Tangible Braille Plot: Tangibly Exploring Geo-Temporal Data in Virtual Reality

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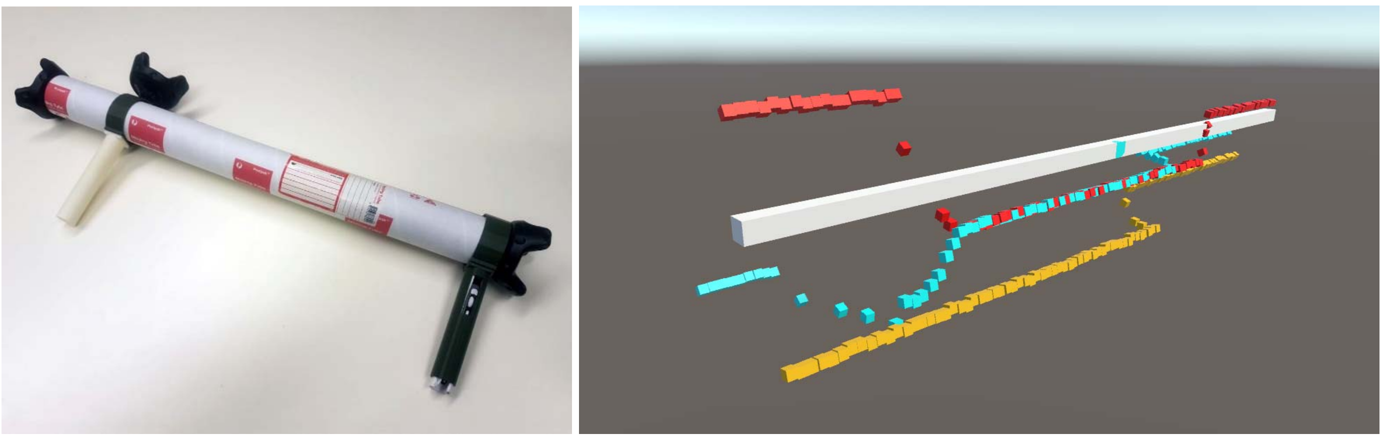

Fig. 1 The tangible pipe input device showing two handles with button input, and the matching VR view of the data along the pipe's axis (shown in white).

***Abstract*—Despite the resurgence of virtual reality (VR), the primary method of interacting with the environment is using generic controllers. Given the often-purpose-built nature of applications within VR, this is surprising, as despite the effort put into the design of the application itself, the same attention is not paid to the input control. This is despite the advantages that tangible interfaces have for user understanding, especially in the context of visualization, where user understanding is paramount. This paper presents the adaptation of a previous 2D temporal-geospatial visualization into VR, and more importantly, describes the development of a novel 8DOF Tangible User Interface developed to support the exploration of that data. For our application, this centers around the exploration of geospatial data to explore colocation and divergence of entities, but could easily be extended to other domains. We present our novel controller as an example of the benefits of the utilization of purpose built physical controllers as a first-tier method of enabling immersive analytics. We describe the immersive system and controller, followed by an example use case and other applications encouraging further development of novel tangibles as a key component of immersive data analytics.**

Keywords—virtual reality, geo-temporal, temporal geospatial, immersive analytics, tangible user interfaces

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I. Introduction

Recent advances in virtual reality (VR) technology have fuelled mass adoption, enabling its usage outside the research domain, and further into other existing areas including visualization. These advances are behind the development of fields such as Immersive Analytics that seek to leverage the immersive component of those displays to benefit understanding [1]. Whilst immersiveness has been shown to aid understanding, one of the main questions becomes how to handle the interaction with the data, given that keyboard and mice are no longer viable, and generic controllers limit the method of input and exploration by the user. Immersive systems need equally immersive input controls [2]. In this paper, we extend a previous geo-temporal [3] visualization into VR, and present a novel tangible user interface to control the visualization, including a map component.

The increasing importance [4] and density [5] of geospatial data sets has presented a challenge for those needing to understand it, suffering from the impact of the five V's of big data. This is true even when using visualization and is compounded when three or more dimensions (e.g. longitude, latitude, and time) need to be visualized on a 2D display. However, the recent advances in high-fidelity VR display and input technologies mean such datasets can now leverage VR as a primary means of use. This is especially advantageous for geo-temporal datasets that focus around latitude, longitude, and time, given VR natively supports 3 dimensions in the spatial sense alone.

Our previous work within the geospatial domain focused around developing visualizations to assist in queries relating to *convergence* and *divergence* [7]. This resulted in the development of two new visualizations, referred to as the Braille Plot, and Parallel Schedule View (PSV) (Fig. 2), presented in detail in section III.

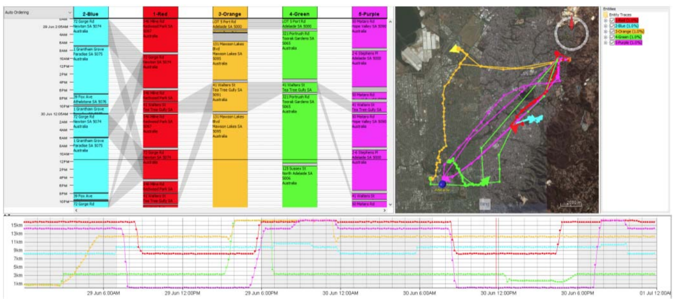

Fig. 2 The original 2D system showing the PSV (top-left), Braille (bottom), and map (top-right) components.

The Braille Plot is a 2D graph of the distance of entities from a location of interest (Y-axis) over time (X-axis). This means that when entities were collocated, and thus equidistant from the location of interest (LOI), their plot lines intertwine (even when the dataset contained significant noise). This approach was akin to converting the dataset into polar coordinates relative to the LOI, and visualizing only distance, whilst dropping the angle (Fig. 3).

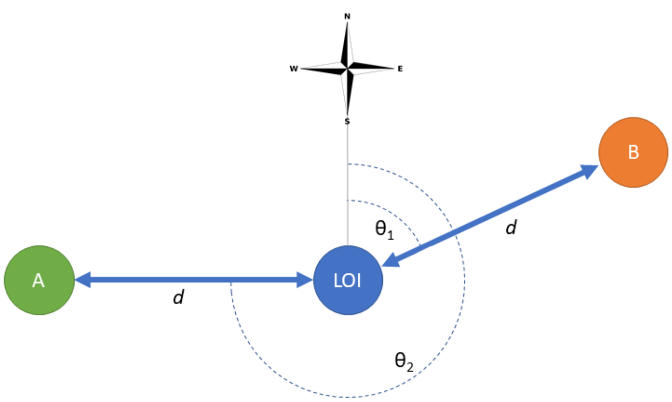

Fig. 3 Two entities equidistant from the LOI but at different locations.

This reduction of parameter space is not without a loss of information. When two entities were equidistant from the LOI, but on opposite sides of it, they would appear adjacent to each other on the Braille Plot, creating a false positive. It was noted however, that had we been able to visualize the Braille Plot in VR, we could incorporate the angle, as a rotation around the X-axis, and thus remove this adjacency fallacy. As such, this paper presents a VR adaptation of our original system, focusing on the the Braille Plot, and incorporating the development of a novel tangible input device (nicknamed *The Pipe*) created as a natural method of direct interaction with the VR Braille Plot.

This project was motivated in part by the concept of a broad set of specialised tangible tools, a toolbox per se, to support particular tasks. An excellent example of this concept is the digital tape drawing device [8] that only supports one specific task, specifying 2D curves for industrial design. The digital tape drawing tool is a haptically rich device that combines visual and tangible feedback to allow the designer to specify the 2D curve better. Our new tangible visualisation tool also allows a close interplay between the visual and tangible senses. While the device is not designed for a wide array of tasks, the new devices are designed to support this vital visualisation task well. As such, we investigate the feasibility of our novel input device when paired with the corresponding VR pipe view that mimics the input device (i.e. a linear physical input device linked to a liner visualization as output).

The primary contribution of this work is a novel tangible device with two complimentary degrees of freedom that directly map to the visualization, enabling direct interaction. The secondary contribution of this work is an immersive adaptation and extension of the Braille Plot in Virtual Reality as an interactive means of exploring data. The novel Tangible User Interface (TUI) is presented as the main contribution, with applications outside of our explicit use case, and serves as a discussion point for further exploring the use of tangible user interfaces when paired with immersive environments.

The next section of this paper explores related work, outlining the requires of visualising geo-spatial data, immersive visualisation, and tangible inputs. Following this, we describe the Braille Plot and PSV in detail, with the remainder of the paper describing the development of a tangible device to control the Braille Plot, along with a use case, discussion and future work, and final thoughts.

II. Background

The amount of geospatial data being generated is increasing every day. Whilst such data has long had a role in society (for example with Mindard's view of Napoleon's march on Russia [9]), our reliance and analytics of that data is increasing. This means that the exploration and visualisation of such data in 2018 is just as important as in 1869 (when Minard drew Napoleon's march) and earlier. Spatiotemporal data has always presented a problem for visualisation, presenting the analyst with three dimensions at minimum (latitude, longitude, and time), and until recently only two dimensions with which to represent that data (either physically on paper or digitally on a screen). As such, space and time are still open research problems for visualization experts [4, 10, 11]. This is compounded by the fact that it is no longer about representing just a single entity, but the interplay between multiple entities (e.g. convergence for meetings). Users must now look at the relationships between multiple traces, not just a single one (a more complex problem [12]).

A survey of recent geo-temporal visualization approaches was presented by Aigner, et al. [13], noting there is no 'best' visualization, but rather that different views are suited to different types of analyses, with multiple views being especially useful for time-focused data. The representations with said data are not static, with users continually adjusting the configuration of the data until the underlying relationships become apparent [14].

One example of this is the Space-Time Cube (STC) [15]. By utilising a third axis in a visualisation, the STC and subsequent implementations [16, 17] are able to represent both location (X and Y axes) and time (Z axis). Whilst on traditional displays this introduces complexities for the user in terms of managing their orthographic view of the data. However despite this overhead, the STC has been found to be superior for users require an understanding of the overall structure of the data set [18].

A. Tangible Interaction

Given immersive visualizations often leverage multiple degrees of data, users should ideally be able to control such representations using a natural, direct mapping. One of the primary advantages of TUIs is their bi-manual control of multiple DOFs simultaneously [19], and have been shown to be more effective for managing 3D content compared to both mice and touch interaction [20, 21]

When used with 2D displays, TUIs do not necessarily generate an automatic improvement in performance [22]. Given their higher dimensionality, 3D content displays can require higher DOF input devices that can be mapped to real world space [19]. This leads to their natural pairing of TUIs with VR displays, coupling 6DOF inputs with a display capable of displaying output for the same dimensionality. This is compounded by the fact that 3D stereoscopic displays can increase performance by 60% on average [23, 24]. Given this ability to utilise real world space, the direct applicability of TUIs is evident [25]. However, they are not without drawbacks, the foremost being fatigue, and the need for physical objects in the space [20].

B. Immersive Visualisation

As previously mentioned, VR's resurgence over the past decade has been fuelled by a new generation of display technologies and the rendering technologies powering them. Given recent advances, the issue now becomes how do we develop better applications of that technology, rather than how do we improve the technology itself. As such, VR is now seeing adoption outside of traditional research realms, meaning that immersion, defined by its ability to deliver an illusion of reality to the user a natural attribute of VR [26], is now being leveraged across these new domains. This new immersion changes users' engagement with the data, affecting both data analysis and decision making [26], leading to Immersive Analytics. However, immersion is lost if the user must withdraw from it in order to control their enviro nment. Given TUIs support a bimanual, direct method of interaction, they are a natural solution for developing immersive interfaces.

III. Original Visualisation

Our previous work in geospatial visualization involved identifying and communicating the convergence, colocation, and divergence of entities, whilst finding patterns regarding the movement of entities over time (people, vehicles, etc.). The end visualization we developed consisted of three synchronized, complimentary views (Fig. 4). the Braille Plot (BP), Parallel Schedule View (PSV), and a traditional 2D Map, collectively referred to as CVA, or the Coordinated Visual Analysis system.

As introduced earlier, the Braille Plot is a 2D point/line chart of each entities' distance from a selected location of interest (LOI) on the map. The user selects a LOI, generally a common location for a single entity (e.g. home), or shared location of interest such as a meeting place. With time increasing left-right across the X-axis, and distance from the location of interest increasing up the Y-axis, we show the distance of each entity from the LOI at any point in time. The idea being that any colocation of entities means they will all be equidistant from the LOI, and thus their plot lines will appear to intertwine. The result means the analyst only has to look for overlapping entity traces to identify colocation.

The issue for this is that we are effectively converting the location on the map into polar coordinates relative to the LOI, and visualizing distance but dropping the theta angle. If we have two entities equidistant from the LOI, but on opposite sides of the LOI, their plot lines will still intertwine on the Braille. Whilst this is a false positive, it came as an accepted trade-off since the plot helps in reducing the search space for the user, and any intertwined lines can be confirmed by hovering over the period of interest and viewing the entity locations on the actual map.

The second component, the PSV, used a calendar metaphor, representing idle periods for multiple entities. This was extended with the inclusion of additional columns between entities, allowing for links between idle periods at the same location for multiple entities, i.e. if both events were at the same location, even if at different times, there would be a physical link between calendar entries for different entities. Whilst this does not scale to hundreds of entities, it works effectively for small groups of entities, as was our use case.

The final component was a traditional 2D map showing the traces of the entities. Following our previous study comparing the results of our work to the STC existing technique for visualizing colocation, we incorporated the STC as an option, allowing the display of a 2D map, or a 3D map showing the traces as STC spirals. The results of a user study indicated CVA was superior for certain types of questions, generally those of higher complexity, as defined by [6].

IV. Immersive View

During development of the Braille Plot we encountered the equidistant false positive condition, as previously highlighted. In attempting to resolve this false positive, it was proposed that by putting the plot into 3D using VR, we could solve the lack of the theta/angle in the 2D plot. This section describes the development of that view, along with the implementation of the PSV and map control also into VR.

A. Visualization

In implementing the Braille Plot in VR, we can represent time (x-axis), the distance of each data point from the axis (y-axis), as well the angle with the data points wrapping around the axis in 360^o (z-axis rotation) (Fig. 4). This would be akin to placing the axis on the LOI, perpendicular to the map, and having the STC wrap around the LOI as the central axis. Looking length-wise "down" the length of the axis (Fig. 4), the user sees the traces, the angular position and relative distance to the LOI of each data point (subject to orthographic projection). This new visualization is essentially contained within the outer radius' bounds of an invisible VR pipe, consisting of a central

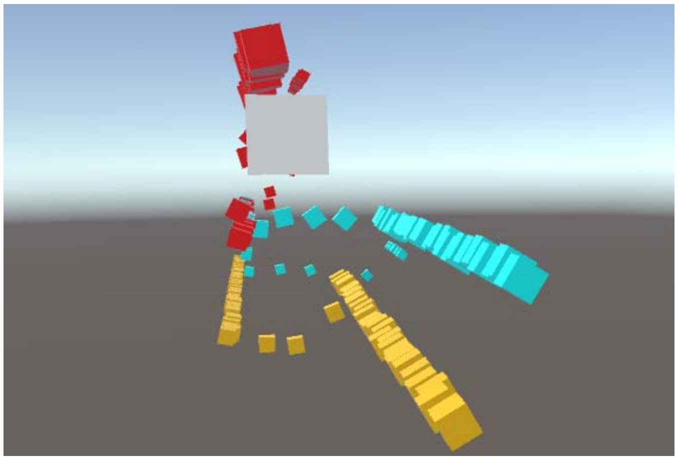

Fig. 4 View of the pipe looking from the end along the central axis (white), showing the relative position of the data points relative to the location of interest (e.g. with blue mainly being active south-east of the LOI).

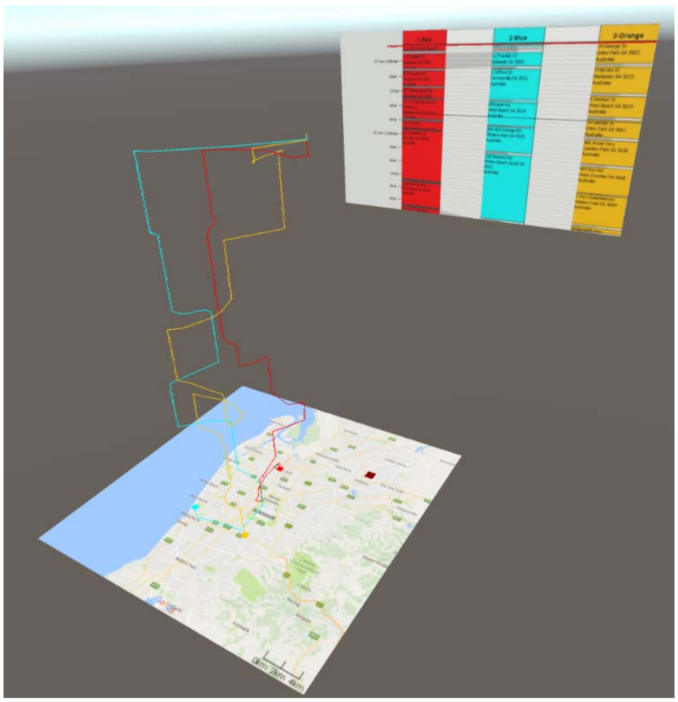

Fig. 5 The two complimentary views of our geospatial data: a map utilizing a Space-Time Cube (left) and Parallel Schedule View (right).

axis (shown as a white rectangular prism), with points between the axis and a maximum radius pipe axis. In addition to the Brail, the PSV and map elements are also presented, registered to the environment (Fig. 5). This allows the full CVA system to be presented to the user, Braille, PSV, and map (as 2D or 3D with STC), with the Braille pipe as the centre point. The colours used for the cubes are not representative of any other information, and only serve to identify the respective data sets.

To enable navigation and exploration of the data set, the user can "zoom" into any part of the data set on the pipe, shown by increasing the distance between neighbouring points. A transparent plane is then presented to the user to show the selected point in time on the pipe, with markers on the map showing the location of the entity at that point in time, as well as a vertical line going from that marker on the map, to the corresponding data point on the spiral. A horizontal line on the PSV shows the corresponding location and selected time of the data point. The LOI can be set using the map based on the centre of their field of view, discussed in detail later.

B. *Input Device*

The development of the VR Pipe does not map well to standard input techniques, even when using the "standard" handheld VR controllers provided with the commercial HTC Vive and Oculus VR systems. As such, we developed a tangible prop that can be used as a direct input device for the VR visualization. This consists of a physical tube that is designed to represent the virtual axis shown in VR, giving the user the ability to physically hold the VR Braille Plot using two handles (Fig. 1). One handle contains two buttons and a scroll wheel, the other is a simple handle but can slide along the length of the pipe, whilst rotating up to 180°. This hard 180° limit is enforced using two 90° pieces of dowel rod stuck down the length of the pipe, with physical notches on the insides on the handle's ring that encapsulates the pipe (Fig. 6). These notches then press against the dowel edging to provide a physical limit for the user.

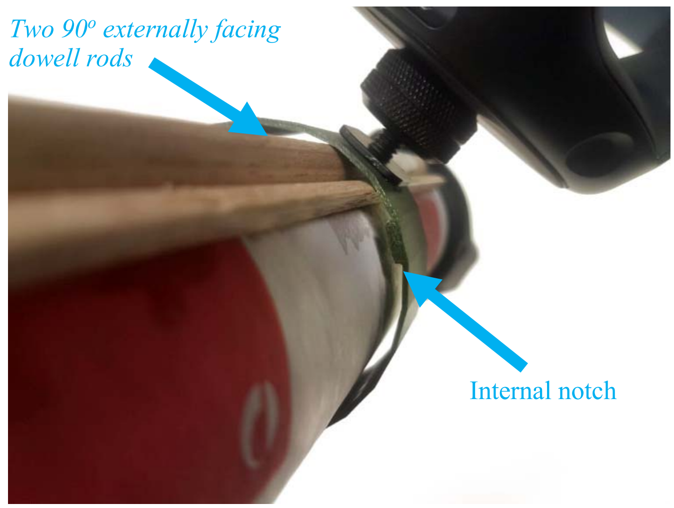

Fig. 6 The physical locking mechanism on the pipe consisting of two 90° sections of dowel, and notch on the inside of the ring.

Fully "zoomed out", all data points appear on the virtual axis of 660mm length (the same as the length as the physical pipe). In order to communicate to the user the selected point in time/data point, the visualization shows a semi-transparent white plane that slides up/down the tube and intersects with the selected point in time on the axis. Using the handle sliding and rotation as the two degrees of input, the user can quickly navigate to anywhere in the data set using a complimentary slide and rotate action. In order to track the position/rotation of the handles, we use wireless HTC Vive markers to give us position and orientation, attached to either end of the pipe, and the sliding handle.

The tube is made from a cardboard mailing tube, with 3D printed handles attached to 3D printed collars that wrap around the tube. We had experimented with tubes of varying materials, diameters, and length, settling on a cardboard tube (light), of 60mm diameter (that proved to be large enough to slide/rotation the handles firmly), and of 660mm length (just over shoulder width's apart when held in both hands). During the design of the device we also tried using: no handles (but rather two circular collars), one handle and one collar, and two handles. From our own internal use, two handles offered greater control and was preferred by the authors, and assisted in preventing the user's limbs obscuring the sliding marker used for tracking.

In order to control the LOI on the map component, we embedded a pen mouse into the fixed handle on the pipe. This provides two unary inputs, along with a scroll wheel to the user, with the actual mouse component of the pen not used. Our system only utilises the primary unary input for controlling the map control's LOI. When the user views the map control, a marker appears on the map showing the center of their field of view (FOV) using ray casting. To change the LOI the user selects the location using their FOV and clicks the primary input button. The LOI is then updated to the selected location, and the corresponding STC traces on the map and the pipe are immediately updated. The second unary input is used to switch the Braille between incorporating the theta angle or not, allowing the user to view the original Braille plot as the 2D version would have shown, albeit on the 3D axis of the pipe. The secondary input and scroll wheel could potentially be used to click-drag the map and map zoom respectively, however given that we utilise a static map, this behaviour is not supported in our current implementation.

V. Use Case

This section presents a use case for the system, providing an example of the types of interactions and results users can experience with the system. The scenario begins with the user loading their dataset on the computer from a CSV file and putting on the headset. Processing is immediately done during ingestion. This identifies the idle periods for the PSV for each entity (based on a set of predefined thresholds), before then displaying the data on each component of the CVA system. At start up, the entire dataset is visible to the user along the pipe's axis. This serves two purposes. The first is the user can immediately ascertain characteristics from the data, for example certain reoccurring patterns are visible in the data as entities perform routine movements (e.g. home > work > home). This also helps the user to identify how dense the data set is, with large numbers of data points immediately visible on the pipe.

The user then views a period of "flat" data points when a given entity was idle, and slides their handle to select that point in time, before twisting the handles to zoom in on the idle period. Once zoomed in, the user scrolls across this period to notice a subtle movement during that period, realising that the user wasn't completely idle for that entire period. They also notice another entity's movement has the second entity idle at that same location (with plots intertwined), indicating that the original entity was collocated with the newly discovered entity.

In exploring the relationship between the entities, the user zooms out to show all the data and looks down the length of the pipe, showing that despite the second entity leaving the meeting location, their movements don't stray far from the current LOI. The user then zooms in fully and scrolls the dataset "beginning to end", looking for subtle movements when in periods where the user appeared idle. This scroll is performed as a single, continuous operation with the user's hands, rather than a number of repeated actions using a traditional input (such as a scroll wheel). The use of an absolute input device, rather than a relative one allows the user to ensure they are aware of their location within the data set, based on proprioception alone, even when the user is fully "zoomed in" to the data. However, the PSV control denotes the currently selected date/time, with the map also showing the selected data point relative to the top/bottom of the STC spiral. By using a tangible input device, the user is able to maintain temporal contextual awareness within the data using their own body, without relying on any external prompts.

VI. Discussion and Future Work

The core requirement that led to the system's development was the need to resolve the false-positive that was generated as a result of removing the theta angle for the Braille Plot. As such, the direct translation of the same visualisation into VR enabled an additional dimension onto which we could map that angle. However, the immersive and isolating nature of that visualisation necessitated the development of a new input method. Given the discrete, linear data used, it made sense to directly map this to an absolute, linear input control, with distinct beginning/end points that allow the user to leverage their proprioception/muscle memory. Fundamentally a physical timeline assists in navigating the data given the direct mapping. Another benefit is the user can both scroll the timeline, whilst adjust zoom level (and potentially interact with the map) simultaneously, leveraging bi-manual interaction. The other benefit is that this input device is self-explanatory, by picking the device up, and feeling the handle immediately slide and rotate, the user is naturally prompted to continue those actions, negating the coordination issues experienced with some TUIs [19].

The representation of the data within the physical space of the user comes with both benefits and trade-offs. Whilst the physicalization of the control can aid interaction and understanding, the lesser resolution of current VR displays, along with the need for the physical input device, results in a larger visualization digitally, and physically. This means that although we have gained the additional dimension to resolve our false position ambiguity, we have introduced a possible interaction constraint in terms of physically manipulating the pipe—the user must make gross motor actions rather than the fine movements possible with a mouse as an abstract input. Whilst this is not direct physicalization of the data (given the virtual nature of the output), the direct mapping to the TUI is similar in approach with physicalization. Physicalization has been shown to aid user understanding and comprehension [27], which prevents possible benefits over using the TUI in conjunction with a 2D visualisation (no VR visualisation).

Another limitation of the system comes from its greatest benefit: perspective distortions and object occlusions. Given the orthographic projection of the user's FOV, viewing the data from the end of the pipe along its axis means data is partially obscured given the perspective. However, this could potentially be addressed with a toggle to parallel projection from the end viewpoint. Occlusions are a harder issue to resolve, and are, ironically, also the result of removing a dimension from 3D to 2D, similar to the original goal of compressing data dimensions that created the braille in the first place.

A. *Future work and applications*

Whilst this paper has presented the sytem itself, a full evaluation remains as future work. To perform a full evaluation of the 3D Braille versus the 2D, future work can examine both exploratory tasks directed question/answer, exploring the problem space presented in [6]. This would seek to indentify the explicit advatanges of the Braille in 3D versus 2D, and vice-versa.

Despite the direct application of the pipe input device to control the VR Braille plot as a physical metaphor, the device itself has applications to other systems and domains. The absolute positioning makes it ideal for scrobbling through large amounts of temporal data, especially when there is a secondary dimension in that data to explore that can be mapped to the rotation. By using hand-held tangible controls that are designed to directly map to the data presented in VR, we can extend the immersive nature of VR outside of the digital realm, and into the physical. As such, this work argues not only for the application of the pipe to other temporal-based systems, but for the development of TUIs to support immersive analytics in general. For example, the pipe could be used as an input method for exploring vary depth-slices of a longitudinal medical scan, extending previous TUIs in that space [28]. This does not have to be limited to specialized domains but is applicable for the development of purpose-built tangible controllers in general. Conclusion

New advances in VR, rendering, and tracking technologies have enabled a new generation of immersive systems. By adopting these technologies to address the limitations of previous 2D systems, we can change how users see, interact with, and extract information from data. Despite their proven advantages to users in providing a method of direct manipulation, TUIs are yet to be fully realized in VR. In this paper we presented our novel 8DOF (6DOF position + 2DOF input) tangible controller as a physical prop for exploring geo-temporal data. Despite its application to a specific domain for our system (geo-temporal), such a prop, and variations, would be applicable to other systems requiring a similar 6+2DOF input of discrete values using absolute positioning. Given the purpose-built nature of VR applications, we encourage the research community to continue to explore the opportunities for novel UI techniques given VR as an enabling technology, to ensure the input technologies continue to advance in equal hands with the visualisation output, given each both have a hand in allowing users to extract insights from data.

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