and sends it to the *overseer*. The *overseer's* AR device after receiving the normalized location co-ordinates updates it on the 3D printout.

3.3.3 Remote Communication

The *explorer* interface and the *overseer* interface communicate with each other through an intermediate server which handles the information exchange through standard REST APIs (Figure 3.4).

The information to be exchanged is encapsulated as JSON packets. A sample

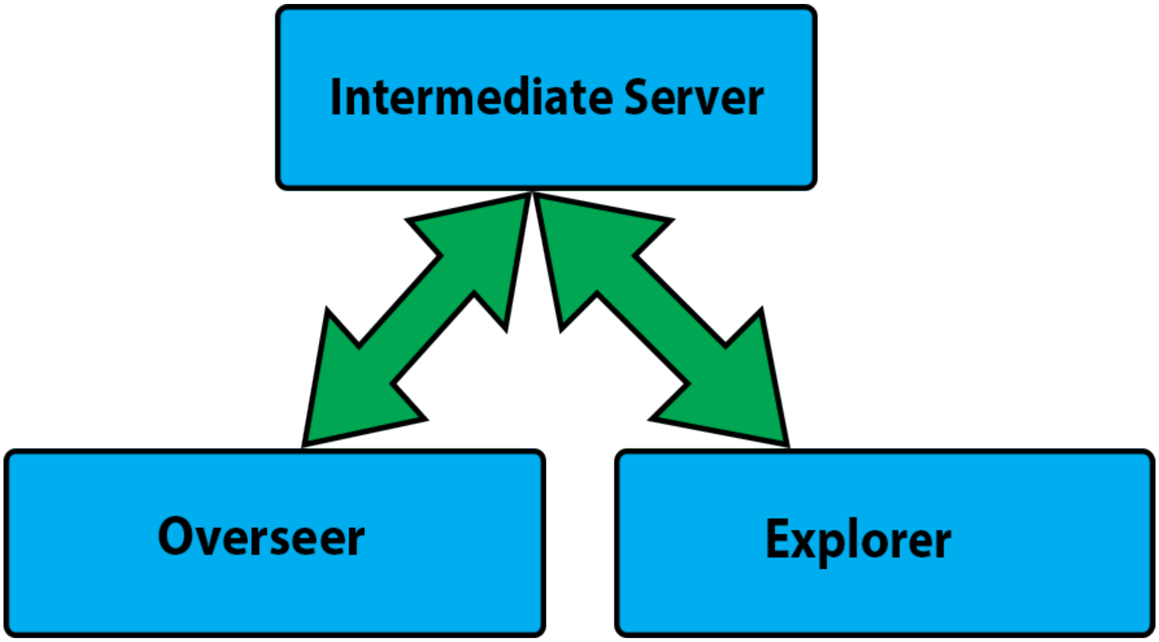

Figure 3.4: Block diagram showing the bi-directional communication between the *explorer* and *overseer* interfaces with the intermediate server.

location packet(contains the normalized GPS coordinates of the *epxlorer*) which is sent from the *explorer* AR device to the intermediate server is shown below.

```
{
  ‘‘type”:‘‘explorer”,
  ‘‘location”:[0.25,0.12350]


}
```

The corresponding JAVA class for de-serializing the received JSON string is shown below.

```
public class ExplorerLocation
{
    private String[] location;
```

```

    private String type;

    public String[] getLocation ()
    {
        return location;
    }

    public void setLocation (String[] location)
    {
        this.location = location;
    }

    public String getType ()
    {
        return type;
    }

    public void setType (String type)
    {
        this.type = type;
    }


}
```

3.4 Technical Evaluation

In this section we reflect on the potential of our system and report the results of the technical evaluation of our system. We measured the accuracy and latency of our system.

3.4.1 Accuracy

The GPS accuracy of the current day smartphones and tablets is 10-20 meters and varies from device to device. 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 20cm x 20cm 3D printout, which scales 1cm on the 3D printout to 300 meters on the actual physical reservoir terrain. This means that the *explorer* has to walk for 150 meters for the *overseer* to observe a change of 0.5mm in the location of the *explorer* on the 3D printout. This scale issue might negatively impact the application design. Depending on the required accuracy and exploration styles, (e.g. rough exploration by a car or a detailed exploration by walking) the impact of this metric varies. To offset this scale issue, we suggest the use of dynamic multi- scale visualization on the 3D printout where the detailed information can 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. Alternatively a much larger 3D printout could be used, thereby reducing the 3D printout to real world scale ratio, but this could be a trade-off for portability.

3.4.2 Latency

Latency refers to the time taken for the data transmission from the *explorer* to the *overseer*. We measured the average time taken for a JSON packet to reach the *overseer* from the *explorer*'s AR device. We measured the latency by logging the timestamps of the packets sent from the *explorer*'s device to the intermediate server. An automated script on the server logs down the time stamps on the packet and calculates the latency in milliseconds. We measured the latency by sending the packets for duration of 60 minutes and calculated the average latency. The total turnaround latency was 2.4 seconds. We used public commercial cellular carriers (3G) to transmit data between the *explorer* and the *overseer*. Such latency value strongly depends on the transmission infrastructure, and we believe that the latency can easily improve with a more reliable, customized infrastructure. Nevertheless, the latency is acceptable because the distance covered by the *explorer* in such a short time is negligible when compared to the scale of the 3D printout.

3.5 Lessons Learned

Though we did not perform formal evaluation on our *Shvil* prototype, we did demo our proof-of-concept prototype to various other graduate students , visiting researchers ,professors, and industry professionals who visited our lab and also at international HCI conferences where we presented our work. These discussions gave further insights into the design of our prototype and we will describing each of those in this section. We have adopted some of the design decisions into other prototypes in this thesis while some of the other research ideas are out of scope for this thesis.

The lessons learned from our discussion can be summarized into the following :

- **Tangible Interactions** : Our current prototype supports no major interactions for the users, other than visualizing content overlaid onto the different scales of the same terrain. One of the major feedback we received was the design of tangible interactions specifically for the *overseer*. One of the design decisions which we adopted based on this was the design of pen-based interactions for the *overseer* interface which allow the *overseer* to sketch paths over the 3D printout and send them over to the *explorer*. These interactions are implemented in our other prototypes, described in chapters 4 and 5.

- **Scale Of the Printout** : One of the other major discussion theme was the scale of the printout. Our current printout is 20x20cm in width and height respectively and is highly portable. While smaller printouts support high portability, they have the disadvantage of offering limited resolution. The larger printouts on the other hand can offer higher resolution at the cost of limited portability. We therefore suggest that the scale of the printout be tailored specific to the application design. For example, in case of geological applications, the resolution of the printout could be very crucial whereas for a trivial navigation application, lower resolution and a smaller printout could be sufficient.

- **Mobile Augmented Reality Approach vs Projection Mapping** - One of the key discussion points during our interactions was the use of alternate AR methods for overlaying content onto the 3D printout. This is very much related to the portability aspect which we described previously. Though our mobile augmented reality approach is very much portable and works well within its own limitations on the small scale 3D printout, it might not be appropriate for overlaying content on much larger, higher resolution 3D printouts. One of the simplest approach for this issue is to use projection mapping to project content onto the 3D printout. Though this might effect the portability by constraining the setup to a laboratory environment, it offers higher degree of collaboration where multiple *overseers* can visualize the shared content.

- **Personal and Public AR Displays for Overseer** - The final key discussion point was related to supporting both personal and shared workspaces similar to the ones supported by tabletop systems [Scott et al., 2004]. One of the ideas was to use the projection mapping as a means to display shared content while the tablets or wearable displays could display private content. Though this research idea is worth exploring, currently, this is out of scope for this thesis.
- **User Hierarchy** - We use the terms "*overseer*" and "*explorer*" for our indoor and outdoor users respectively. This signifies a hierarchy between the users, where the *overseer* is "guiding" or "managing" the *explorer*. This might be true in some applications such as military or police operations. However, it might not hold good for various other applications such as gaming, and rescue missions.

3.6 Critique And Limitations

Our *Shvil* prototype is currently a proof-of-concept. The 3D printed model of the terrain we used in our prototype is a placeholder of the actual terrain. However, in the appendix(A.2) we describe in detail, a simple automated procedure for fabricating 3D printouts of realistic landscapes and we also exemplify this effort by 3D printing a wilderness park near our university.

In our current prototype version, we offer only visualization on both the *overseer* and *explorer* interfaces. In further chapters (chapter 4 and chapter 5) we developed interactions which enable the users to interact and exchange dynamic information.

Besides the aforementioned technical limitations, we are also aware of limitations related to our design approach. Our augmented reality mediators are based on consumer-level tablets. This results in the users, especially the *explorer*, needing to interact with relatively inconvenient and heavy hand-held devices. This design approach could be improved dramatically by moving *Shvil* onto head-mounted or wearable devices, such as Google Glasses, that would likely provide a more natural experience.

On the other hand, obtaining our current 3D printed topographical terrain required considerable resources, and certainly there exist approaches that use other tangible mechanisms to represent the terrain [Ishii et al., 2004] [Leithinger and Ishii, 2010]. However, with the progression of 3D printing technology driving down the cost, and with more precise 3D printers becoming abundant, this barrier could be reduced if not completely eliminated.

3.7 Future Work

We would like to extend the *Shvil* concept to multiple (non-collocated) *explorers*, and also to multiple (non-collocated) *overseers*, all relating to the same geographical location by either walking on top of it physically or by interacting with copies of its 3D printed representation. Another improvement to *Shvil* we are planning is to incorporate more sophisticated interaction techniques, such as using touch directly on the 3D model in the case of the *overseer*, and gestures in the case of the *explorer*. We are exploring the possibility of applying *Shvil* to domains where the topography of the physical site could be augmented with meta-data well beyond *Shvil*'s current basic terrain surface navigation. For example, we are planning to use *Shvil* for collaborative exploration of interactive visualizations of oil and gas reservoirs, where enabling collaboration between remote *overseer* experts and in-situ *explorers* can be very useful to track and explore complex domain specific features.

3.8 Summary

In this chapter, we presented a collaborative land navigation system named *Shvil*, which uses Augmented reality(AR) and 3D printing technologies to facilitate and visualize route planning and execution. This system allows two collaborators, an in-situ *explorer* and a remote *overseer*, to exchange route information during a field exploration using terrain as the interactive medium. Although *Shvil* is a design concept with only a proof-of-concept prototype implementation, we discussed some of our preliminary reflections and future directions and improvements for *Shvil*.

Chapter 4

PlanWell : Spatial User Interface For Collaborative Well Planning

In this chapter we present an engineering application scenario where interactive spatial representation of physical maps could be beneficial. We apply our design concept to the task of collaborative well planning in the domain of petroleum engineering. Collaborative Petroleum well planning is one of the crucial steps in the oil and gas E & P (Exploration & Production) cycle where experts from multiple departments collaborate to plan the specific and optimal locations of petroleum-wells. In this chapter, we present our preliminary experimental prototype *PlanWell*, a spatial augmented reality interface that facilitates collaborative field operations in collaborative well planning. We present the details of the design and implementation of *PlanWell* prototype in the context of petroleum well planning and drilling and discuss some of the preliminary reflections of two focus group sessions we conducted with domain experts.

4.1 Overview

Oil and gas reservoirs are sub-surface portions of earth which contain pool of hydrocarbons. An oil or a gas reservoir is a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.A variety of domains are generally involved in extracting these hydrocarbons, producing, refining and transporting it for our daily commercial use. Some of these domains include geology (the study of the Earth-its history, structure, composition, life forms and the processes that continue to change it), geophysics (the study of the physics of the Earth, especially its electrical, gravitational and magnetic fields and propagation of elastic (seismic) waves within it. Geophysics plays a critical role in the petroleum industry because geophysical data are used by exploration and development personnel to make predictions about the presence, nature and size of subsurface hydrocarbon accumulations), reservoir engineering,and petroleum engineering. As shown in figure 4.1, exploration and production(commonly referred as E & P in the oil and gas domain) is one of the most preliminary and primary steps in resource extraction and production.

Oil and gas exploration and production(E & P) is one of the main important steps which itself consists of several stages of data gathering, simulation ,data analysis, well-site planning and preparation, and drilling. It involves complex tasks comprising work-flows with pipelined processes that require processing a large volume of variables related to multidisciplinary data sources from geophysics, geology, reservoir & production engineering, and reservoir economics.

Exploration is the initial phase in petroleum operations that includes generation of a prospect or play or both, and drilling of an exploration well. Appraisal, development and production phases follow successful exploration. During appraisal, delineation wells might be drilled to determine the size of the oil or gas field and how to develop it most efficiently. Development is the phase of petroleum operations that occurs after exploration has proven successful, and before full-scale production. The newly

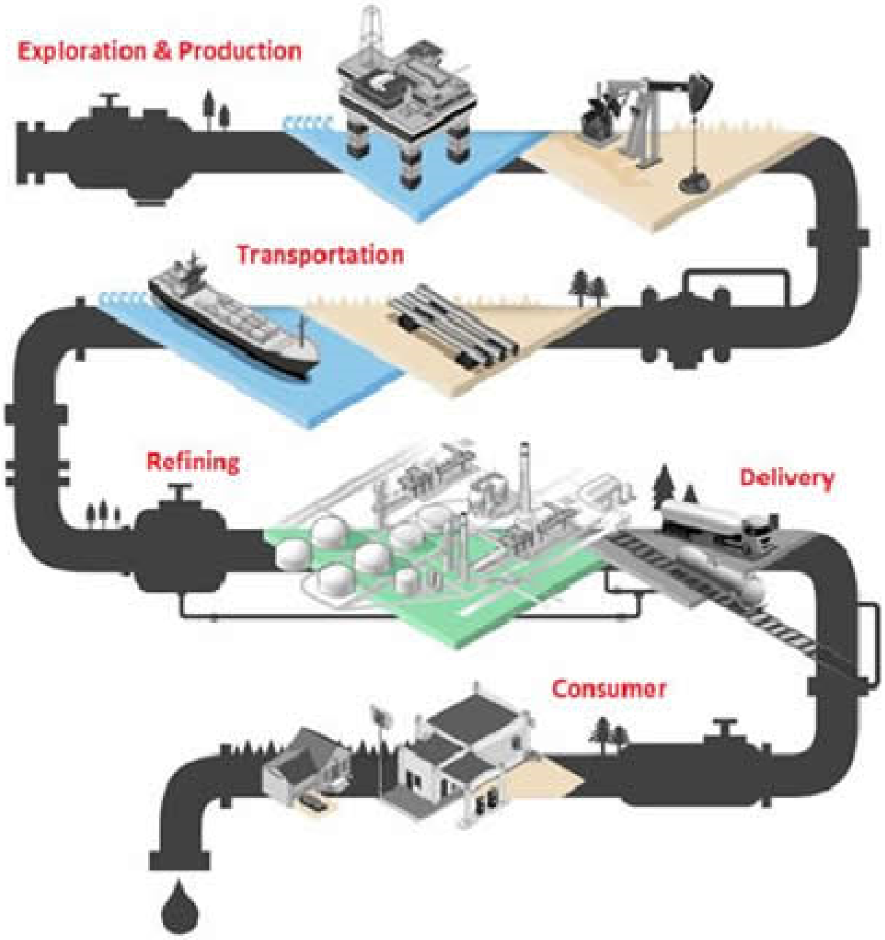

Figure 4.1: The oil and gas production cycle. Image Courtesy : Climate.org

discovered oil or gas field is assessed during an appraisal phase, a plan to fully and efficiently exploit it is created, and additional wells are usually drilled. Production is the phase that occurs after successful exploration and development and during which hydrocarbons are drained from an oil or gas field. It involves planning and installation of production facilities, equipment, monitoring, etc.

Geophysicists and geologists study the earth and its sub-surfaces, using gravity, electrical and seismic methods and prepare mathematical and computational models of a particular area (Figure 4.2). These experts are engaged in exploration in search of oil and gas reservoirs which contain hydrocarbons. Once the ideal sites are explored,

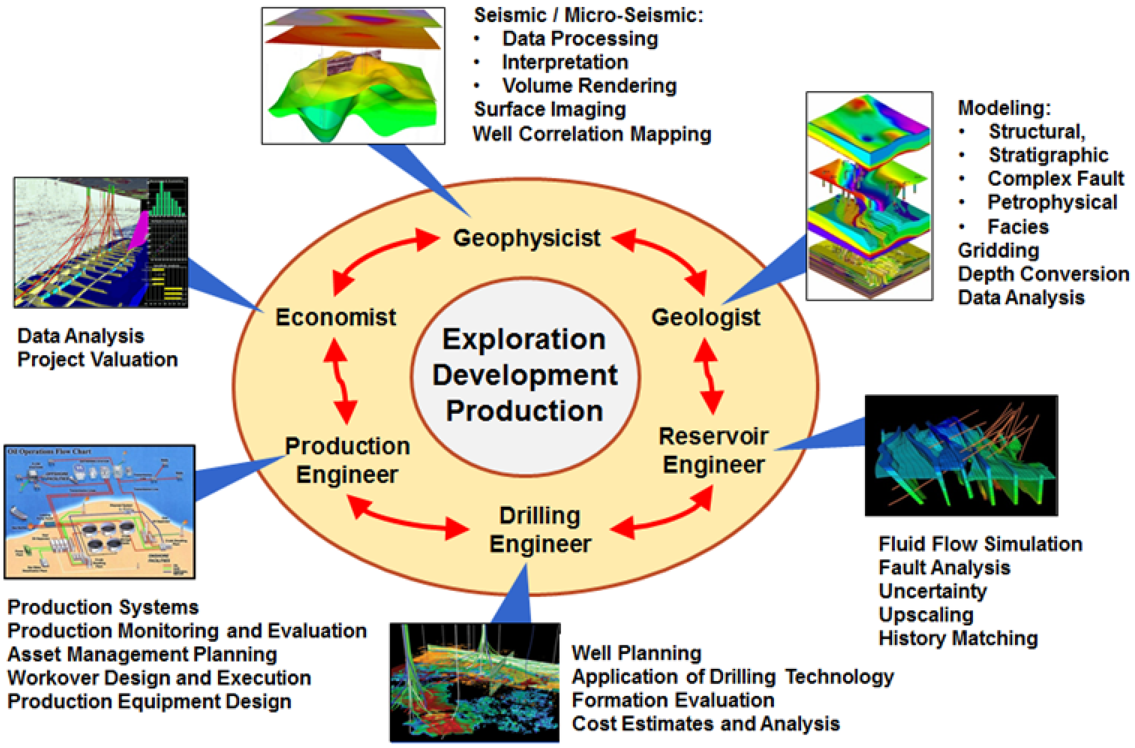

Figure 4.2: Oil and gas exploration, development and production (E, D & P) stages and the various disciplines and tasks involved [Sousa et al., 2015].

reservoir engineers study these reservoir models, prepare reservoir simulation-models and analyse the reservoir for ideal locations where wells could be placed for production. Once the well locations are planned and decided, an on-field team of drilling engineers design and implement procedures to drill wells as safely and economically as possible, while at the same time protecting the health and safety of workers (construction engineers,and contractors) who are responsible for well construction. Once the well locations are finalized, the terrain surface is evened out by digging the dirt and well pads are constructed which can accommodate multiple wells. Once the wells are set-up, the production engineers and economists take care of the logistics involved in the production cycle.

Figure 4.3: An oil-rig constructed at a well location.

Figure 4.4: A multi-well pad site containing four wells.

4.1.1 Well-Planning

We briefly explained the oil and gas exploration and production (E & P) cycle in the previous section. In this section we will briefly explain the well-planning process and the opportunities that have motivated the design of *PlanWell*.

The process of well-planning is highly interdisciplinary and involves a number of experts from various domains such as geology, geophysics, petroleum engineers and planners. This team of experts is often known as the “surface team” as they analyse sub-surface portions of earth. 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 (Directional drilling is the practice of drilling non-vertical wells). 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. 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 archaeological 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. With *PlanWell*, we hope 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.

4.2 *PlanWell* - Spatial User Interface For Collaborative Petroleum Well Planning

PlanWell uses augmented reality and 3D printing to provide both *overseer* and *explorer* with spatial interactive representations of the task, enhancing situational awareness and sense-making.

Though *PlanWell* can be applied to various collaborative terrain exploration scenarios and tasks such as military operations and rescue missions, in this chapter 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 group discussions with domain experts to gather qualitative feedback of our prototype and design approach.

Our work makes following contributions:

- 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.

- Application of the technique to a realistic engineering scenario, based on feedback and suggestions gathered during interviews with domain experts. This application is further supported by a set of design guidelines developed based on information from the subject matter expert interviews.

- 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.

In the remainder of this chapter, we will describe in detail, the design, implementation of our *PlanWell* prototype. We will also be discussing in detail the evaluation efforts and the results of two focus group discussions we conducted on *PlanWell*.

4.2.1 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 Printout as a Tangible User Interface***: Previous TUI research has confirmed that physical representations help in understanding complex spatial representations and relationships [Harris et al., 2011] [Gillet et al., 2005] [Jansen et al., 2013]. Geology and Urban planning communities have already explored the effectiveness of 3D printing to print physical models of GIS data [rase2009visualization]. They believe that such physical printed models enhance the spatial situational awareness during collaboration.

  Implications on Design: This previous interdisciplinary research inspired us to use physical 3D printed representation of the terrain 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 the zooming and panning, they disconnect the user from the actual physical environment. We hence used Augmented Reality to ensure that the users (both the *overseer* and the *explorer*) can perceive the actual local environment as well.

- ***Interaction Design***: Based on our discussions with domain experts, we learnt that the Surface Team is responsible for driving and planning the drilling operations and the on-field drilling team performs the required tasks. Based upon this setting,we envision the *overseer* as the major force who drives the entire task, while the *explorer* is the user who typically "executes" tasks based on the directions from the *overseer*.

  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 Experimental Apparatus***: Another obvious requirement is that the system should be small and easily setup because of its possible usage in various domains and realistic field studies. 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, using a projector for overlaying content on the 3D printout. However these solutions are very difficult and non-intuitive to setup and confine the apparatus to laboratory. Hence we use the Mobile Augmented Reality (MobileAR) approach.

4.2.2 Design

Our design concept enables two remote users to share the same spatial experience via an intelligent interface that bridges distance, differences of scale and perspective, allowing one, the *explorer* to use the actual physical space as an interactive medium, and the other, the *overseer*, to use a 3D scale printout model of the same environment as her interactive medium. We realized the design concept merging the 3D printing techniques and augmented reality and by designing for a specific oil-and-gas task scenario where our approach can be deployed and tested in a valid setting. Below we describe the design of *PlanWell* and the interactive reservoir exploration and analysis scenario. *PlanWell* contains two major components: the mission control part, which we name as the *overseer* interface, and the in-field part, which we name the *explorer* interface.

The *overseer PlanWell* interface uses a 3D printout as the physical representation of the topographical and reservoir model. Though this particular printout was provided by a 3D printing service vendor (Shapeways Inc.) based on the digital model

Figure 4.5: The *overseer* interface which consists of the 3D printout of the terrain, an iPad as the AR device and a stylus.

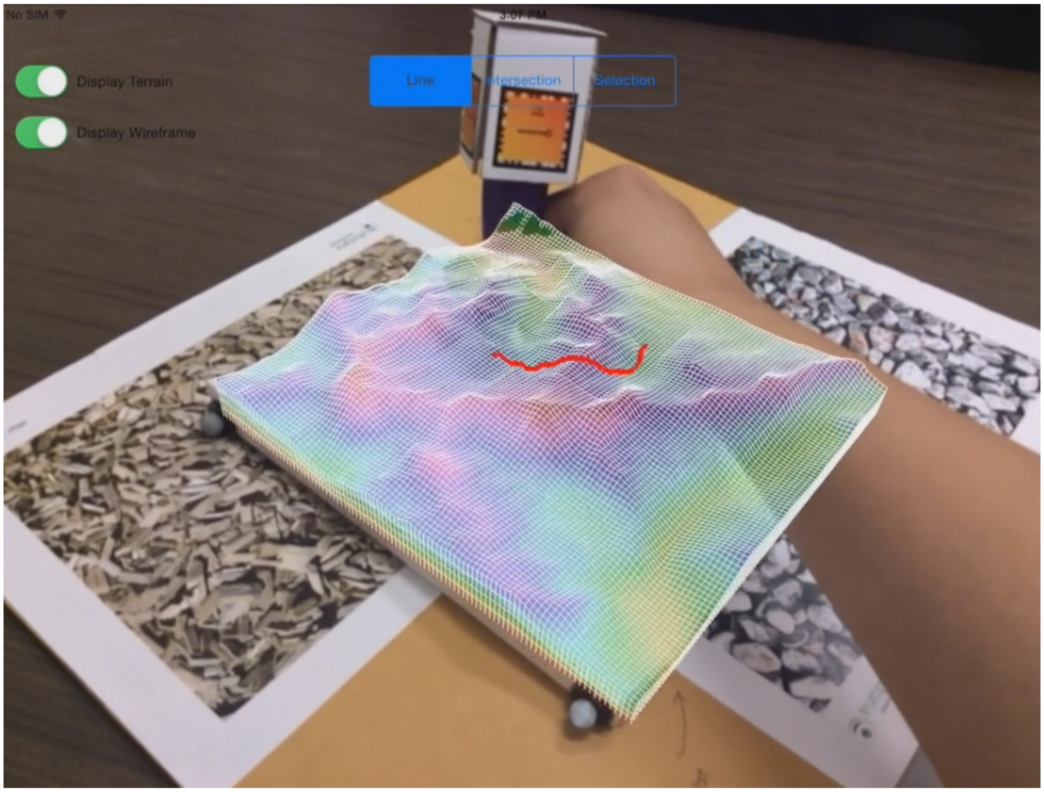

Figure 4.6: The *overseer* can sketch on the 3D printout with the AR- based stylus

of the reservoir terrain, the printing process is quite standard and can be replicated with any regular commercial 3D printer. Augmented reality is used to superimpose necessary application-specific virtual information, onto the 3D printout, as well as, dynamic data reflecting the geo-location of the *explorer* and other points of interest. The combination of the visual illustration and the tangible access of the topographical shape of the model allows the *overseer* to understand the topographical properties of the terrain and the related spatial structure of the reservoir model, along with its association to the simulation visualization in a direct manner, allowing physical (e.g. by touch) and visual exploration of the reservoir model. The goal of this arrangement is to offer the *overseer* direct physical representation of the topographical spatial properties, accessing the 3D printed TUI both visually or by touch, maintaining overall awareness of the activities on the reservoir in real time via the AR visual feedback, and enabling 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 4.5 and Figure 4.6). The stylus enables the *overseer* to draw a relatively precise path or select an area on the surface of the 3D printout and send it to the *explorer*, cut open a vertical intersection to examine the interior structure of the or drag and move an existing point-of-interest (POI), which in an oil-and-gas exploration scenario could be an oil well, to a new location, in order to allow the *explorer* to examine it in the field.

The *explorer PlanWell* interface uses augmented reality to superimpose the application-specific data (in this case, reservoir data) onto the terrain around the *explorer*, presenting static information such as aforementioned reservoir properties, as well as dynamic information broadcasted from the *overseer* such as paths, selected areas,

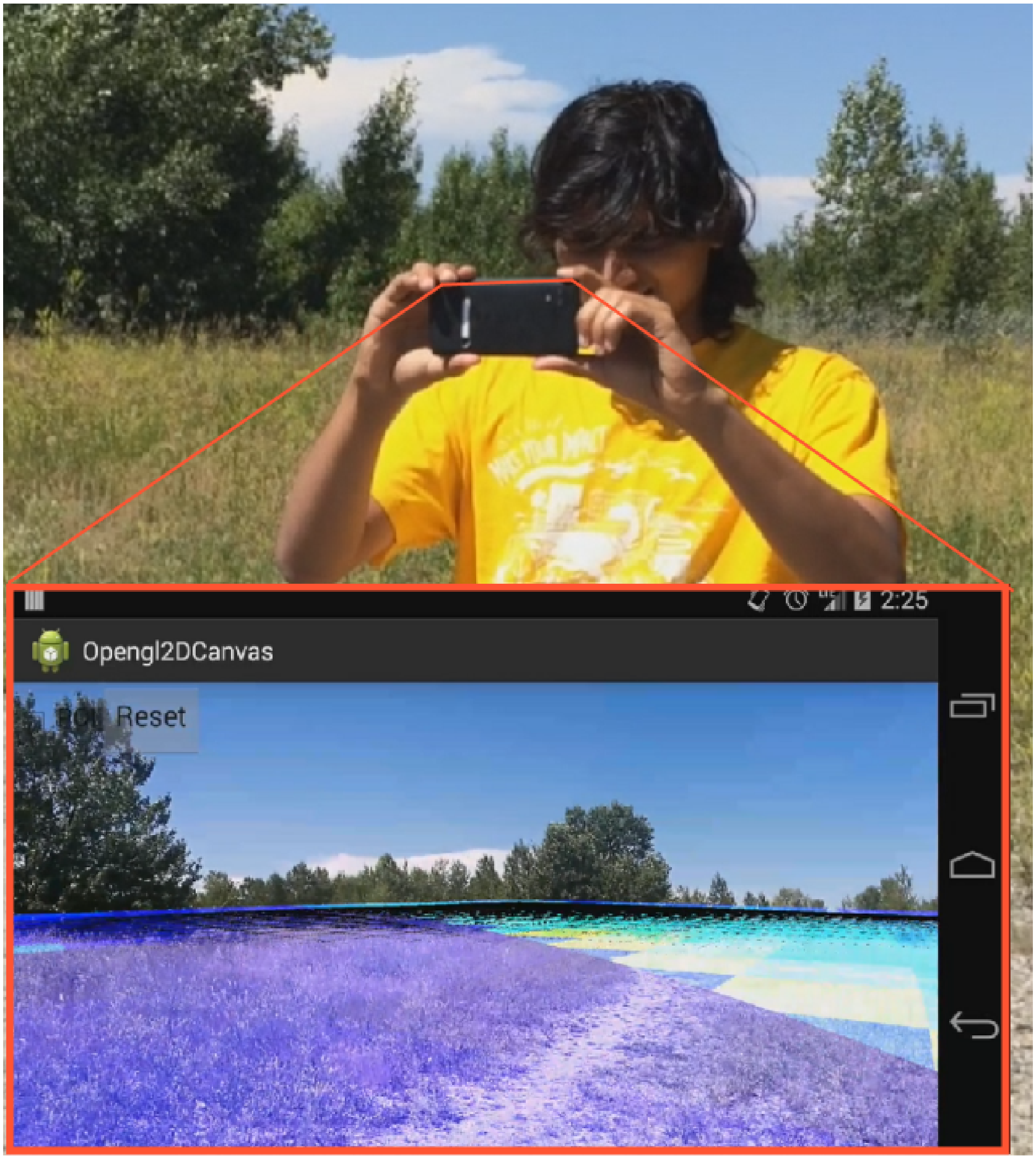

Figure 4.7: The *overseer* interface is mobile geo-location based Augmented Reality(AR) system, that superimposes various domain-specific data on the surrounding physical terrain.

and suggested locations of wells (Figure 4.7). The communication is bidirectional.

4.3 Implementation

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 [vuf, 2016] 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 4.6 and figure 4.7. Both interfaces use OpenGL ES to provide the visual elements.

4.4 Interaction Techniques

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.

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 , the *explorer*'s geo-reference is continuously sent to the *overseer*, allowing the *overseer* to maintain the spatial awareness of the *explorer* (Figure 4.8).

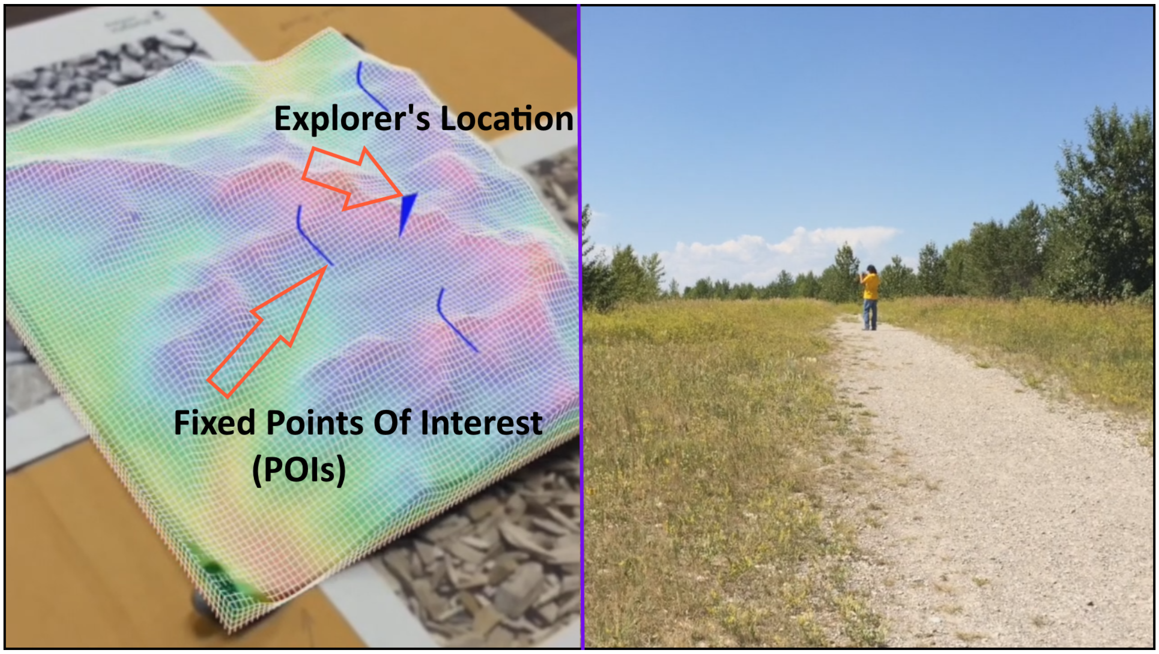

Figure 4.8: The *explorer* position is dynamically updated on the 3D printout(left) as he navigates in the field(right)

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 4.9).

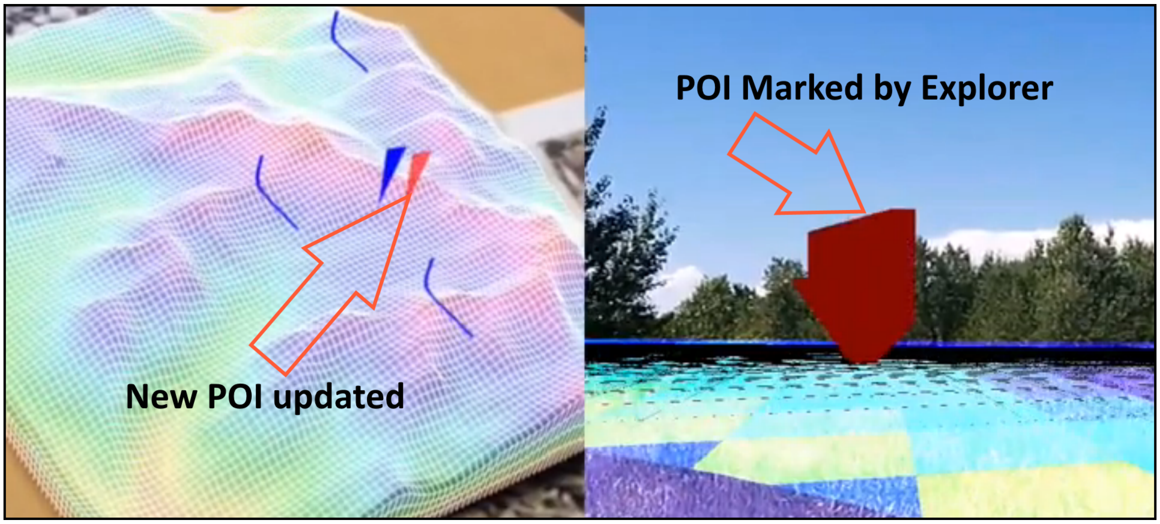

Figure 4.9: The point-of-interest(POI) selected by the *explorer* is updated on the 3D printout (left). The point-of-interest is labeled in the *explorer*'s interface (right)

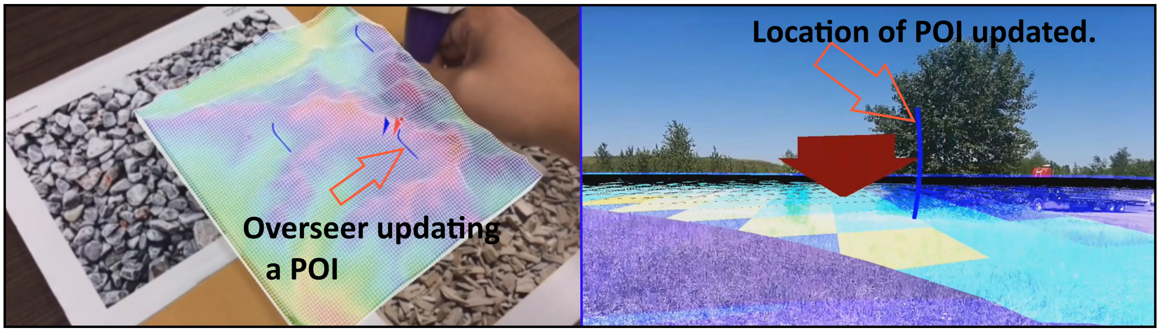

Figure 4.10: The *overseer* updating a point-of-interest(a well location in this particular case) with the pen tool (left). Updated position of the well is shown on the *explorer*'s interface(right)

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 4.10 (left)). Meanwhile, the *explorer* could also see the well representation appear on his AR interface (Figure 4.10(right)) 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.

4.5 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 and discussion points that emerged out of our focus group discussions.

4.5.1 Focus Group Study Design

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 on a daily basis.

Based on this, we believe our participants were qualified enough 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. 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 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. The entire protocol that was followed for conducting the focus group study can be found in the Appendix A.1. section. 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 [Corbin and Strauss, 2014]. 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 , I3.

4.5.2 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.

The Role of 3Dprintout for Better Spatial Understanding

Previous TUI research has confirmed that physical representations help in understanding complex spatial representations and relationships [Harris et al., 2011] [Gillet et al., 2005] [Couture et al., 2008]. 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, its easier to get to know the appropriate pad sites for well construction which ultimately helps in reducing the time and cost and eliminates guess-work. 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, she was unsure how 2d maps 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 whats there on the ground and the features help in reducing the time and cost." - I1

"In Mexico, when I used to work a project, we were drilling 20-30 wells per month and the way, the field-team decides on the well platforms and locations are by using 2D maps. I dont exactly how they do it but I am pretty much sure that this 3D model could be very much useful there." - A1.

''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.

The domain expert also claimed that given the scale of the 3D printout, precise approximations of the elevations can also be made which is important for the well-construction operations. With the current tools most of the elevation approximations have some guess-work involved.

"*precise knowledge of the elevation is important because, even if the elevation difference is 5 meters , then they have to dig out the dirt to even out the pads , and this is very expensive and costs about 1 million dollars for evening out a place with even 5m elevation difference. This tool gives a tighter estimate about the project rather than guess work with the current tools.*" - I1.

Though all the opinions and results of the focus group discussions show that the 3D-printed terrain model could facilitate better spatial understanding, with respect to quantitative measures such as task efficiency and productivity, it is not known how 2d maps would compare against a 3D printed model. We believe that a quantitative task-based evaluation would help us in answering this question.

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 upfront, 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 very much evident that the collaboration facilitated by *PlanWell* can help the remote teams to dynamically plan change and edit well locations and operations there by reducing the turn-over time and cost.

The power of Spatial Augmented Reality

Our experts were impressed with the AR interface and the ability to overlay information onto 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, floodplains 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.

3D printout as a Co-located Collaborative Interface

The current PCs and desktop computers which are widely used are single-user centric and donot support comfortable and effective collocated collaboration. Tabletop systems have been developed that support such collocated collaboration and these systems have supported 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. For example, *Designer's Outpost* is such tangible interface that supported collaborative website design [Klemmer et al., 2001]. 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 useful collaboration tool which could 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.

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 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 doesnt much relate to the real world.*" - I1.

Although the computer generated models provide 3D visualization, these visualizations are often complex and there are always 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. The experts during the focus group discussion revealed the various perception issues which are introduced by the commercial 3D software packages. 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 is with 2D interfaces such as mouse and keypads. This makes the interaction 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 its 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 provides is the natural 3D stylus- based interactions which allow the *overseer* to sketch and draw on the 3D printout. This is in particular useful as it provides natural 3D interaction with the physical world, when compared to the 2D sketches on 3D data as offered by the current commercial software packages. Many of the times, the experts interact with the high resolution data and sketching 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 the current sketching is multi-step approach. The users have to make 2D sketches and these need to 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, 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 into the actual 3D printout and there are no perception issues. More 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 a 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-bsaed 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.

Mobile Augmented Reality Based Approach

In our design considerations section we mentioned that one of the goals of our system design should be that the experimental apparatus should be simple to setup. Due to this design goal, we used mobile augmented reality approach to design our *overseer* and *explorer* interface. The focus group discussion helped in evaluating this design approach of ours. The experts liked our approach and claimed that this mobile AR based approach would particularly appeal to the users as most of the users carrying out the domain-specific tasks are not tech-savvy and technology friendly.

"*I like this approach of cell phones because; the guys doing the scouting are not the technology friendly guys. They have cell phones. The guys are generally old about 65 years, and they would prefer using the cell phones.*" - I1.

However, they did suggest that projection-based AR approach for the *overseer* interface could be experimented as it could facilitate co-located collaboration between the experts. Apart from this the experts also presented insights into more sophisticated technological systems that could aid their daily tasks. For example, one of the experts suggested modelling clay like interface for the *overseer* which would allow the geologists to manipulate, shave and carve and perform various other operations with the sub-surface data. This suggestions strongly resonates with Ishii's [Piper et al., 2002] illuminating Clay prototype which was developed for landscape simulations.

"*Sometimes we geologists could add some modelling clay and most of the time geologists think about shaping it, shaving it and carving and various other operations . physicality of sub-surface mapping is also very useful and advantageous.*" - I2.

Applicability of PlanWell 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, geomatics and civil engineering.

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

“*Civil engineers could also use PlanWell, for construction of roads, structures etc*” - 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.

Based on this feedback, we envision that our *PlanWell* concept could be useful and applicable across a various domains for a variety of tasks.

4.6 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) *explorer*s and also to multiple (non-collocated) *overseers*, all analyzing the same reservoir model.

4.7 Summary

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.

Chapter 5

Flying Frustum : A Spatial Interface For Enhancing Human-UAV Awareness

In this chapter we present another application of 3D physical maps. We present *Flying Frustum*, a spatial interface that enables control of semi-autonomous UAVs (Unmanned Aerial Vehicles) using pen interaction on a physical model of the terrain, and that spatially situates the information streaming from the UAVs onto the physical model. Our interface is based on a 3D printout of the terrain, which allows the operator to enter goals and paths to the UAV by drawing them directly on the physical model. In turn, the UAVs streaming reconnaissance information is superimposed on the 3D printout as a view frustum, which is situated according to the UAVs position and orientation on the actual terrain. We argue that *Flying Frustum*s 3D spatially situated interaction can potentially help improve human-UAV awareness and enhance the overall situational awareness. We motivate our design approach for Flying Frustum,present our preliminary prototype using both handheld and headset augmented reality interfaces, reflect on Flying Frustum's strengths and weaknesses, and discuss our plans for future evaluation and prototype improvements.

5.1 Introduction

Unmanned Aerial Vehicles (UAVs) are increasingly ubiquitous and have many well established uses, including various reconnaissance applications in search-and-rescue and military settings [Goodrich and Schultz, 2007] [Mitchell et al., 2005]. There are also many other applications emerging, from cinematography [lil, 2016][1] (Figure 5.1) to shipping and delivery [ama, 2016] (Figure 5.2)[2] .

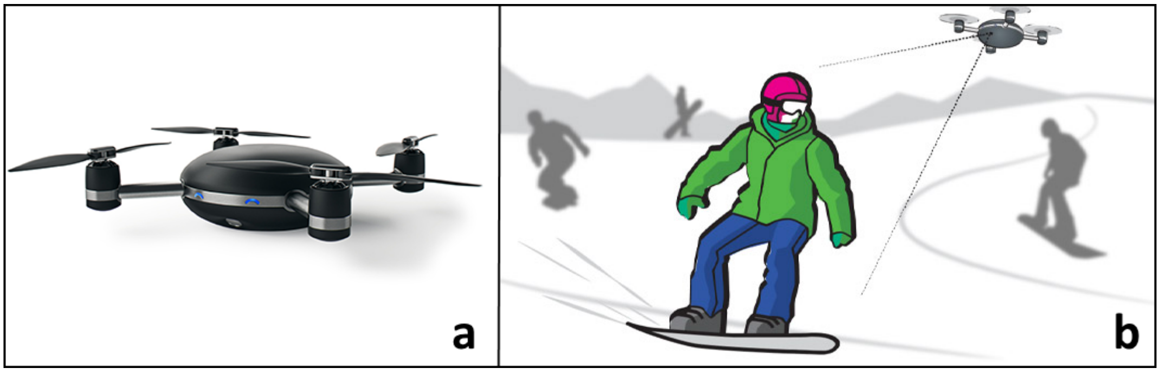

Figure 5.1: (a) Lily Camera (b) Sketch of a Lily Camera in action

Figure 5.2: Amazon air prime drone prototype in action.

As UAV technology is emerging, many of the challenges of controlling these robots remain acute, from more efficient interaction with their low-level flying mechanisms, to higher-level issues of tele-operation and control [Goodrich and Schultz, 2007] [Mitchell

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[1] Lily Camera. `https://www.lily.camera`

[2] Amazon Air Prime. `http://www.amazon.com/b?node=8037720011`

et al., 2005]. *Flying Frustum* focuses on the highlevel issues of teleoperation when interacting with UAVs which are performing a reconnaissance task over a remote terrain. *Flying Frustum* provides the UAV operator with a 3D printout of the terrain, which can be used to plan and draw flight paths for the UAVs. A visualization of the UAVs position on the 3D terrain is superimposed on the 3D printed model and a correctly situated frustum can display real-time information about the UAV. In the case of this prototype the information displayed is a video feed from the UAVs camera. *Flying Frustum* is designed to provide a remote operator an enhanced level of human-UAV awareness [Drury et al., 2006b] [Drury and Scott, 2008] and improved situational awareness [Endsley et al., 2000] when controlling one or more semi-autonomous UAVs. Our approach closely follows the footsteps of Drury, et al. [Drury et al., 2006a] which argues that situated streaming information from a UAV would increase the operators situational awareness. However, *Flying Frustum* extends this paradigm by using a 3D terrain printout with augmented reality visualizations as the interactive medium (Figure 5.3).

Figure 5.3: *Flying Frustum*; (left) the operator draws a path using a pen on the augmented 3D printout of the terrain; (middle) the UAV, a quadrotor in the current prototype, flies along the path in the field; (right) live video footage streaming from the UAV is displayed as a view frustum situated at the correct location on the 3D printout, using augmented reality

In this chapter we present a prototype realizing the *Flying Frustum* concept, based on visualization superimposed on a 3D printout using either a hand-held or headset augmented reality interface, and a Parrot Bebop drone[3] as the UAV. While our current prototype is still preliminary, it does allow us to reflect on the strength and weaknesses of the *Flying Frustum* approach, argue the benefits of providing streaming information from the UAVs correctly situated and superimposed on their current 3D location, and to outline our future plans regarding this interface.

5.2 Designing Flying Frustum

The original motivation for our design came from control difficulties and interface limitations discovered in real-world scenarios during geo-science and petroleum field explorations. Such an excursion may require one or possibly multiple UAVs to efficiently cover geological features that are difficult or even impossible to reach, such as cliffs and canyons. In other cases UAVs may provide a more cost effective and less labor intensive alternative to manned aircraft when collecting data over a piece of terrain such as done by SkyHunter[4] (Figure 5.4). In both scenarios users have basic knowledge of the terrain that is to be explored, however the challenge is to rapidly deploy and effectively tele-operate the UAV while maintaining a high degree of overall situational awareness and human-UAV awareness simultaneously.

Our design goal when creating *Flying Frustum* was to develop a situated 3D interaction with a UAV. The foundation for our spatial interface design is the 3D interactive medium, which is based on a scaled down model of the terrain that the UAVs are exploring. We create this medium using 3D printing, generating a physical representation of the terrain. The 3D printout provides users with a tangible entity that accurately and intuitively communicates detailed topographic information through

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[3] Parrot Bebop Drone. `http://www.parrot.com/ca/products/bebop-drone/`

[4] Skyhunter Corporation - `http://www.skyhunter.ca/`

Figure 5.4: The drone used by SkyHunter Inc. for geophysical surveys.

both visual and tangible sensation. Augmented reality is used to superimpose spatial information onto the physical printout(figure 5.5).

We designed the augmented reality layer of *Flying Frustum* considering both see-through AR headset (using Epson Moverio[5]) and handheld AR screen (using iPad Air) (Figure 5.6). The 3D terrain printout is used as the interactive medium for sending user commands to the UAV by sketching on the terrain model, and for communicating information back to the user via 3D situated visualizations superimposed on the terrain. In order to correctly situate the various 3D information components, *Flying Frustum* needs to track the position and orientation of the handheld or the headset interface relatively to the 3D printout, and the position and orientation of the 3D sketching stylus.

We designed a set of pen-based interactions performed directly on the physical model of the terrain(similar to the ones designed in the *PlanWell* prototype in chapter 4) that allow the operator to control the movement of the UAV. We used physical pen-

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[5] http://www.epson.jp/products/moverio

Figure 5.5: (left) using a 3D printout model as a physical representation to the topographical terrain; (right) augmented reality visualization is superimposed onto the model

based interactions to address the “fat finger” problem and to enhance the precision of the operator commands to the UAV, while still allowing direct, tangible interaction and intuitive understanding of the topography of the 3D printout and therefore the terrain (Figure 5.7).

Similar to drawing a path on a traditional map, the operator may define a path for the UAV by sketching a line upon the surface of the physical model.

After the operator has created a path, the drone will fly to the location that is marked the start point of the path on the model, and then move along the path until it reaches the end point. The visualization of the UAV flight on the model corresponds spatially and temporally to the actual flight path of the drone in the real world.

Once the UAV starts following the path the operator traced on the 3D model, it streams live video footage from its camera and displays it on the far plane of a view frustum which is situated on the physical model according to the location and orientation of UAV on the actual terrain. The view frustum constantly adjusts its position and orientation to mirror the real-time activities of the actual UAV in the field (Figure 5.8). This design is based on the paradigm that situated streaming

Figure 5.6: (*Flying Frustums* augmented reality devices including (left) handheld screen and (right) see-through headset

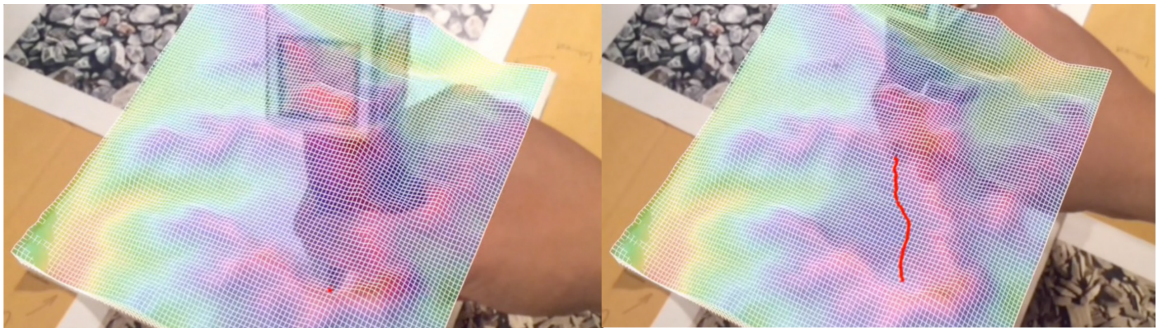

Figure 5.7: (*Flying Frustum*'s augmented reality devices including (left) handheld screen and (right) see-through headset

information would enhance the human- UAV awareness and situational awareness by helping the operator understand exactly where the drone is and what it is doing at the same time, with the streaming video correctly situated on top of the 3D physical terrain. This builds upon work demonstrating similar ideas in 2D non- AR settings [Drury et al., 2006a].

With a certain level of automation [Parasuraman et al., 2000], we expect Flying Frustum to further release the operator from constant observation of the drones

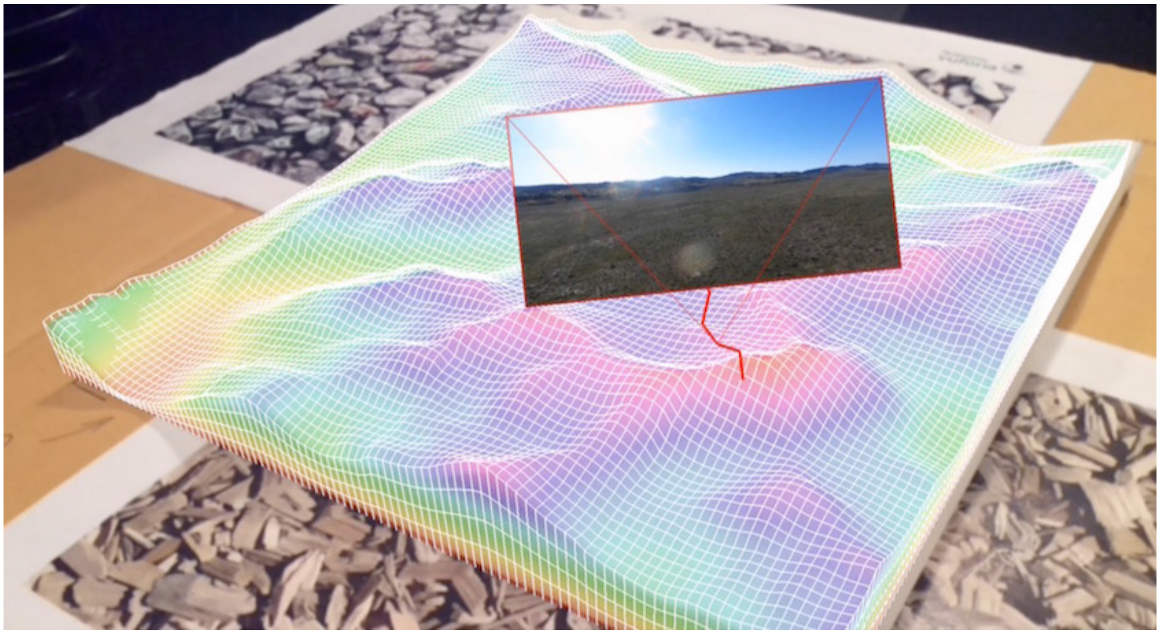

Figure 5.8: (live video footage captured by the drone is displayed on the view frustum in the augmented reality visualization

activities, which is common in traditional linear controlling of UAVs. Our design assumes that the UAV is semi-autonomous, meaning that it is able to hover and follow a predetermined path without human supervision until receiving any further instructions.

We believe that such an interface can help the operator maintain a high level of situational awareness without dramatically increasing the workload or cognitive load, which in turn could enable the operator to control multiple drones simultaneously.

5.3 Implementation

The prototype of *Flying Frustum* presented in this chapter is a preliminary proof-of-concept. The 3D printed interactive medium including the augmented reality functionality, the pen input and the 3D video frustum are fully realized and are completely functional. However, direct control and communication with the UAV has not been implemented and we use the Wizard-of-Oz prototyping method when flying the UAV and when playing the video back to the user via the situated frustum.

Our prototype was tested with both an Epson Moverio2 headset and an iPad as the augmented reality devices, and the Qualcomm Vuforia3 engine was used to illustrate the visualization. The 3D printout is made from strong flexible plastic[6] and was acquired from a commercial 3D printing company (Shapeways Inc.). We use the iPad as our primary augmented reality device to realize our proof-ofconcept.

Figure 5.9: The Parrot Bebop drone used in *Flying Frustum*.

A Parrot Bebop Drone[7](Figure 5.9) is used as our UAV. It is a lightweight drone capable of performing 3-axes movements, and recording full HD video footage.

Due to the lack of reliable network coverage by commercial cellular networks and ISPs at certain locations the drone was operated, the communications between the operator and the UAV is implemented by means of the Wizard-of- Oz technique [Dahlbäck et al., 1993], including sending the instruction and receiving the video footage (Figure 5.10). We believe that this comprise still allows us to reflect on the overall validity of the *Flying Frustum* concept.

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[6] `http://www.shapeways.com/materials/strong-and-flexible-plastic`

[7] `http://www.parrot.com/ca/products/bebop-drone`

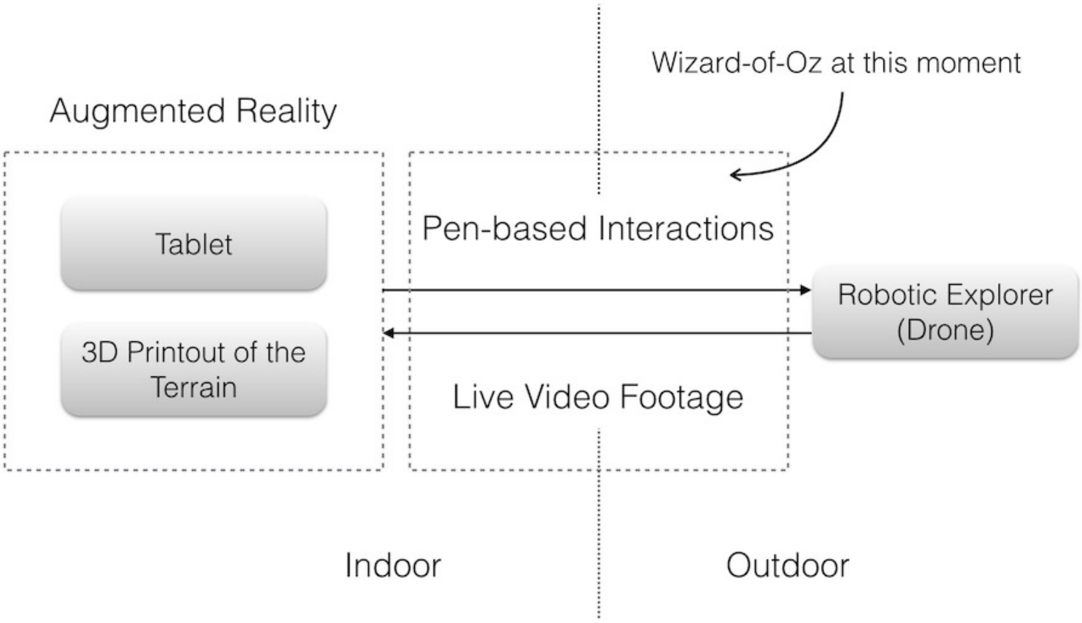

Figure 5.10: *Flying Frustum*'s block diagram

5.4 Limitations And Future Work

Although we see *Flying Frustum* as a direct extension of past work that demonstrated that situated streaming information improves human-UAV awareness [Drury et al., 2006a], our augmented reality approach still requires formal evaluation and validation, and the preliminary prototype we presented here still needs to be solidified to make sure it is ready for use in an actual user study.

One limitation is the current state of augmented reality technology, and specifically the questionable usability of see-through headsets primarily due to the limited field of view. However, we believe that with the rapid development of this technology future augmented reality headsets will have much larger field-of-view and higher fidelity. We are looking forward to integrating future headsets (e.g. Microsoft HoloLens[8]) in *Flying Frustum* as well as to exploring other visual augmentation approaches such as

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[8] `https://www.microsoft.com/microsoft-hololens/en-us`

projection mapping on top of the 3D model.

We would like *Flying Frustum* to support a much richer gesture vocabulary. For example, allowing the operator to sketch a loop to indicate an area on the 3D printout, or to use a pre-defined search pattern (e.g. spiral or grid), which will direct the UAV to continuously monitor a path above the terrain, to search a specific area, or to follow a specific flight pattern. Such an extended gesture vocabulary could have applications and benefits to various tasks such as search and rescue operations.

In addition, we plan to study how *Flying Frustum* can improve the operator-UAV ratio, and allow control of a several UAVs simultaneously. We are interested in learning the overall workload and performance impact of *Flying Frustum* on operators of multiple UAVs, especially in comparison to other UAVs control mechanisms (e.g. [Mitchell et al., 2005]).

5.5 Summary

In this chapter we presented a new human-interface we call *Flying Frustum*, which facilitates spatial situated remote interaction with drones. *Flying Frustum* uses a 3D printout of the terrain as an interactive medium. The UAV operator can use pen-based interactions to input flight paths and send commands to the UAVs by sketching directly on the physical topographical model of the terrain. The UAVs can in turn present information such as streaming video back to the operator via the augmented reality overlay on the terrain model. The information is situated in a 3D view frustum on the model in the correct location corresponding to the UAVs current position. We outlined our design approach using handheld and headset augmented reality techniques, and our current preliminary prototype based on a Parrot Bebop drone.

Though our work on *Flying Frustum* is still ongoing and while we have not performed a formal evaluation, we believe that *Flying Frustum* provides a unique human-UAV interface, and that the 3D real-time situated interaction it affords is intuitive and increases human-UAV awareness over previous works.

Chapter 6

Lessons Learned And Discussion

In this chapter we present some of the lessons we learned while designing spatial interfaces for physical representation of maps. We discuss our reflections based on our design and implementation efforts. The lessons we provide here may not be a comprehensive set since they are based only on our experience within the limited scope of this thesis, however, we believe that the themes we discuss here are valuable and embody fundamental concepts for the design of collaborative spatial interfaces for physical representations of maps.

In the first section we describe some of the lessons we learned and general design guidelines pertaining to the physical scale of the 3D physical representation of maps. We then present our reflections and then conclude this chapter by presenting limitations of our work.

In this chapter we describe the lessons we

6.1 Lessons Learned

In this section, we detail our insights regarding the scale of the physical representation. These insights have been developed based on our experiences while realizing the prototypes in this thesis and also on the current limitation of 3D printers.

Lesson #1 : Choosing the Appropriate Scale

One of the current limitations of 3D printers is that they cannot print large high resolution areas. So, the size of the medium, and thus, the resulting 3D maps, and the resolution in which fine details can be written upon it, are both limited. For example, the maximum dimension of the printout we could obtain from a commercial 3D printing service (Shapeways Inc) was 26cm x 54cm x 6cm (breadth x length x height, shown in Appendix B.1)(Figure 6.1). This printout covered an area of 2.8 km x 4.9 km which results in a scale ratio of 1: 10800 cm along the width (X-axis) and 1:9000 cm along the Y-axis. We use linear interpolation along X and Y axis to convert a latitude longitude co-ordinate to the normalized co-ordinate on the 3D printout (see Appendix B.3 for details on this conversion). As per this calculation, for every 100 meters travelled by the explorer, the corresponding travelled distance on the 3D printout will be 1cm.

We suggest that the scale ratio is an important consideration to take into account based on the application. For example a scale ratio of 1:100000 cms might not be appropriate for a walking-based exploration application wherein the explorer would need to travel 1km, for a 1cm update on the 3D printout. In contrast, such large scales might be a better fit for other explorations wherein the exploring entity is a vehicle or a drone.

Lesson #2 : Portability vs Resolution

One of the other major design decisions that has to be made for an application is the trade-off between portability and the resolution of the printout. Larger 3D printouts have the advantage of offering higher resolutions and lower scale ratios but they can be very bulky and non-portable.

We used mobile based Augmented Reality approach for all our prototypes which makes our apparatus highly portable (Figure 6.3). For larger printouts, mobile based AR approach might not be suitable as the area to be tracked is larger, and given the limited field-of-view (fov) of the current mobile cameras, the robustness of the tracking

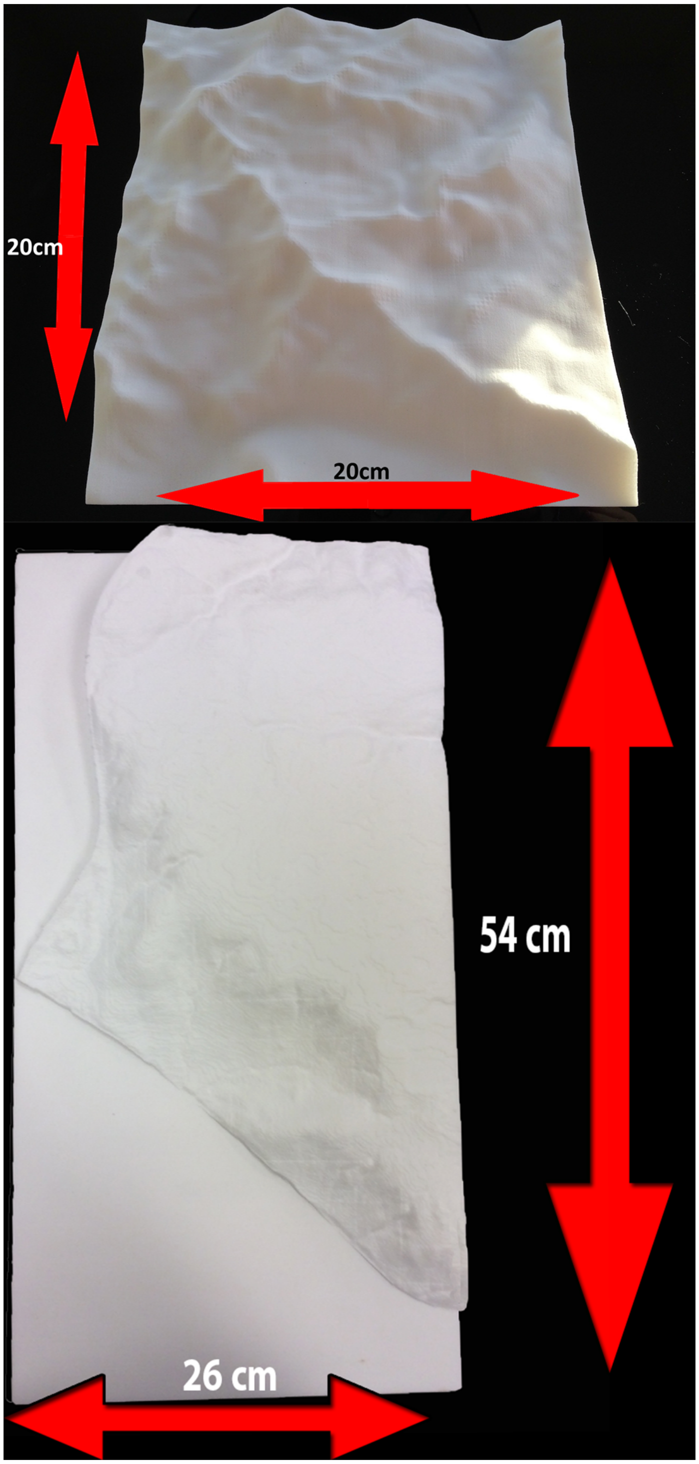

Figure 6.1: (top) Small scale 3D printout with 20cm x 20cm dimension and (bottom) larger scale 3d printout with 26cm x 54cm

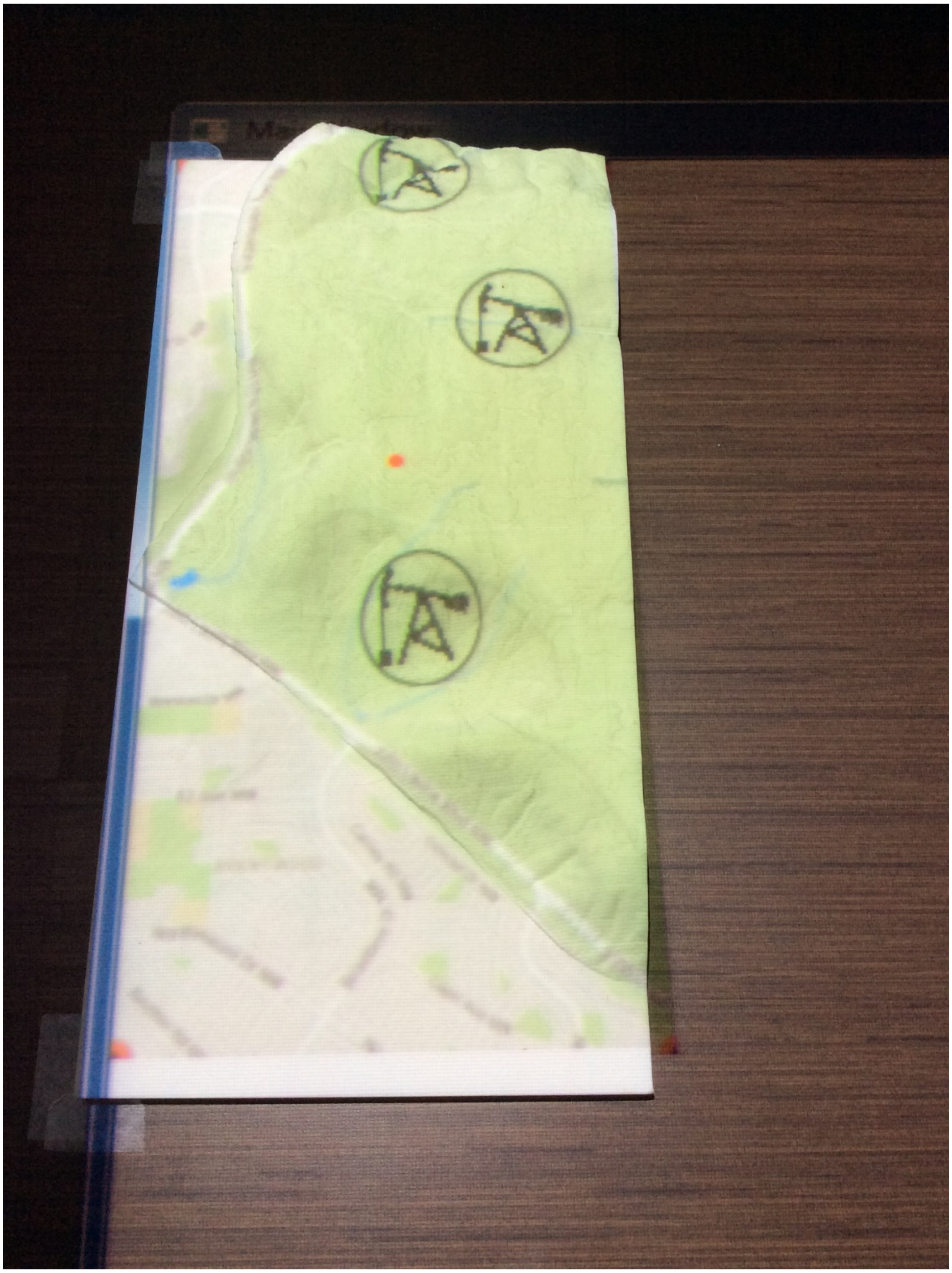

Figure 6.2: Projection Based Augmented Reality overlays content on to the 3D printout

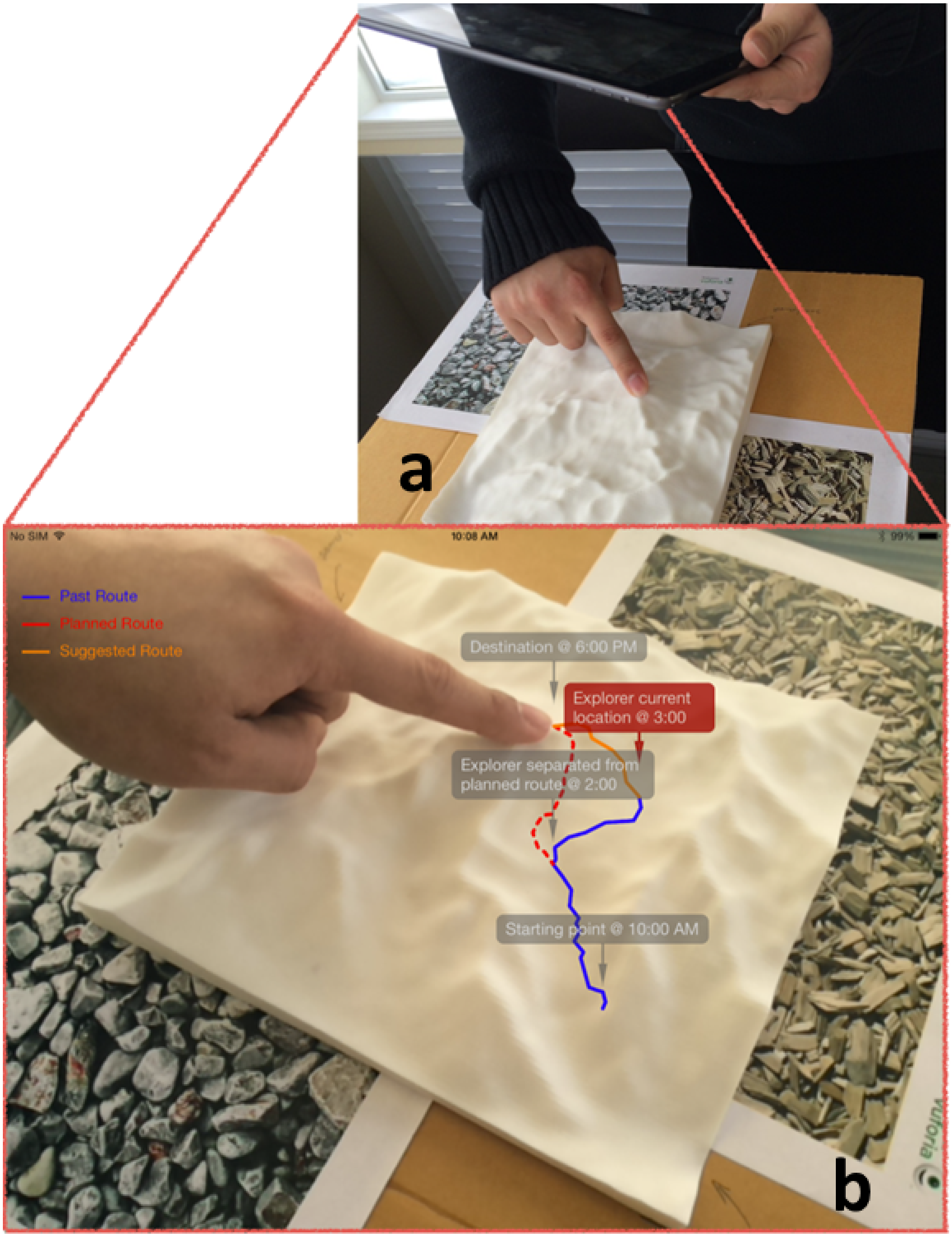

Figure 6.3: Mobile based augmented reality where the content is superimposed on an iPad screen

could be mediocre. Projection mapping could be used to project content onto such large physical representations (Figure 6.2). Another major advantage of projection mapping is that it allows multiple users to view the content simultaneously enabling a highly collaborative environment. However, the disadvantages of projection mapping are:

- It might confine the apparatus to a laboratory environment.
- Projectors might require calibration and setting up the entire apparatus could be tedious and non-intuitive for non-tech savvy users.

Wearable devices can be integrated into our current design eliminating the need to hold the mobile devices for long periods of time. Wearable devices could also be useful when the content is overlaid onto the physical map through projection based augmented reality. In such a case, wearable devices can serve as private displays for individual users, while the projection based AR could function as a shared public display.

Lesson #3 : Printing Higher Resolution Models

As previously mentioned, one of the major limitations of the current 3D printers is that they cannot print large-scale high resolution 3D printouts. One of the approach we suggest to print higher resolution models is to print-by-parts. The high-resolution 3D model can be divided into separate parts, each of these parts could be printed separately and then the modules can be united into a single map. The scale of all the separate parts should be maintained constant. We created 3D models of such individual parts of our university locale (these parts include a hill, a small pond) (Figure 6.4) so that these could be integrated into one large landscape enabling us to scale a 300m x 300m area into a 30cm x 30cm physical representation which gives us a high scale factor of 1: 1000 (compared to 1: 30000 scale for the 3D printouts in our prototypes). We intend to conduct controlled experiments for collaborative navigation tasks using 3D physical maps (also described in the future work section of chapter 7) and we followed this print-by-parts approach to generate a higher resolution printout of a small area.

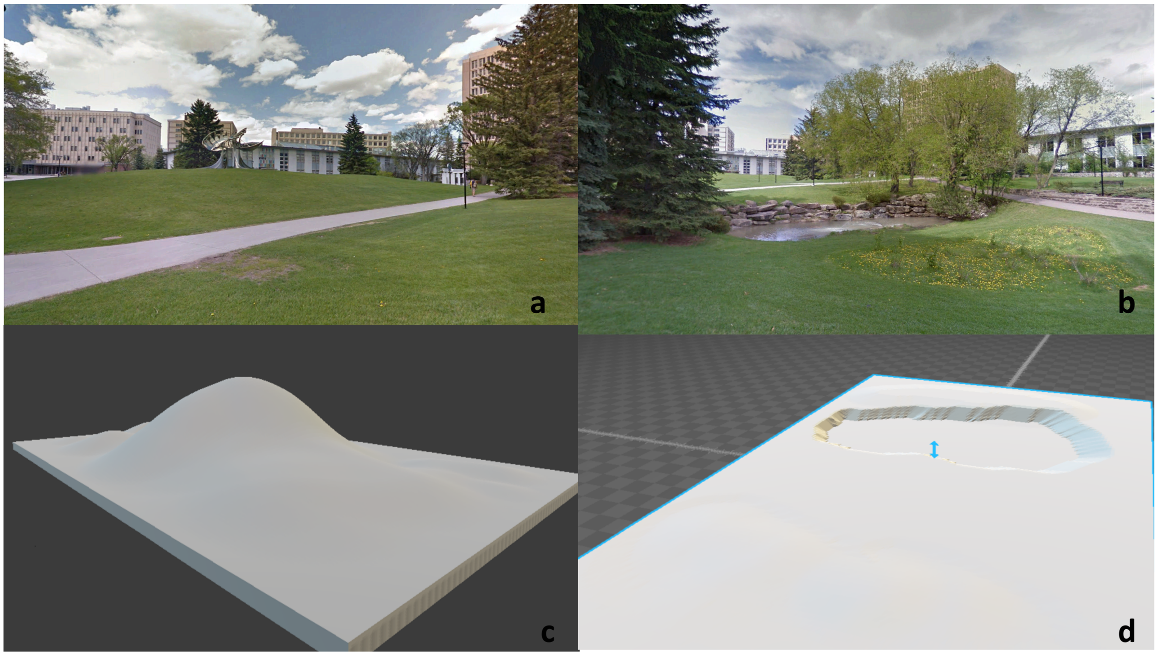

Figure 6.4: (a)Picture of a “chicken-hill” in our university locale (b) Picture of a pond in our university locale (c)a 3D model representing the “chicken-hill” area designed in Blender (d) a 3D model representing the pond designed in Blender

6.2 Discussion

In this section we provide some of our insights into the design of interactions for physical interactions of maps.

6.2.1 Direct Physical Interaction

Classic 2D maps offer physicality but the interaction on them is very restricted or non-existent. For example, they do not allow various operations such as sketching, painting and deleting regions. 2D digital maps offer these interactions with various tools such as pen, brush and eraser, which enable users to perform a variety of actions such as sketching, painting and deleting regions. However, the downside of digital maps is that they do not offer physicality and spatiality. Since the physical 3D maps offer spatiality and physicality, we advocate the design of direct interactions on the physical representation instead of the traditional interfaces such as a keyboard or mouse (Figure 6.5). This is also shown by our design of stylus-based interactions in our *PlanWell* and *Flying Frustum* prototypes which enable the user to sketch, and annotate on the 3D printout. Another advantage of having direct interactions on the 3D printout is that it eliminates depth-perception issues, which are very common with 3D software packages and virtual environments. This was also highlighted by one of the domain experts during the evaluation of our *PlanWell* prototype.

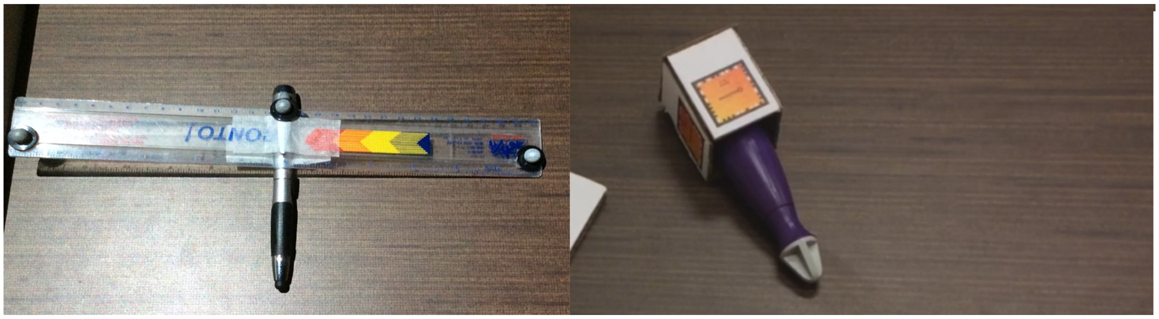

Figure 6.5: Various stylus prototypes used in our experiments. (left) Vicon based stylus. Three reflective markers are attached for Vicon tracking. Since the Vicon requires a larger area for tracking, the area of stylus has been increased by attaching a scale to it (right) stylus based out on augmented reality. Fiducial markers are attached at the top for AR tracking.

6.2.2 Co-located Collaboration

Physical paper maps have been powerful co-located collaborative mediums for a wide range of activities such as spatial planning, navigational activity planning, and defence missions. They enable multiple users to work, plan and view maps together supporting collaborative decision making. 3D physical maps can also serve as powerful co-located collaborative mediums similar to the paper maps. The scale of the physical map could be one of the factors effecting collaboration. For example, larger higher resolutions maps can support more number of people when compared to a smaller low-resolution one.

6.2.3 Multi-Resolution Visualization And Zooming

One of the limitations of 3D physical maps is that they have fixed resolution and do not support common operations such as zooming and multi-resolution visualization, which are offered by the 2D digital maps. We suggest the following approaches to counter this limitation:

Printing Multiple Maps

The brute-force approach for having multiple-resolutions is to 3D print multiple maps with different resolutions. With advances in 3D printing technology, this approach could be more feasible when 3D printers become more ubiquitous and cost-effective.

Physical Tools For Multi-Resolution Zooming

One of the other approach is to have a 3D flexible and tangible lens tool to provide multi-resolution visualization [Looser et al., 2007](figure 6.5). This enables the users to perform various natural interactions such as stretching,bending and twisting, for visualizing in multiple resolutions.

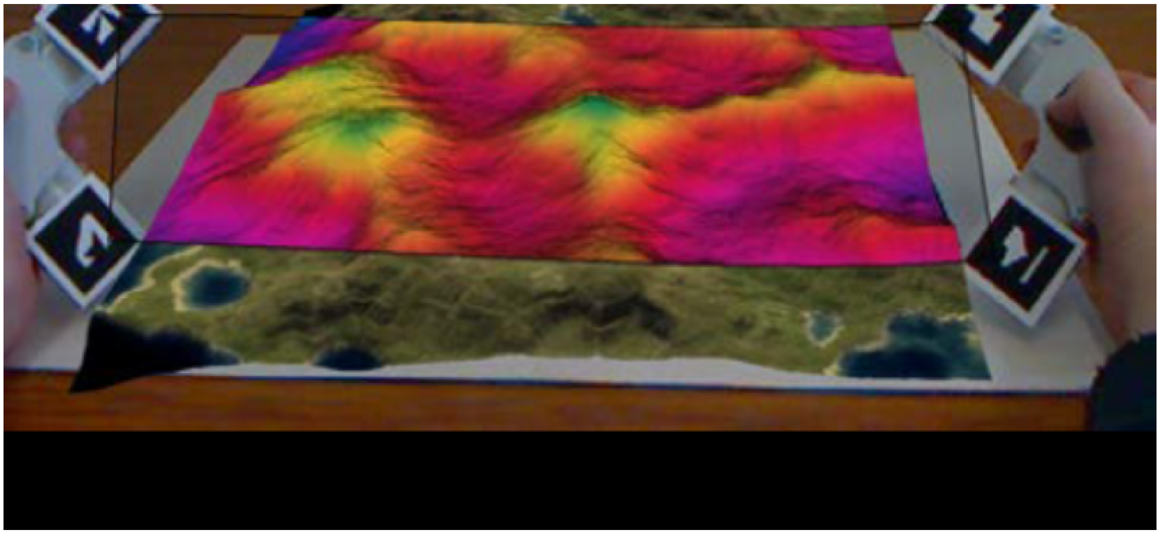

Figure 6.6: A Tangible flexible lens developed by [Looser et al., 2007]. The lens can be bended, twisted, stretched, enabling various AR visualizations

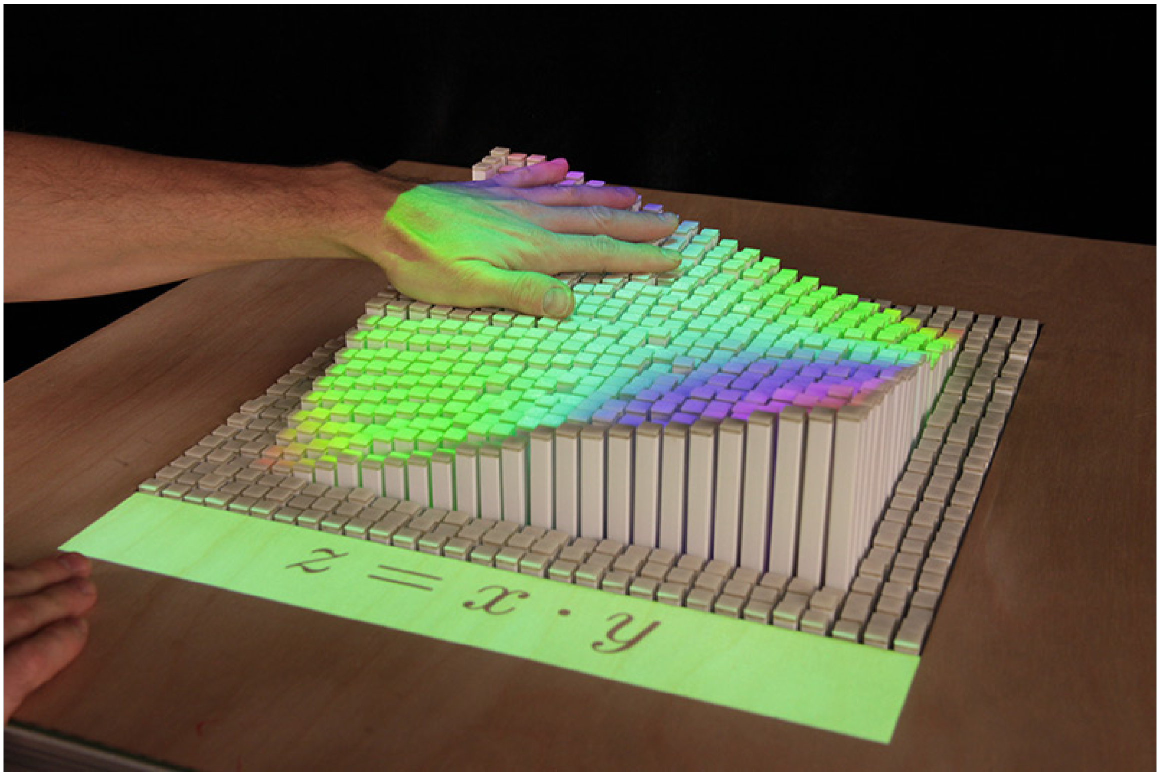

Figure 6.7: Shape displays realized by Leithinger et,al. [Leithinger et al., 2015] can render dynamic 3D shapes. These shape displays could be used to render dynamic physical maps.

Shape Displays

Shape Displays are new class of I/O devices that dynamically render physical shape and geometry [Leithinger et al., 2015](Figure 6.6). Such shape displays could be used to render 3D physical maps. The advantage of shape displays is that they can dynamically render maps with multiple resolutions. The current drawback of shape displays is that they have limited resolution(30 x 30) but in the near future this resolution could improve enabling the rendering of high-resolution physical maps.

6.3 Limitations

Our approach for this thesis follows breadth-based approach, where we explore application areas and developed prototypes for a variety of tasks compared to a depth-based approach, in which a prototype is designed, developed and thoroughly evaluated using user-studies. While our approach enabled us to explore multiple prototypes, we could not conduct task-oriented evaluations for each of the prototypes. Our future efforts would be focused on evaluating each of these prototypes.

All of our prototypes are exploratory prototypes and though we had demonstrated and had qualitative discussion with various personnel (including domain experts, designers, and HCI researchers) we did not conduct a full formal evaluation of our prototypes. Therefore we think that future efforts call for conducting a detailed evaluation study of our prototypes, thoroughly assessing the validity of the presented prototypes in a more comprehensive way (e.g task-oriented scenario).

Conducting full evaluation of our prototypes also presents various challenges, for example, the logistics involved in having a participant exploring at a remote terrain are complex. Also there could be various other technical issues such as limited internet connection, and low cell-phone network coverage of the traditional telecom service providers. One of the solutions for such problems could be to conduct the evaluation on a lower scale (e.g in a university locale) in a controlled setting.

One of the other limitations is the cost and ease of fabricating physical terrain models. The terrain models used in our prototypes are fairly simple and it still took us considerable resources to obtain these printouts. The current 3D printers have limitations on the dimensions of the printouts. For example, the maximum dimension of the printout we could obtain was 26cm x 54cm x 6cm (breadth x length x heightm, shown in Appendix A.2)provided by a professional 3D printing service company (Shapeways Inc.). While this size is large, it might still be insufficient for applications that require high resolution and size. Even for the navigation based tasks, the scale issue (actual distance vs scaled 3d printout distance) cannot be completely eliminated. With the advances in 3D printing technology, we believe that the future 3D printers will be able to fabricate larger scale printouts with lower cost.

Direct physical interactions on the 3D printout offer many advantages over the traditional 2D interfaces and devices. However, we believe that these interactions should not be evaluated against the 2D interfaces (such as keyboards, joysticks, mouse and touch interactions on traditional touch-screen devices). This is because the underlying technology behind traditional 2D interfaces (such as touch sensing) have been evolving over a long period of time and are more-mature than our current physical interactions. Hence we believe that it is too early to have a comprehensive evaluation of our physical interactions and compare them against the 2D interaction devices.

6.4 Summary

In this chapter we presented some of the lessons we learned while designing and implementing all of our prototypes. We centered our discussion on three major themes:

Scale of the 3D printout, interaction design for physical maps and collaborative design. For the first theme, we discussed the lessons learnt regarding the selection of appropriate scale of physical maps, and also touched upon the portability vs resolution trade-off. For the second theme we described some of our reflections with regard to physical interactions and their comparison with the traditional 2D interfaces. Finally, we presented some of the additional modalities for facilitating richer communication and collaboration experience and concluded by outlining the limitations of our work.

Chapter 7

Future Directions And Conclusion

7.1 Conclusion

In this thesis we presented our research efforts in the exploration of novel spatial interaction techniques for 3D physical maps. Through the design,and implementation of three prototypes - *Shvil*- an augmented reality interface for collaborative terrain navigation , *Planwell*- a spatial interface targeted for collaborative petroleum-well planning and *Flying Frustum*- a spatial interface for enhancing human-UAV awareness - we gained new insights on these new prototypes, to complement the present technologies and provide enhanced user experience and potentially foster better decision making. A set of design guidelines have also been presented along with this research effort detailing various lessons we learned during the design and implementation of our prototypes and encompassing several other points of relevance.With this, we revisit the main contributions of this thesis as follows:

- **Design and implementation of *Shvil* - an augmented reality interface for collaborative terrain navigation** : in chapter 3 we detailed the design and implementation efforts of our *Shvil* prototype. We also presented some of the lessons we learned while realizing this prototype.

- **Design, Implementation and Preliminary Evaluation of *PlanWell*- a spatial interface for collaborative petroleum-well planning** : in chapter 4 we presented our application scenario for interactive physical maps. We designed and implemented a spatial user interface for collaborative petroleum-well planning. We gained new insights into our efforts by conducting two focus group discussions with the domain experts.

- **Design and implementation of *Flying Frustum* - a spatial interface for enhancing the user spatial awareness during a remote UAV (Unmanned Aerial Vehicle) interaction task**: in chapter 5 we provided a brief introduction on situational and human-UAV awareness and detailed the design and implementation efforts of our *Flying Frustum* prototype.
- **Lessons learned from the design of spatial interfaces for 3D physical maps** - in chapter 6 we presented the lessons learned and our reflections while designing and implementing our three prototypes. We believe these lessons and reflections can inform the community of the insights we gained and how similar design efforts can be approached in the future.

7.2 Perspective For The Future

In the chapters 3,4, and 5 immediate follow-up work was discussed, pertaining to each individual effort. In this section, more general instances of future work are presented, and briefly discussed.

7.2.1 Designing For Wearable Displays

Currently , the design of all our prototypes is based on the consumer-level mobile devices and tablets. While this approach has the advantage of deploying our prototype without any additional hardware and simple, readily-available experimental setup, ergonomically it is not suitable for performing tasks over a long period of time. One of our immediate goals is to extend our current prototype to the wearable displays on both the indoor and outdoor devices(for example, wearable head-mounted displays such as Google Glass or Microsoft Hololens could be used to view the augmented reality content at both the *overseer* and *explorer* sites). However, on the flip side, the current wearable devices have some serious drawbacks with respect to hardware, battery, display resolution, power consumption and usability issues such as lack of natural input and output modalities for interaction. This makes the current wearable devices unsuitable for our applications. However we hope that, with advancing hardware technologies the current drawbacks of wearable devices could be mitigated if not completely eliminated, which would make them more suitable for our applications.

7.2.2 Multiple *Explorers* and Multiple *Overseers*

Our current prototypes are simple versions with only one user on both the sites. However, this could be easily scaled to multiple overseers and multiple explorers. In case of the *Flying Frustum* prototype, this could mean multiple operators and multiple drones operating over the same terrain.

Multiple overseers and explorers/drones,would open a plethora of opportunities for future research. Some of those directions are :

- Single Overseer tele-operating multiple drones : It would be interesting to study how a single overseer can tele-operate multiple drones and the role of the 3D printout in such tasks. “How does the 3D physical representation perform in reducing the cognitive load for a multiple drone controlling task?”.

- Studying Collaboration Between multiple overseers : As discussed in chapter 4, terrain models could be an effective collaborative tool similar to the current day tabletops. We would like to study how 3D physical terrains could be used for collocated collaboration for various tasks such as collaborative navigation, petroleum well-planning and remote drone operation. Apart from these domain-specific tasks various other generic aspects such as workspace and spatial awareness [Tuddenham and Robinson, 2009], collaborative interactions [Rogers et al., 2006] which were studied in tabletop interaction can also be investigated for 3D physical maps.
- Multiple Overseers overseeing multiple explorers : Another interesting avenue for research is to study how multiple overseers can oversee multiple explorers, how they would distribute the tasks among themselves to perform collaborative goals, the modes of collaboration with the explorers and the role of 3D printout in facilitating such collaboration.

7.2.3 In-the-wild Collaborative Way-finding Study

In chapter 3, we presented *Shvil* an augmented reality interface for collaborative navigation. Though we designed and implemented our system and performed preliminary laboratory evaluations, it is still unknown how the system would perform in real-life collaborative way-finding tasks. How would the collaboration unfold? What modalities would the users use the most? (e.g text, audio/video, or our sketching based

Figure 7.1: Multiple *overseers* collaborating over the physical 3D map.

Figure 7.2: (top) Google map image of the wilderness park near out university. The red rectangle is the area which we 3D printed and (bottom) the 3D prinout of the area marked in the google map image.

input). We believe that a collaborative, task-oriented evaluation would be truly valuable to unveil some of these aspects and many more. One of the initial steps we took in this direction is the fabrication of a large-scale 3D printout of a wilderness area near our university (Figure 7.2). We intend to conduct task-oriented way-finding study in a realistic setting with the *explorer* physically present in the wilderness area and the *overseer* operating on the 3D printout.

7.2.4 Projection Mapping For Overseer Interface

All of our prototypes discussed in this thesis are mobile augmented reality interfaces. While this approach has the advantage of deploying our prototype on off-the-shelf mobile devices and tablets, ergonomically it is not suitable for performing tasks over a long period of time. Projection-mapping was one of the alternative techniques discussed during our *PlanWell* prototype focus group session. Our future efforts would include designing projection-mapping based augmented reality interface for the *overseer*.

One of our initial efforts in this direction is the projection of content on the 3D printout (Figure 7.3). We superimposed various information such as the mock-locations of the explorer and petroleum wells. For stylus based interactions we are currently designing and exploring various prototypes. We used Vicon system for tracking the stylus. The vicon setup used for our experiments is shown in figure 7.5. The tracking volume of a Vicon system is larger when compared to the size of a traditional pen (which we originally intended to use as a stylus), hence we had high tracking inaccuracy due to various reasons such as occlusion by hand, occlusion by body and also due the inherent smaller size of the pen. To achieve better tracking accuracy, we increased the size of the stylus. We are still experimenting various sizes

Figure 7.3: Mock locations of petroleum-wells superimposed onto the 3D printout. The red dot represents the location of the *explorer*

Figure 7.4: User interaction on the 3D printout with a stylus.

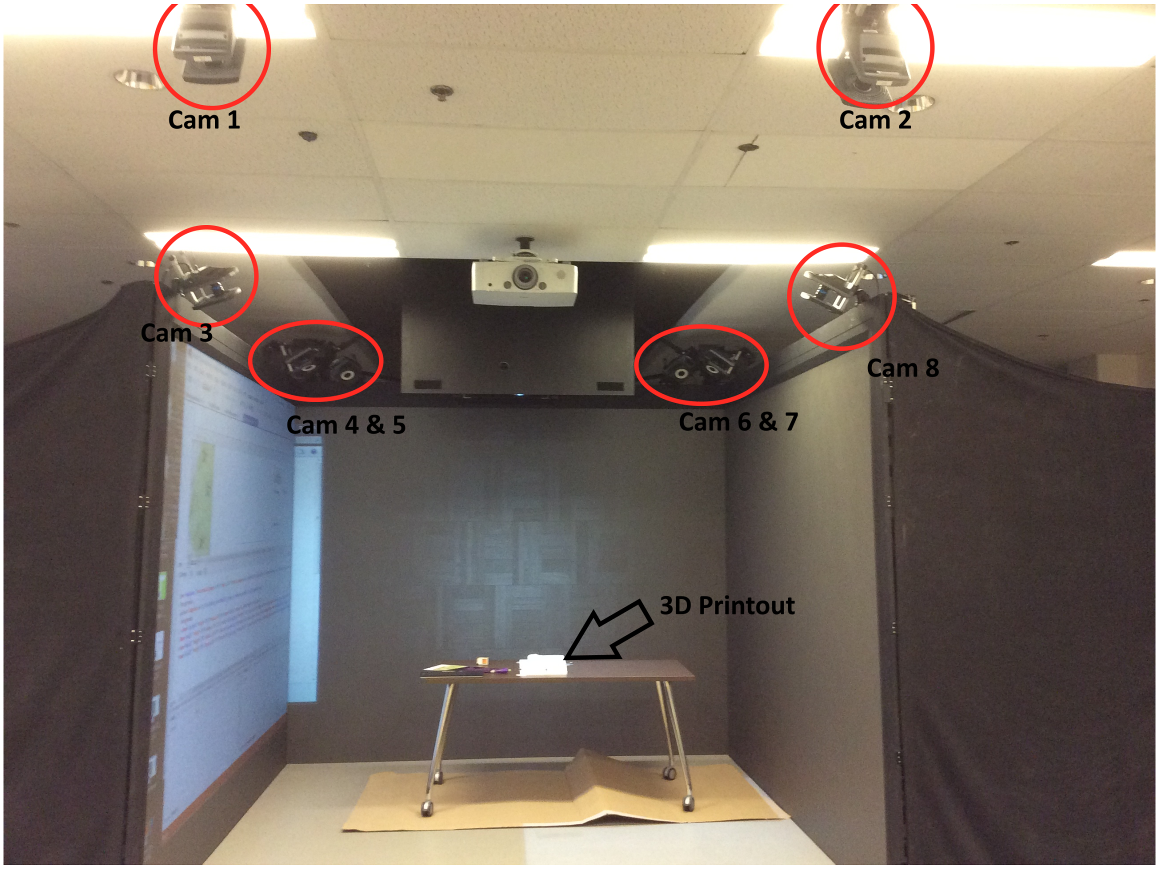

Figure 7.5: Our projection-based augmented reality setup. A Vicon system with 8 cameras is used for tracking the stylus.

Figure 7.6: Our Stylus prototype with 3 vicon markers.The stylus has been elongated by attaching a scale, for better visibility of the markers.

of styluses and working on improving our tracking efficiency. One of the initial stylus designed is shown in figure 7.6.

7.2.5 Studying the Spatial Perception On Physical Terrain Models

One of the other avenues for future research is to study how 3D physical maps can enhance the spatial awareness of the terrain. "How do 3D Physical maps perform in enhancing spatial awareness of the terrain when compared to the traditional techniques of height representation on 2D maps?". We intend to study this research question by conducting in-depth task-oriented user studies. We intend to use traditional methods used in cartographic studies such as line-of-sight determination, relative altitude comparison. Apart from these quantitative measures, qualitative feedback from the participants would help us in understanding the benefits of 3D physical maps.

7.2.6 Exploring Other Input Modalities for Interaction with 3D Physical Maps

In this thesis, we primarily used only a simple stylus based interaction with the 3D physical maps. The stylus-based interaction was based on augmented reality and uses fiducial markers for tracking. We would like to explore other devices and technologies for our future iterations of our prototypes. One of the devices which we would like to integrate into our prototypes is the Phantom Haptic Interface [Massie and Salisbury, 1994]. The Phantom Haptic Device was originally designed by Massie and Salisbury in 1994 and commercialized by Sensable Technologies , Inc.,(Woburn , MA, USA) [1]. This system is widely used in the haptics community and as an haptic interface in virtual environments(VE) communities for a variety of applications due to its high position precision, low intertia, and low friction.Though this system is majorly used

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[1] Phantom Haptic Interface. `http://www.dentsable.com/haptic-phantom-omni.htm`

as an haptic interface, we could use it as an alternate high-precision stylus in our prototypes.

Figure 7.7: The Phantom Haptic Interface. The stylus could also be used on 3D physical maps for various operations such as sketching, annotating, and erasing.

Apart from this it would also be very interesting to add touch functionality to 3D physical maps, enabling the users to touch any part of the map and view corresponding information overlaid onto the 3D printout.

7.2.7 Exploring Other Application Instances

In this thesis we presented three specific application instances of 3D physical maps. We would like to explore various other application scenarios of 3D physical maps such in Gaming, and in performing arts.

3D physical maps could be a powerful spatial interactive medium which can enable multi-player gaming. Apart from real geographic maps, game designers can design, and generate imaginative terrains and 3D print them to create new gaming experiences. Wearable devices such as Microsoft Hololens could be used to create immersive gaming experiences which can open new avenues for physical gaming.

Another application area for 3D physical maps could be in creative and performing arts such as Dance and theatre. Performers and directors can plan their shows with 3D physical maps of the stage sets. This could include various aspects such as planning lighting positions, planning and analysing the movements of performers/actors.

7.3 Closing Remarks

This thesis presented our exploratory research, supported by the design, implementation, and preliminary evaluation of three experimental spatial interfaces for physical representation of maps. Our efforts encompass three novel prototypes, *Shvil* - a augmented reality interface for collaborative land navigation, *PlanWell*- a spatial interface for collaborative petroleum-well planning and *Flying Frustum* - a spatial interface for enhancing human-UAV awareness, that were designed and implemented, followed by critiques from domain experts. Insights obtained from these efforts materialized into a concise lessons, guiding future efforts in this area of research. All these prototypes are meant to augment the existing tools and practices but not replace them.We believe that there are vast possibilities for improvement within this area of interactive physical representations. We hope this work can prove useful in inspiring and guiding future endeavours in this area of research.

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Appendix A

APPENDIX A

A.1 PLANWELL Focus Group Protocol

Good morning / afternoon, my name is XXX . Thank you very much for participating the brainstorming session of PlanWell.

PlanWell is a collaborative tool that facilitates remote field navigation between the indoor mission control, named overseer, and outdoor explorer individuals or teams. In this project, we experiment the possibility of using augmented reality and 3D printout to enhance the situational and spatial awareness during the collaboration, and enrich the user experience as well. We aim to apply this project to the field of oil and gas E &P cycle and your feedback on the applicability, validity of this approach would be very much useful for us in improving our prototype. Also, this is not an attempt to replace the existing methods and approach but we envision that this could be potentially useful in future.

[Show the video]

At the current stage, we focus on the 1-to-1 configuration. That is, the collaboration between one overseer and one explorer. The overseer part uses a 3D printout as the physical representation of the topographical terrain. Visualization is superimposed on the physical model via the augmented reality technology. Point-of-interests are displayed situated on the model according to their actual position in the real-world.

[A quick demo and trial of the overseer interface]

On the other hand, the explorer interface superimposes visual information upon the actual surrounding of the user, to create an in-situ experience.

[A quick demo and trial of the explorer interface]

Various kinds of information can be communicated with the aid of PlanWell. For instance, the real-time position of the explorer is visualized in the overseers interface constantly. Interactions and data manipulations from either side can be broadcasted and displayed on the other users interfaces. And there are many more possible cases.

However, these are all conceptual ideas, from the computer science perspective. Here we are seeking opinions, experience, and possibly real-world scenarios from your expertise in reservoir engineering / geo-science / etc.

Questions (from general to specific):

- What do you feel about the system?
- Do you think this system is useful / helpful in your working environment? Can you think any scenario in specific that such a system can be really valuable?
- Certainly many activities can be performed on regular display or interact mediums, such as traditional computer screen. However, we are providing the enhanced spatiality and physicality via using augmented reality and the physical model. Can you think any condition in your working experience that such spatiality and physicality can be the fundamental and unique features that differentiate it from alternative solutions?
- We use augmented reality technology to superimpose various information on both the overseer and explorer interfaces to create more im-

mersive experiences. How would you compare this technology to the existing ones, could you comment about the advantages/disadvantages of such a technology, and could you comment about the validity of the technology for real-world tasks?

- In our prototype system, we provide real-time dynamic communication and information exchange between the remote users. We hope that with this communication along with enhanced spatiality could potentially reduce the turn-around time for some specific tasks. Are there are scenarios and tasks in the oil and gas e& p where such communication could help reduce the overall turn-around time and fasten the decision-making process?
- We use 3D printout as a spatial representation of the terrain, does this 3D physical spatial representation be valid in any of the various oil and gas e & p tasks?

Appendix B

APPENDIX B

B.1 3D Printed Models of Landscapes

The recent price drop in personal fabrication tools and 3D printing [Malone and Lipson, 2007], makes them available to a broader audience and enables a range of applications. We envision that such 3D printing could be useful in ubiquitously printing out models of landscapes and terrains.

The approach for 3D printing realistic terrains can be described in the following three steps :

- *Digital Elevation Models(DEM)to GrayScale Image Conversion* : In this first step, we obtained the Digital Elevation Model(DEM) of Nosehill Park(a wilderness park near our university). The DEM data was provided by the SANDS(Spatial And Numeric Data Services) department at the University of Calgary. Once the data was obtained, we used ArcGis [Arc, 2016](which is the most commonly used software package to visualize Geographic Information System(GIS) data) to visualize the DEM data and exported into a grayscale depth map image.
- *Grayscale to Heightmap Conversion :* In the second step, we generated a 3D heightmap of the terrain from the grayscale image. There are number of ways to generate landscapes as described by [Macklem, 2003]. In our case, we used the simple height-map approach to generate the 3D mesh. The algorithm scans each and every pixel in the

image and the intensity of the pixel value(since the image is a grayscale image, the intensity ranges from 0 to 255) is taken to be the corresponding height value for each grid point. The algorithm takes the maximum and minimum height values as inputs and maps the intensity values to these height values. For example, if the maximum and minimum height values provided by the user are 0 and 20 units respectively, then a pixel with intensity value of 255 will have height of 20 units while the pixel with intensity value of 0 will have height of 0 units and the pixel with intensity of 128 will be linearly interpolated and will have a height value of 10 units. The generated 3D mesh from the grayscale image is shown in the figure below.

- 3D Printing Mesh : Once the 3D digital model is available, the 3D printout of the model could be obtained from an off-the-shelf 3D printer. However, in our case, the 3D printout was obtained from a commercial 3D printing service vendor(Shapeways Inc [Sha, 2016]). The dimensions of our model are 27 x 54 x 5 cm (width,depth and height respectively) and the material used was strong and flexible plastic.

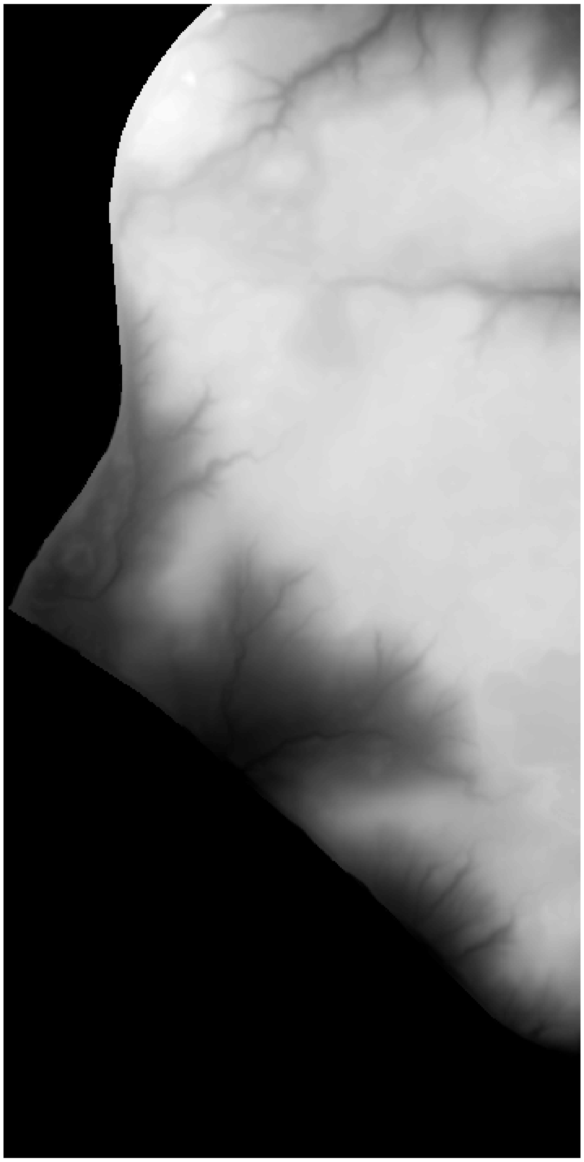

Figure B.1: Grayscale image of the Digital Elevation Model(DEM)

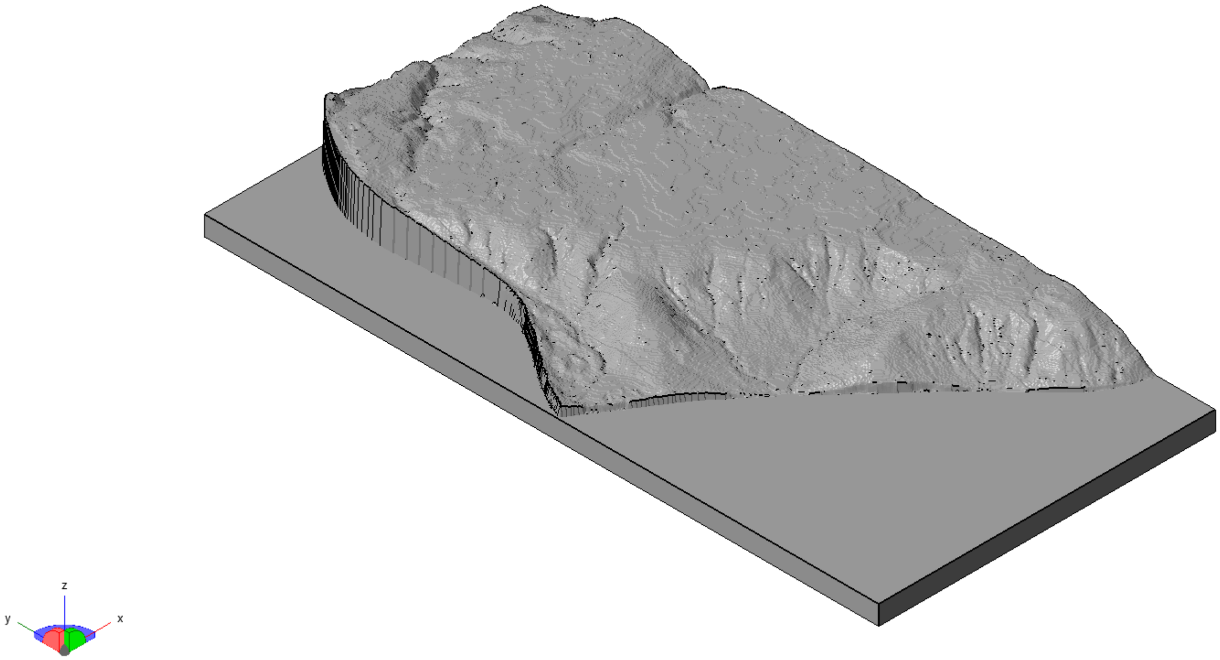

Figure B.2: 3D mesh of the obtained from the Grayscale image.

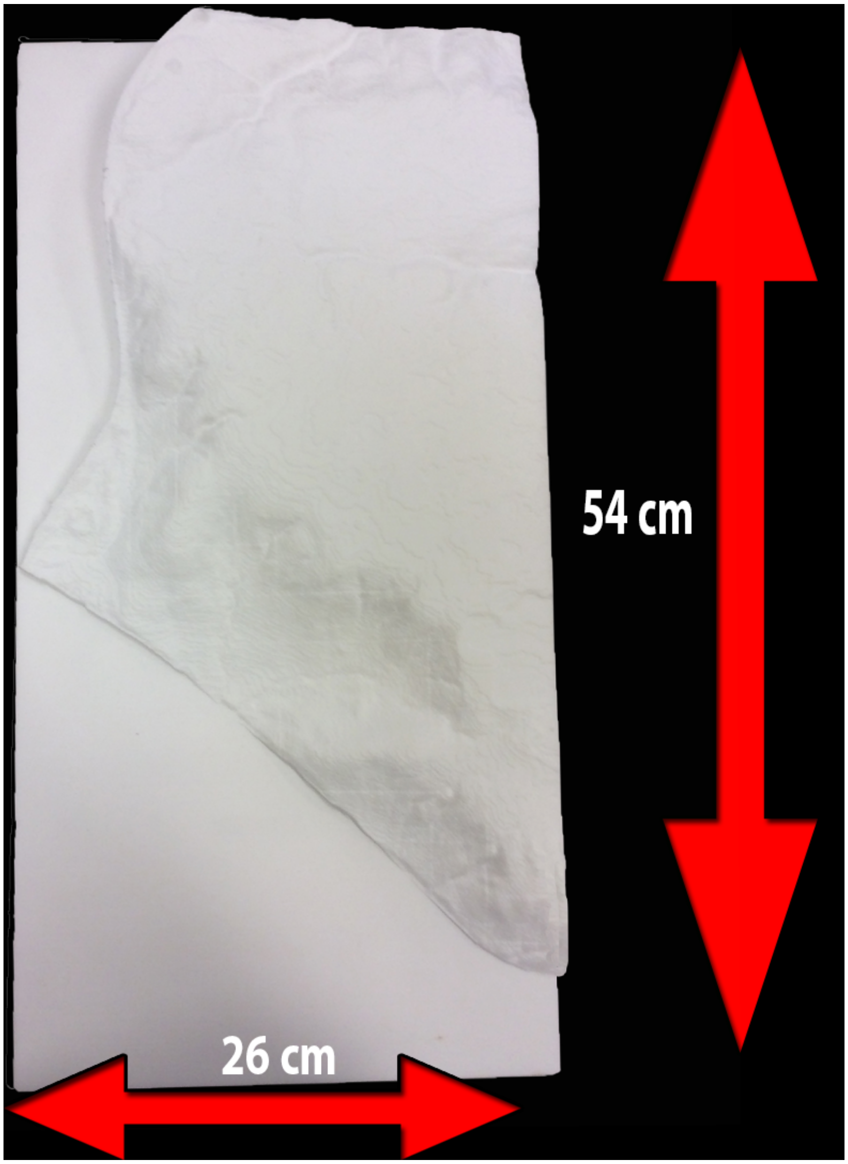

Figure B.3: 3D printout of the terrain model.

B.2 Low-Pass Filter

In this section we will be explaining the low-pass filter which we implemented for smoothening the compass sensor values. The algorithm was implemented for the *explorer* interface to reduce the noise in compass readings. Though we present the JAVA version of the algorithm for Android OS, this can be easily ported across various other programming languages and operating systems.

The filter has been implemented as a JAVA class and is called in the *onSensorChanged(SensorEvent event)* event handler in android. The *onSensorChanged* event handler is called by the Android system when there is a change in the sensor readings.

```
@Override
        public void onSensorChanged(SensorEvent event) {
                // TODO Auto-generated method stub
                int type = event.sensor.getType();
                float[] values = null;




                switch (type) {

                case Sensor.TYPE_MAGNETIC_FIELD:
                        LowPassFilter.filter(event.values,
                        mMagneticValues);
                        values = mMagneticValues;
```

```
                    break;


                default:
                    break;
        }


        }
```

The above code shows how the *LowPassFilter* class could be used to filter the compass values.

The *LowPassFilter* class which handles the filtering, is shown below :

```
/**
 * Low pass filter class to filter the sensors noise.
 */
public class LowPassFilter {


        /**
         * Time smoothing constant for low-pass filter 0 - 1 ;
         a smaller value
         * basically means more smoothing.
         *
         *
         */
        public static float ALPHA = 0.03f;

```

```
/**
 * Filter the given input against the previous
 values
 * and return a low-pass
 * filtered result.
 *
 * @param input
 *              float array to smooth.
 * @param prev
 *              float array representing the
 previous values.
 * @return float array smoothed with a
 low-pass filter.
 */
public static float[] filter(float[] input,
float[] prev)
 {
        return filter(input, prev, ALPHA);
}

/**
 * Filter the given input against the
 previous values

 and return a low-pass
```

```
         * filtered result.
         *
         * @param input
         *            float array to smooth.
         * @param prev
         *            float array representing the
         previous values.
         * @param alpha
         *            Time smoothing constant
           for low-pass filter 0 - 1 ; a smaller
         *            value basically means more smoothing
         * @return float array smoothed with
         a low-pass filter.
         */
        public static float[] filter(float[] input,
        float[] prev,
        float alpha) {
                if (input == null || prev == null)
                        throw new NullPointerException("input
␣␣␣␣␣␣␣␣ ␣␣␣␣␣␣␣␣ ␣␣␣␣␣␣␣␣and


prev␣arrays␣must␣be␣non-NULL");
                if (input.length != prev.length)
                        throw new IllegalArgumentException
                        ("input
```

```
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣and␣prev␣must␣be␣the␣same␣length”);

                for (int i = 0; i < input.length; i++) {
                        prev[i] = prev[i] +
                        (alpha * (input[i] - prev[i]));
                }
                return prev;
        }
}
```

B.3 GPS Co-Ordinates to Physical Co-Ordinates Conversion

In this section we will explain how we converted GPS latitude and longitude co-ordinates to the co-ordinates on the 3D printout.

In this example, we will be using the 3D printout of Nosehill park(a wilderness area near the University of Calgary). The section of the nosehill park which we chose to 3D print in shown in A.4(left). The latitude of the area ranges from 51.0903 to 51.1297 and the longitude ranges from -114.1400 to -114.1100. For our 3D printout we used normalized co-ordinates i.e the the co-ordinates vary from 0 to 1 on both the X and Y axis (Figure A.4 right).

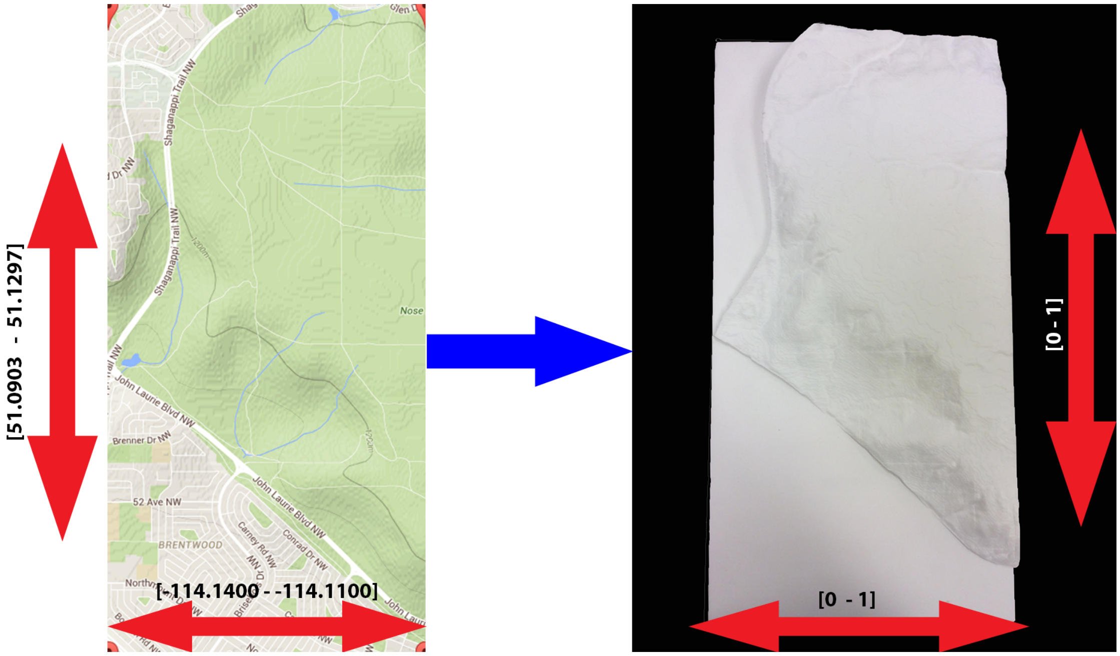

Figure B.4: (left) The section of the Nosehill park we used for 3D printing and the corresponding range of the latitude and longitude co-ordinates (right) 3D printout with co-ordinates mapped to [0-1] range.

We use simple linear interpolation to convert a latitude and longitude co-ordinate to a physical co-ordinate on the 3D printout. The pseudo-code below shows the conversion of a latitude and longitude co-ordinate to the physical X and Y co-ordinates on the 3D printout.

```
/* Constants to declare the latitude and longitude
 bounds of the Nosehill area.

const float NOSEHILL_MIN_LATITUDE = 51.0903f;
const float NOSEHILL_MAX_LATITUDE = 51.1297f;
const float NOSEHILL_MIN_LONGITUDE = -114.1400f;
const float NOSEHILL_MAX_LONGITUDE = -114.1100f;

// converted physical co-ordinates

float physicalX, physicalY;

public float convertLatitudeToPhysicalY(float latValue)
{
        if(latValue < NOSEHILL_MIN_LATITUDE)
                return NOSEHILL_MIN_LATITUDE;
        else if(latValue > NOSEHILL_MAX_LATITUDE)
                return NOSEHILL_MAX_LATITUDE;
        else
        {
physicalY = (latValue - NOSEHILL_MIN_LATITUDE) /
(NOSEHILL_MAX_LATITUDE - NOSEHILL_MIN_LATITUDE);
        }
        return physicalY;
```

```
}


public float convertLongitudeToPhysicalX(float longValue)
{
        if(longValue < NOSEHILL_MIN_LONGITUDE)
                return NOSEHILL_MIN_LONGITUDE;
        else if(longValue > NOSEHILL_MAX_LONGITUDE)
                return NOSEHILL_MAX_LONGITUDE;
        else
        {
physicalX = (longValue -NOSEHILL_MIN_LONGITUDE) /
 (NOSEHILL_MAX_LONGITUDE - NOSEHILL_MIN_LONGITUDE);
        }
        return physicalX;
}
```