Snakey: A Tangible User Interface for Well Path Planning in the Context of Reservoir Engineering

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Abstract. We present *Snakey*, a tangible user interface (TUI) designed for the field of reservoir engineering. The *Snakey* interface focuses on intuitive manipulation and interaction with 3D curves common to underground well path planning. Our paper discusses design goals and prototyping solutions relating to the physical materials, sensing technology, input/output mapping, and multi-modal information feedback of the *Snakey* TUI. The paper also discusses a design critique of the latest prototype interface performed by domain experts (experienced reservoir engineers) and concludes by outlining our findings regarding the next steps required to improve the current *Snakey* interface prototype.

Keywords: Tangible user interfaces (TUIs), physical interaction, real-time 3D curve manipulation, interactive visualization techniques, reservoir engineering

1 Introduction

The petroleum industry has been exploring and proposing different solutions for well planning tasks [1,2,3].Well planning (and subsequent drilling) is the final and often most expensive component of the oil and gas exploration and production (E&P) workflow. Traditionally, well planning is an iterative process, involving teams of multi-disciplinary experts with specific constraints and goals. In addition, the well trajectory is often laid out only in 2D maps and cross sections, making it difficult to understand the exact spatial relationships between the 3D reservoir model and the planned well-bore.

Desktop-based solutions for well planning have been adopted by the industry, typically with WIMP interfaces. Each well trajectory is represented on the screen as a 3D curve located inside a 3D digital model of the reservoir geology and its flow properties. The task of positioning well trajectories involves a large number of control-point operations applied along each curve representing the well, leading to a time consuming and non-intuitive operation.

Well planning tasks can benefit from the increased immersion, true-to-life scale, and larger amounts of simultaneous visualization data afforded by virtual reality (VR) interaction systems. However, the VR systems that have been adopted by industry usually required specialized visualization rooms (e.g. CAVE environments) and hand-held interaction device technologies; both of which can often be non-intuitive to use, provide weak (or no) physical affordances, are difficult to maintain, and are not immediately conducive to large group collaborations. [4, 5]

Instead, our approach is an attempt to match some of the unique properties of tangible user interfaces (TUIs) to the inherent physical and collaborative nature of 3D well-path planning in reservoir engineering.

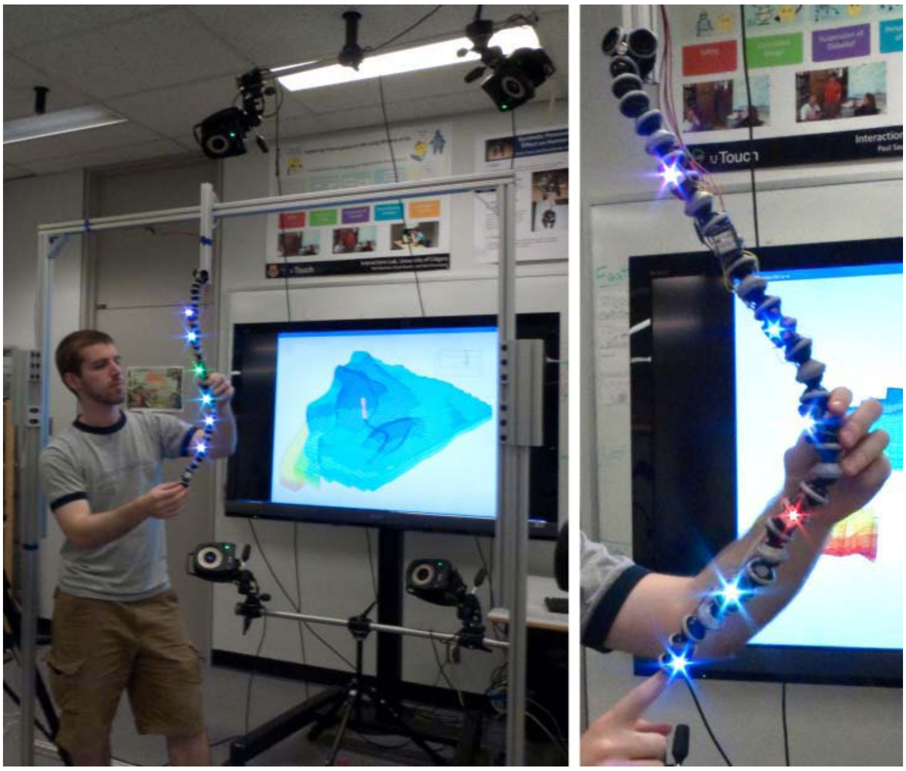

Figure 1 – The *Snakey* interface, visual display, and camera array

This paper describes our design work on "*Snakey*"*;* an intuitive, collaborative tangible user interface in the task-specific context of designing and manipulating 3D well paths for reservoir engineering. As can be seen in Figure 1, the *Snakey* interface consists of two main components: 1) a graspable, semi-rigid physical device (similar to a long plastic "snake") which directly mirrors the shape of an underground well path, 2) a large visual display directly behind the hanging physical object which reflects the users' physical manipulations onto a virtual model of a well path and surrounding geological survey data, and 3) output elements (LED lights and vibration motors) embedded in the physical device that provide direct haptic and visual feedback to the user holding *Snakey*.

Snakey's design leverages peoples' natural abilities to use their hands for controlled and fine-tuned manipulation of everyday physical objects to provide meaningful representation and direct control of the virtual 3D well path [6]: *Snakey* directly couples the 3D well path input and output spaces into a single physical object, lowering the cognitive load required for interaction and improving the spatial mapping and ease of use [7]

In this paper, we describe our explorations of the physical materials used for the *Snakey* interface, the configuration of the workspace surrounding it, the design of input/output mappings between the physical and virtual workspaces, and the supporting computer software. We conclude with a design critique evaluation of the *Snakey* interface and a discussion of some of the efforts required to further improve the current prototype.

2 Design Goals

The primary design goal of *Snakey* was selecting the TUI's properties so as to warrant an interaction metaphor that would be valid for the design and planning of 3D well paths in reservoir engineering visualization tasks. From this, *Snakey's* unique characteristic is the ability to afford simple and intuitive physical manipulation of 3D curves in real time *while maintaining* its 3D shape throughout the interaction session, unless directly manipulated by the user. We envisioned reservoir engineers, a single user or a collaborative group, being able to relate to the 3D physical *Snakey* as a constant and consistent representation of the virtual well. Devising a means for *Snakey* to persistently represent the well (e.g. physically keeping its shape even when not being held by the user), while at the same time allowing users to manipulate and interact with its curve was our main design challenge.

Snakey's secondary design goal emerged from the need to allow easy access to the 3D curve manipulation and its mapping to reservoir engineering well path explorations. Reservoir engineers need to visualize the overall trajectory of the well and do so from different viewpoints in relation to the reservoir model (e.g. 'looking below the surface'). This directly affected the way we setup *Snakey's* interaction space and spatial layout.

Modularity in the design of wells can be an advantage as they are often planned with junctions and forks, establishing multilateral well configurations. This prompted the need for a modular TUI device that could be reconfigured, branched, and decomposed with minimal effort.

We also thought of ways to integrate other physical properties, beyond the spatial, into *Snakey*. We envisioned the integration of other secondary visual cues into *Snakey*, beyond its direct 3D mapping to the well path's curve. We wanted *Snakey* to be able to indicate, potentially through attached miniature display screens or embedded lighting indicators, sections of the well path that needed further attention.

We also envisioned haptic feedback embedded into the interface, allowing users to have haptic access to some of the well properties, such as fluid flow through the well path or in its vicinity, or as a tangible indicator of having reached one of the well's or the reservoir's physical constraints. (e.g. exceeding a minimum safe radius of curvature)

Although the reservoir engineering applied domain played a key role in our design considerations, we also see benefits in *Snakey's* design goals that go well beyond its current applied task, and believe that there are other interaction tasks, such as robot navigation planning, that can benefit from its more general physical 3D curve manipulation properties.

3 Related Work

Physical manipulation of 3D curves was one of the early focuses of TUI research. In 1999, Balakrishnan et al. [8] and later Grossman et al. [9], presented their work on using Measurand's ShapeTape^{TM} as an input device that can sense its 3D bend and twist for interactive manipulation of 3D curves and surfaces. ShapeTape is a rubber ribbon which integrates internal tracking via embedded fiber optic bend and twist sensors. Balakrishnan et al. mentioned attaching spring steel to ShapeTape to provide more physical constraints to the rubber core [8], however to our knowledge there is no published work on integrating ShapeTape into an interface that can physically hold its shape consistently in a manner required by our design goals.

Several past research directions explored interactive creation and manipulation of 3D shapes: for example using 6 degree-of-freedom tracking devices [10], direct creation and interaction of 3D shapes via hand movements [11]. Others leveraged real-world physicality, such as by painting on physical, previously scanned, surfaces [12], or using stylus based haptic force feedback device [13].

Research efforts of tangible user interface construction sets also inspired our work. For example, Moneys [14], ActiveCube[15] and Topobo[16]. While these are all interactive, modular, and maintain their physical shape throughout the interaction, none of them provides the level of detail and resolution of physical expression we seek with our project.

AR-Jig [17] provides interactive physical mapping to 2D curves using a handheld pin-array, which can be used to control 3D surfaces. However, the pins provide a relatively small, and physically discrete spatial control area that we believe would be difficult to meaningfully map to direct 3D interaction with large 3D curves.

Closer to our applied domain of reservoir engineering, GeoTUI[18] provided a tabletop TUI for interaction with geological data, however the interface does not support 3D physical interaction and spatial manipulation of the 3D curves of well paths. Ishii et al. Illuminating Clay [19] affords direct 3D interaction with geological data via physical surface sculpting. A similar 3D physical sculpting interaction concept was used recently by Fogelman [20] to allow users to manipulate and explore detailed geological tasks. However, these physical 3D surface interfaces do not answer our design goal of allowing physical interaction with a consistent, shape holding 3D curve that can be mapped to spatial explorations of wells in reservoir engineering.

From the perspective of reservoir engineering, well-planning is a task for which the domain has been seeking visualization solutions for a long time, including different

VR approaches [21, 22, 23] as a means of providing intuitive ways of manipulating 3D objects, interpreting complex 3D structures, and viewing data at true-to-life physical sizes. While VR solutions for well planning have been adopted by the reservoir engineering domain in some instances, these are typically suitable for large, specialized visualization rooms (e.g. CAVEs) which require the use of special interaction mediators (e.g. HMDs, handheld trackers) and are often not as accessible or used as desired. Moreover, these solutions focus on the 3D visual aspects of the well curve, but provide little (or no) physical representation or feedback. Like others [18], we believe that the reservoir engineering domain requires the exploration of new interfaces that will afford a more intuitive and natural interaction with the well path planning task. [1, 24]

4 Implementation

In this section, we detail the current *Snakey* prototype's implementation. We discuss our vision-based real-time tracking solution, *Snakey's* material exploration, the TUI interactive space and support structure, *Snakey's* dynamic topology capabilities and the haptic and visual feedback mechanisms embedded within the TUI.

4.1 Tracking Solution

One of the first alternatives considered for how to sense the physical *Snakey* object's shape and convert it into a representative 3D model was the Measurand "ShapeTape" device previously discussed [8]. Although this product is specifically designed as a continuous bend and twist sensor, its relatively short length, inability to hold a rigid shape without external support, and questions about its ability to easily bend in every direction reduced the attractiveness of ShapeTape as solution for our specific needs. (e.g. its "ribbon" structure allows for easy bending in one direction but only limited twisting and no bending in the transverse direction)

Instead, an available Vicon 3D motion capture camera system[25] was chosen as a more flexible tracking solution. With this system, a number of retro-reflective markers are placed within a given tracking volume. An encompassing array of infrared emitters and cameras each detect the 2D positions of the markers from their respective perspectives and, using triangulation algorithms, collectively reconstruct the positions of the markers in 3D space in real-time. For the *Snakey* TUI, the discreet 3D positions of the tracking makers were then interpolated to yield the continuous 3D curve path.

Utilizing the Vicon 3D camera system provided *Snakey* with larger possible tracking volumes, greater adaptability (e.g. multi-prong curves), and essentially unlimited curve lengths (e.g. by adding more markers). Choosing a visual tracking system did introduce the problem of temporary occlusions (e.g. when the user covers a marker with their hand during manual manipulation), which we solved by designing for redundancy. We have found that with a sufficient number of adjacent tracking markers attached, our interpolation scheme was sufficiently robust and these occlusions rarely presented a problem.

With a tracking solution selected, our design explorations then turned to find a suitable core material. That is, the physical object that the user would be grasping and to which the tracking markers would be affixed.

4.2 Material Selection

Our primary focus during the development of the *Snakey* prototype was the choice of material to be used for the core physical object, as this would impact all other aspects of the device's design, such as how easily the device could be tracked, how it would be manipulated, and whether or not it could provide direct information feedback to its users. Our design criteria for the core material selection were:

1. the ability to easily form and modify three-dimensional curves using hands-on manipulation
2. the ability to hold its shape when the user lets go of the curve
3. the ability to accurately and reliable track the three-dimensional curve in real-time

The various materials that were considered (Figure 2) are briefly described below.

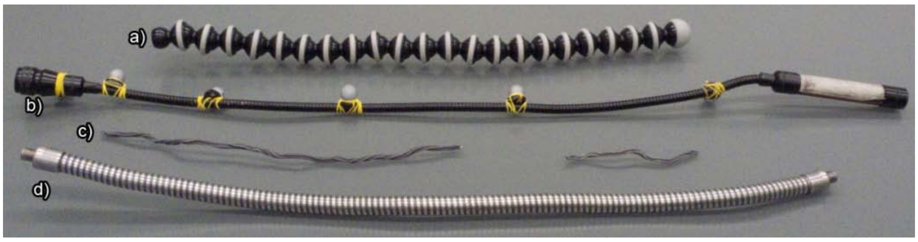

Figure 2 – A variety of the materials considered for the TUI. From top to bottom: a) Joby's "GorillaPod" camera tripod, b) light-weight "goose-neck", c) solid core wire, and d) heavy-duty "goose-neck"

Solid Core Wire (Figure 2, c): Inspired by how coat hanger wire can be bent into impromptu hooks, scaffolds, and arbitrary three-dimensional shapes, solid core wire served as a basis for comparison for the *Snakey* material exploration. Solid core wire benefits from being a compact and relatively stiff material. It is able to hold its shape even in heavily cantilevered situations. Unfortunately, simple solid core wire is not meant for repeated manipulation and quickly wears out after prolonged use. Since the process of shaping a piece of solid core wire relies on plastic deformation (an inherently destructive and irreversible process), it proved difficult to return a bent piece of wire to its originally straight shape without leaving permanent kinks in the material. Continued manipulation of the wire eventually also led to complete mechanical failure, causing it to break into multiple pieces.

Although different types of wire (e.g. gauge, material, braiding, etc.) were experimented with (each exhibiting various combinations of stiffness, ease of manipulation, and durability) every type suffered the same fundamental flaws and were quickly deemed not suitable for our purposes.

"Goose-neck" Devices (Figure 2, b and d): Next, a series of "goose-neck" devices were tested for their suitability. These materials rely on a special configuration of interlocking, flexible metal rings and stiff sheathing material to provide long, flexible supports for a variety of applications such as desk light, repositionable mechanic's lamps, and medical endoscopy. In comparison to solid-core wire alternatives, the elastic properties of these goose-neck devices provided much better durability, good repeatability, ease of manipulation and excellent size/shape characteristics. While a promising step towards meeting our design goals, these goose-neck devices suffered from an inability to hold tight, complex formations, were relatively infirm and, because they are constructed primarily of metal, are quite heavy; leading to poor cantilevered rigidity. We attempted to address these shortcomings with the use of stiffer, more heavy-duty goose-neck devices but the associated increase in physical strength required to manipulate these more robust devices quickly proved tiring (if not impossible) for test users.

"GorillaPod" Camera Tripod (Figure 2, a): The most successful prototype material came from an exploration of an unexpected source: camera tripods. Joby's "GorillaPod" [26] brand of flexible tripods consists of a set of interlocking plastic orbs (a series of ball and socket joints) which are both easily manipulated and able to hold rigid shapes even when under significant loads. Because these tripods are made out of plastic instead of metal, they are also exceptionally lightweight; further improving their cantilevered rigidity.

Depending on which size model is used, each "orb" link ranges in diameter from approximately 1.5cm to 4cm and each tripod can rigidly support cameras weighing from 325g up to 5kg. In terms of the ability to hold tight curves, the current *Snakey* prototype, using the mid-range *GorillaPod SLR-Zoom* model, can form curves with a minimum bend radius of 3.5cm. When used to form a single, continuous chain this means that a single can support approximately 25 additional "orbs" arranged in a horizontal line. (Figure 3)

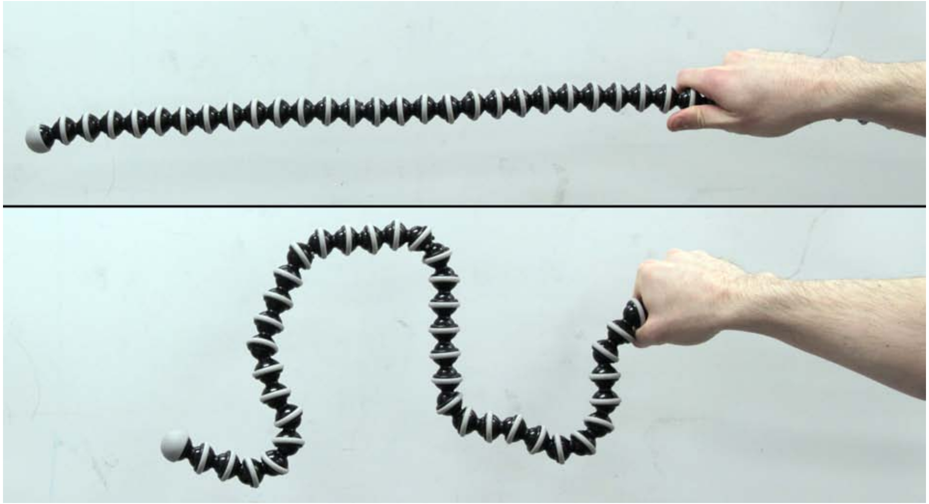

Figure 3 – A demonstration of the “GorillaPod” material’s excellent rigidity even when heavily cantilevered (above) and its ability to easily be manipulated into complex shapes (below). Each “orb” acts as a semi-rigid ball-and-socket joint.

4.3 Modularity

Section of the orb links can be pulled apart with sufficient force and then easily popped/pushed back together. Combined with special branching nodes, this provided a quick and easy “building blocks” style method of creating multi-lateral/branching well path formations; an important component of most reservoir drilling operations. (Figure 4) While the GorillaPod links were physically capable of forming “loops” and other more complex formations, our applied domain of reservoir engineering precludes our need to consider them. While these more complex configurations might prove interesting for more abstract usage scenarios, they do not make practical sense for the current *Snakey* task (e.g. an oil pipeline does not loop back onto itself) and as such were not explored in detail in the current prototype.

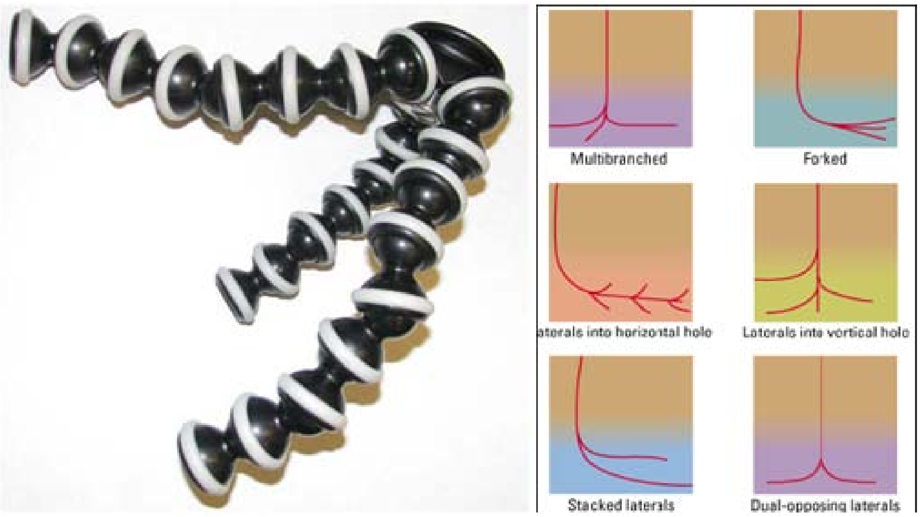

Figure 4 – (Left) A branched configuration of the *Snakey* object. (Right) Examples of common multi-lateral well path configurations.

4.4 Haptic/Visual Feedback

Additional methods of providing feedback to the users (in parallel with the on-screen display) were also directly integrated into the physical *Snakey* device.

Visual feedback was provided by a set of ThingM "BlinkM" programmable tri-colour LED lights [27]. Measuring 2.5cm square and outputting approximately 8000 millicandelas of light intensity (sufficiently bright that they are somewhat painful to look at directly at full power), the LEDs could each be individually programmed to take on a range of colours and intensities using a daisy-chained, two-wire communication bus.

Haptic feedback was provided by a set of 10mm diameter, button-style vibration motors[28]; each controlled in parallel (along with the LED lights) by a central Arduino microcontroller [29].

Both the LED lights and vibration motors were small enough to be mounted directly onto individual GorillaPod orbs without interfering with *Snakey's* flexibility of motion. The Arduino microcontroller was mounted to the *Snakey* support structure.

4.5 Support Structure

As seen in Figure 1, *Snakey* is mounted to a rigid, reconfigurable aluminum frame; allowing the "fixed end" of the *Snakey* chain to be position above, below, or to the side of the working volume as necessary. This approach provides a fixed 3D position in space by which to correlate the physical object with its virtual, on-screen counterpart. It also helps create an open workspace around the physical object wherein multiple collaborating users can interact with and manipulate the *Snakey* device simultaneously (an implementation approach which contrasts with a handheld device which must be passed from one user to the next during collaborations).

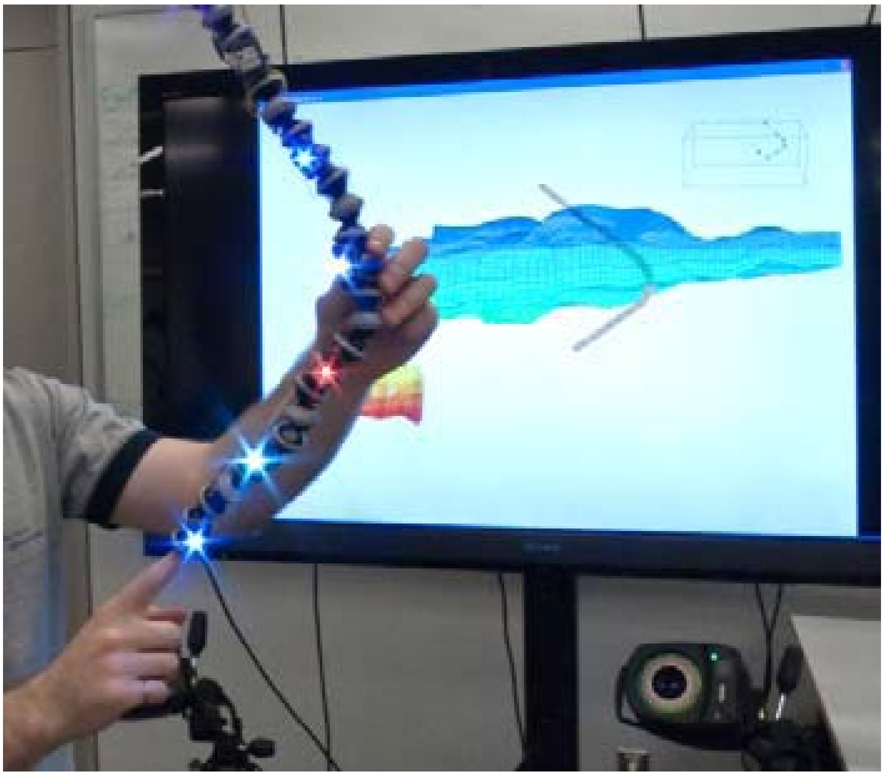

Figure 5 – The direct input/output mapping between the physical Snakey object and its virtual representation

4.6 Visual Display and Software Implementation

The mounting frame is positioned directly in front of a large, high resolution display which, with the help of the 3D position data provided by the Vicon tracking system, displays the reconstructed virtual 3D curve superimposed onto a more traditional 3D geological reservoir model. As the user manipulates the *Snakey* device in the physical space, its virtual representation updates within the reservoir model in real time.

This interactivity forms a direction input/output mapping between the *Snakey* object's physical shape and its virtual representation. (Figure 5) Users can explore the virtual reservoir model immediately and intuitively just by grasping and manipulating the physical *Snakey* device. The interface's physical constraints are expected to translate directly into appropriate constraints for the virtual model: limited bend radius, avoiding self-intersection, and so on are restrictions that are also inherent in the real-world well paths being modeled. *Snakey's* ability to sustain its physical shape memory is an attempt to allow the user to understand the overall well path plan by simply looking at the physical *Snakey* object. It also supports disengaging and reengaging in 3D tasks without needing to reset the task state, as *Snakey* captures and ‘remembers’ the 3D well path task state physically.

As users manipulate the *Snakey* TUI and the virtual well path intersects with and affects the geological reservoir data, important design information can be fed back to the users in real time through the *Snakey* interface. Some possible examples include: a) the on-screen display can indicate that the radius of curvature of a section of the well path is beyond acceptable limits, b) the rumble intensity of the attached vibration motors can indicate to the user, through *Snakey*, the different fluid flow rates in different sections of the pipeline, c) the integrated LED lights can glow red if a section of the well path intersects a dangerous volume of terrain, and so forth.

5 Design Critique

We asked two reservoir engineering experts to evaluate our *Snakey* prototype, critique our design approach and provide feedback on the tangible interface itself. To begin, we found that the experts were particularly enthused by the concept of having a physical manifestation of their three-dimensional well plans directly in front of them. They highlighted that this was a significant step forward in terms of usability and ease of understanding when compared to the “paper blueprints on a table” techniques that are currently commonplace in well planning meetings.

5.1 Manipulating the Virtual World

While the users were able to easily view the physical *Snakey* device from any angle simply by walking around it, they found that rotating or moving the geological data on the visual display still required the use of a desktop mouse and keyboard. This took attention away from the TUI and introduced a critical disconnect their mental models of the physical device and the on-screen representation of the virtual data. That is, as the virtual, on-screen model was rotated (e.g. with a mouse), the physical *Snakey* device would remain station and the users would have to mentally transform their real-world manipulations into their expected virtual outputs. In order to mitigate the physical inconvenience of having to shift between the *Snakey* device and a desktop mouse, it was proposed that a dedicated movement controller such as a joystick, could easily be mounted to the aluminum frame next to the *Snakey* device.

5.2 Interface Control

Experts also highlighted a desire for functionality that would allow them to control interface attributes beyond just the curvature of the physical device using their hands directly. For example, by indicating where a specific operation takes place along the well by directly squeezing a region of the *Snakey* chain, or sliding one’s hand along a region of the chain to mark an area in the geological data. In this way *Snakey* would have multiple additional modes of meaningful physical input, beyond its 3D curvature.

5.3 Shape History and Analysis

Another major feature that was requested was the ability to store the shape of the physical device and compare the stored alternatives. Additionally, once the shape had been stored, users would have liked to “load” the shape back to the physical *Snakey* device and resume editing it. This would require the shape of the physical curve, which may have been manipulated into a different configuration in the interim, to match the virtual shape that was previously stored.

Such a task is difficult to accomplish when *Snakey* is not internally actuated and must instead be controlled by its users. Besides mechanically actuating *Snakey* (in essence turning it into a robotic interface capable of taking on its own formation), alternative calibration schemes were proposed: such as verifying when the physical device has approximately matched its digital parallel by showing green (matched) or varying shades of yellow-orange-red (still out of place) on the attached LED lights. The ability to “re-calibrate” the physical device to match a pre-recorded virtual curve remains a difficult design challenge.

5.4 Scale and Tracking Resolution

One physical limitation of the interface is its precision and resolution of tracking as compared to the scale of the TUI’s internal components. While the Vicon tracking system provides excellent positional accuracy, the physical constraints of the GorillaPod links restricts the user when designing subsections of the well path.

Every part of a well must be designed very carefully, and complete wells are often many hundreds of meters long. Currently, the physical interface has a one-to-one mapping to the entire length of the well. However, because the distance between adjacent orb joints is fixed (i.e. each link is a solid piece of plastic), users cannot specify curves any small than a single link.

A possible solution is to design wells in various stages of granularity. The first stage would map the interface to the well as a general, overall entity; establishing its basic position and shape. The next stage would map the interface to only a portion of the complete well path, allowing that subsection of the well to be design with higher precision. This “zooming in and out” approach revisits the need for the physical interface to match previous, stored curves.

5.5 Multi-channel feedback

The experts felt strongly about the inclusion of the LED lights and vibration motors as additional feedback channels; highlighting how they afforded the *Snakey* interface to relay multiple channels of feedback information to the user at once. For example, having the visual display show pipeline curvature tolerances while the vibration motors indicate fluid flow and the LED lights display rock densities; properties that are all interrelated and difficult to visualize simultaneously on a single, traditional display.

5.6 Collaborative Well Planning

Besides the intuitive physical nature of the *Snakey* interface, the reservoir engineering experts were also particularly enthusiastic about the inherently collaborative nature of the TUI. Any user within a team, regardless of professional training or project role, could instantly step in and manipulate the physical curve, provide meaningful input, and have the result be immediately visible and apparent to everyone involved.

5.7 Multiple Anchoring Points

As was described previously, the anchor point for the physical *Snakey* chain can easily be repositioned to multiple locations on its aluminum mounting frame. The "default" configuration is a "top down" mounting with the anchor point positioned above the user and the free-floating, manipulable section of the *Snakey* chain hanging downwards. While this configuration promotes a large, open working space beneath the TUI in which multiple collaborators can stand and have easy access to the TUI, this configuration may not be ideal for specific reservoir engineering tasks. For example, from a different perspective an underground reservoir of natural gas could be considered the fixed point of a path planning operation and the pipeline's path to the surface and the surface drill site become the variables to be manipulated. In this case, a "bottom up" mounting configuration would be more appropriate; a scenario that the current *Snakey* interface could easily accommodate.

5.8 Visualization Techniques

A large proportion of the experts' critiques were directed at the well planning/integrated geology and reservoir simulation data that the visual display would provide as a result of manipulating the physical *Snakey* device. While the resultant 3D curve can show one-dimensional geological information along its length (both virtually on-screen and physically using the attached LED lights), it was proposed that a 2D cross-section view of the virtual data would also reveal more information. As one example, this could be accomplished by treating the planar projection of the chain's 3D form as a curtain that would "cut" the voxel data at the location of the curve, providing a richer visualization that shows the internal, "under the surface" data to the user. Alternative visualization schemes might include a translucent "tunnel" of surrounding voxel information that is shown within a set radius of the 3D curve.

6 Future Work

Although the *Snakey* prototype has already be demonstrated the potential to become a uniquely intuitive tangible user interface and shown that the *Snakey* concept is desirable to experts within the domain for which it was designed, our preliminary design critique has also highlighted important weaknesses and areas for improvement. Although the physical *Snakey* object is well-suited for interacting with curve data, intelligent exploration of surrounding geological data will require additional, tightly-coupled interaction capabilities such as defining specific sub-sections of interest and virtual cutting volumes, clearly displaying volumetric properties over both space and time, controlling the mapping of scale between the physical device and its virtual counterpart, and switching between multiple, recorded copies of a given path planning project.

Many of these concerns can be addressed by tighter integration between the core GorillaPod orbs and the multitude of additional devices they have been or could be augmented with: retro-reflective markers, vibration motors, LED lights, pressure and touch sensors, etc. Currently, it takes significant effort to physically manipulate the prototype TUI without crushing or dislodging the various attachments. Ideally, these items (and their associated power and communication wiring) could be better integrated within the plastic orbs themselves, allowing for a more robust physical artifact.

Integrating alternative means of providing user input beyond *Snakey's* physical shape also opens up a wealth of new explorations. The integration of push buttons, capacitive touch sensors, or pressure sensors into the physical device could allow the positioning of the user's hands or the strength of their grip to act as an additional input channel; potentially facilitating some of the zooming and subsection selection behaviours discussed earlier, and so on.

Finally, actuating the physical device (i.e. turning it into a robot) would allow it to address a number of the expert users' critiques as well as allow *Snakey* to provide even more sophisticated physical interaction feedback. Not only would it be possible to automatically reset *Snakey's* shape and reload previously saved physical configurations, but it could also serve as a training tool for reservoir engineers who lack experience in either the use of the *Snakey* interface itself or well/drill-path planning in general.

While engineering an actuated version of the *Snakey* TUI would not be a trivial task, projects from the field of robotics research such as Zykov et al.'s "Molecubes" [30] and Festo's "Bionic Handling Assistant" [31] demonstrate that the concept is plausible.

7 Conclusion

We presented *Snakey*, a tangible user interface for the physical manipulation of 3D well paths in the context of reservoir engineering. Our current *Snakey* prototype allows users to interact with and manipulate a physical curve-like artifact which is tracked in real-time and spatially mapped to a virtual 3D curve. In turn, this allows users to intuitively explore complex 3D geological data and collaborate in well path planning tasks with a multi-disciplinary team. *Snakey* affords flexible physical manipulation and is able to maintain its shape when not being held by a user. Other features explored with the *Snakey* TUI are integrated haptic feedback and dynamic visual cues within the physical interface itself as well as dynamically changing *Snakey's* topology as afforded by its modular nature.

This paper details our design efforts and the current fully functional prototype. We presented a design critique of our *Snakey* prototype which was done with domain experts who reflected on the TUI's advantages, limitations, and potential for the reservoir engineering domain.

We also see *Snakey*, with its unique physical properties, intuitive cognitive input/output mappings, and multi-channel information feedback capabilities as another link in a continuous chain of TUI research efforts that explore novel ways to intuitively and directly manipulate 3D curves, surfaces and shapes. Although the *Snakey* TUI's design was informed by the applied domain of collaborate well path planning in reservoir engineering, we feel that the design lessons learned from *Snakey* would also be well suited to other 3D physical path planning tasks (e.g. flight paths, robot navigation tasks, etc.) and 3D curve and surface manipulation in general.

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