SSCA: Situated Space-time Cube Analytics

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Abstract

Spatio-temporal visualization research has been capturing much attention in recent years. Space-time cube (STC) has been commonly used to visualize this data to support analytic tasks. However, the current STC visualization tools are currently not compatible with situated platforms since these tools are often designed for desktop computing. Thus, we propose a situated space-time cube analytics (SSCA) prototype that maps spatio-temporal trajectory data into the environment where the data was captured. Being situated in such an environment while exploring data can provide benefits, and further allows us to explore interaction techniques such as proxemics and embodied interaction. We are confident that with SSCA, and a new generation of augmented reality technologies, researchers can begin to better explore the potential of situated STC analytics.

CCS Concepts

• ***Human-centered computing*** → *Visualization;* • ***Visual Analytics*** → *Situated Visualization;* • ***Visualization*** → *Visualization Systems and tools;*

1 Introduction

Researchers have been exploring spatio-temporal data visualizations to represent changes in events over space and time [ARH*15, FSN20]. Several examples of such visualizations, including 3D Space-Time Cube (STC), support user analytic tasks and are seen for both desktop [ARH*15] and Virtual Reality (VR) platforms [FSN20] and often include static [KLM*04] and/or animated [ARH*15] movement of objects. The two key issues of 3D STC visualizations include: 1) lack of depth perception in the desktop setting (i.e., 2D) [MCH*18]; 2) users frustration when using mouse-based interactions for STC visualizations [War04, BIAI17]. Researchers have suggested that Augmented Reality (AR) could be a potential solution to deal with these issues [MCH*18] through natural viewpoint changing, lack of occlusion, and visual clutter. AR might also improve users' analytic experiences by immersing them in data in real-world contexts [GBF*20, TWD*18]. This situated analytics (SA) is an emerging research field that integrates visual analytics with AR to support a new form of in-situ interactive visual analysis [TWD*18]. The concept of SA is to display data in relation to physical objects, places, and individuals to support users' comprehension and decision-making processes while in the environment the data was captured [TWD*18]. In fact, Alallah et al. [ASI20] found that SA has many potential benefits, such as accuracy and deeper exploration, over traditional desktop platforms. Currently, most, if not all, spatio-temporal visualization implementations and designs are not compatible with situated platforms [BCD*18] because they are designed for a desktop analysis with a mouse and a keyboard. Situated visualization tools should account for the situated nature of the visualizations and can provide new forms of interaction, such as proxemics and embodied interaction, and utilize flexible displays such as Head-Mounted Displays (HMDs). Thus, the visualization research community is now shifting from traditional desktop computing to immersive environments [MCH*18] for STC visualizations.

However, to the best of our knowledge, there is no research that has proposed a tool that maps spatio-temporal trajectory data onto the environment where the data was collected, further allowing users to perform in-situ data exploration with embodied interaction [TWD*18]. Our motivation in building such a tool is to: 1) superimpose in-situ spatio-temporal analysis and interaction; 2) further explore SA benefits and challenges. Thus, we implemented a Situated Space-Time Cube Analytics (SSCA) prototype and present it within this work. Using AR, our prototype allows users to explore spatio-temporal data within the environment where the data was captured. Furthermore, the tool provides proxemics and embodied interaction, taking advantage of these techniques due to the in-situ nature of the data exploration. The contribution in this work is an early prototype, SSCA, which enables in-situ data exploration of spatio-temporal data.

2 Related Works

2.1 Situated Visualization and Analytics

Situated visualization (SV) pertains to data visualizations which are contextualised into their intended contexts of use (i.e., to ob-

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jects, locations, and individuals), by mapping the data into the real environment and onto physical referents [WJD17]. This idea moves beyond traditional computing paradigms; for example, SV systems focus on a range of interactions (e.g., proxemics and gestural interaction) with several form factors (e.g., mobile and wearable devices) and different displays sizes (e.g., HMDs and large wall). Several application domains have used situated visualization such as in engineering [PWE*20] and science [WWS20].

2.2 Spatio-Temporal Data Visualization and Analysis

Spatio-temporal data represents events in both space and time such as movement of one or several objects (e.g., individual) over a geographic region through time. 2D and 3D visualizations are common when representing spatio-temporal data. Examples of 2D visualizations include a 2D map, multiple 2D maps with linked views, and map animations. Adding another axis to represent the temporal attributes results in 3D visualizations that combine space and time. A common example of this is a Space-Time Cube (STC) visualization. Researchers have been extending STC visualizations with interactive techniques such as zooming, focusing, and linking with maps for traditional computing paradigms. STC has well-known limitations in terms of perception and interaction when employed in traditional desktop systems [MCH*18, FFN19]. Thus, to address desktop-based STC limitations, [FFN19] proposed and studied the performance of STC visualizations in a VR platform and on traditional desktops. Although the studies concluded that there were no significant differences between participants' performance for VR and desktops, in terms of completion time and accuracy, the qualitative data suggested that there was improvement for VR in terms of usability and user preferences in relation to reduced simulator sickness and mental burden.

2.3 Proxemics and Embodied Interaction

Proxemics and embodied interaction have recently become popular in HCI and visual analytics. Proxemic interaction is defined as the usage of a user inter-personal distance to mediate their interaction with surrounding devices [YCB*21]. Furthermore, proxemics and the spatial relation between users and a display have been used to pan and scale visualizations in large display spaces [BAEI16], and has been extended to user-display proximity and movement perception for interactions [BAEI16]. Embodied interaction, allows for interaction which is controlled by body parts (e.g., mid-air and feet gestures) [CPL*13, Hor10]. Several embodied interactions have been studied to interact with spatio-temporal data visualizations including hand-touches [DSK11], mid-air gestures [MKD*15, FSN20], foot gestures [DSK11], and various proxemics dimensions related to digital artifacts [TAC*20, BAEI16, WWS20] (i.e., user distance, user body orientation and movement, location). Within this work, we aim to enable these forms of interaction for situated video analytics pertaining to spatio-temporal trajectory data. Furthermore, being in-situ, and allowing for many forms of interaction through a HoloLens device (i.e., proximity, orientation, movement, mid-air gestures) we look to leverage these affordances to create a prototype to perform situated analytical tasks.

3 Prototype

To enable in-situ exploration of an STC visualization, we designed and developed SSCA, an AR application that supports 2D/3D visualizations of trajectory data; see Figure 1. SSCA can import a spatio-temporal dataset and map it onto the environment in which the event took place. For the implementation, the trajectory dataset was extracted from a short video recording of a group of individuals. We implemented a computer vision tool, motion detection, and tracking algorithm for processing video frames and extracting movement data using Python and the OpenCV library [Its14]. The position of the image's pixels is calculated and transformed into a top-down, *birds-eye-view*. Then, we measured key points in the video and physical scene to perform perspective transformation from the image to the measurement. With these transformations, we could map the actor's movement trajectories to the physical space. Finally, we saved the normalized trajectory data as CSV files and used them to map the extracted data to a HoloLens 2 device†. Unity 3D was used to process the CSV files, generate the STC visualization, as well as build out the interactions and user interfaces. The Mixed Reality Tool Kit (V2.6) [Mic19] was used in conjunction with the Microsoft HoloLens 2. Once ready to be used, the user is required to stand on a pre-defined reference point to calibrate and run the SSCA prototype. To see all elements of our prototype in action, as discussed in the following sections, please refer to the supplemental video provided.

3.1 Around-Hand Interface

While focusing on data exploration, we aimed to provide a means for rapid and easy access to system controls and interface components when needed. Around-hand menus are a commonly used technique for enabling rapid access to user interface (UI) components in AR [Mic21]. Therefore, we designed a main user interface (UI) that allows the user to access interface elements, watch and scrub through video data, switch between visualization modes, and filter data; see Figure 1-a. The UI appears/disappears when the user raises/lowers their hand respectively within the field of view of the HoloLens 2. The UI supports two main components: 1) a video player that shows the raw captured video footage (further discussed in subsection 3.2), and 2) user controls to manipulate analytic modes and filters. The design of the UI can accommodate for left and right hand use as well as support effective interaction.

3.2 Analytic Modes and Video Player

Depending on the user's exploratory task and aim, multiple data analysis modes can be enabled. There are two methods to explore spatio-temporal data: sequential data representation (i.e., *sequential*) or with all the data appearing at once (i.e., *data-centric*) [ARH*15, KDA*09]. Sequential mode allows for the situated spatio-temporal trajectory data to be revealed as it naturally would over time. In contrast, all trajectory data can be shown at once while the current position of moving objects remains sequential, when the data-centric mode is used.

The inclusion of raw video footage was deemed a necessary UI element to provide users with a natural and intuitive reference point as well as to validate findings when needed [ASI20]. Thus, we added the video player to the main interface. The user can use mid-air hand gestures to play, pause, and scrub the video. The video timeline is synced with the in-situ visualization, so scrub-

† Dataset is available at this link.

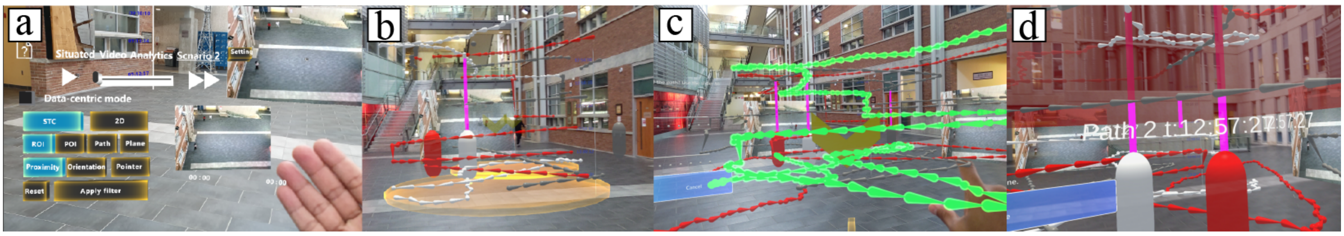

Figure 1: *The diagram illustrates the Situated Space-time Cube prototype (SSCA); (a) the around-hand interface which allows users to explore data by switching between 2D and 3D visualizations, applying various data filters, enabling proxemics/embodied interaction, and showcasing the raw video footage; (b) spatio-temporal movement data seen in a video is mapped into the environment where the event took place for in-situ exploration; (c) a user applying the POI filter; and d) a red measurement plane showing detailed information of each data points it touches.*

bing the video timeline also changes the in-situ visualization and vice versa. There are two ways to watch the video playback. First, the video appears alongside the UI controls, making it easily accessible. However, keeping the hand raised for long periods of time can cause hand fatigue, and thus we added situated video playback within the user's field of view and attached to the physical environment [LDB18, DLH*14]. Placing the video on top of, or very close to, the data can cause occlusion [DLH*14]. Therefore, we placed four large (4x3 metre) video screens on each of the visualization's four exterior walls. The video can be watched even when the hand is down and the UI is hidden.

3.3 Immersive 2D and STC Visualizations

Our tool has both 2D and STC visualizations that can display data within the environment. The main difference between these two visualizations can be seen in their mapping of data within the scene. While 2D visualization places all data on the ground, the 3D STC visualization spreads out the data within the air around the user.

3.4 Data Filtering

Trajectory data analyses often start out with an exploratory search to formulate tentative and broad queries, then leading to a more narrow examination. These primary explorations then lead to further questions, hypotheses generation, and ultimately answers to the questions [Peu02, AAG03]. Analysis task queries could be about the event ('*what*'), the moment in time it occurred ('*when*'), or location where it happened ('*where*') [Peu02]. The majority of STC visualizations support spatial and temporal data filtering [ARH*15, FRFN18] which can greatly aid in these exploratory and investigative processes. In addition, data filtering is the second of three steps in the well-known information-seeking mantra [Shn96]. Therefore, the filter design decisions were made to support the above mentioned task queries. Our prototype includes interactive data filters that help in the in-situ exploratory process such as region of interest (ROI), period of interest (POI), trajectory path selector, and measurement plane. Applying the same filter to the in-situ visualization more than once results in a union of all applied filters. For instance, if the user applies ROI filter to the visualization to select a region then applies another ROI filter to another region at different location, the user will see data in both regions. Applying different filters to the visualization results in an intersection of the applied filters. Ultimately, users can apply filters indefinitely, with the result being a combination of previous filters plus the new filter. In-situ data that crosses the ROI filter can be displayed only if the user selects it, which allows data exploration within a more focused physical space, see Figure 1-b. The POI filter allows users to select a time period of interest, only showing data from that time period, see Figure 1-c. When the user selects a path trajectory in the path selector, all points in the path trajectory are highlighted. To select one or more data points that share the same location on the time axis, the measurement plane filter was implemented for the 3D visualization, see Figure 1-d.

3.5 Data Interaction

We are interested in enabling proxemics and embodied interaction with data for situated STC analysis within SSCA. This will enable researchers to explore how users leverage body movement, orientation, and mid-air gestures to perform analytical tasks on movement trajectory data while in-situ. Thus, we enabled three forms of interaction which allowed for control of the filters and thus ultimately the data displayed within the in-situ visualization. These included: 1) proximity, 2) orientation, and 3) mid-air gestures. Throughout, our goal was to leverage the use of both AR interaction capabilities as well as proxemic and embodied interaction, made possible through the in-situ nature of the data exploration.

Proximity: Since the spatio-temporal trajectory data is mapped into the environment, body proximity supports intuitive and unique in-situ exploration [MDMBG11]. Users can physically navigate and explore the trajectory data in both 2D and 3D visualization views. To change the viewpoint of the situated visualization when embodied interactions are disabled, the user's position and head movement are used (e.g., translate viewpoint up, down, left, and right). Proximity also allows users to filter data based on their location. When Proximity and the ROI filter are enabled, the user's location and interpersonal distance zones are considered input parameters for the ROI filter. For example, the prototype allows the user to create a virtual interpersonal distance zone as a region to explore further. An AR dialogue box allows the user to shrink or expand the virtual interpersonal distance zone. Also, Proximity is the interaction mechanism for the POI and Measurement Plane filters. When Proximity and a POI filter are enabled, users create the filter and select the time period they want to use. A green shader will then highlight part of the dataset, while moving the green shader forward over the timeline and overlaying datapoints within the POI simu-

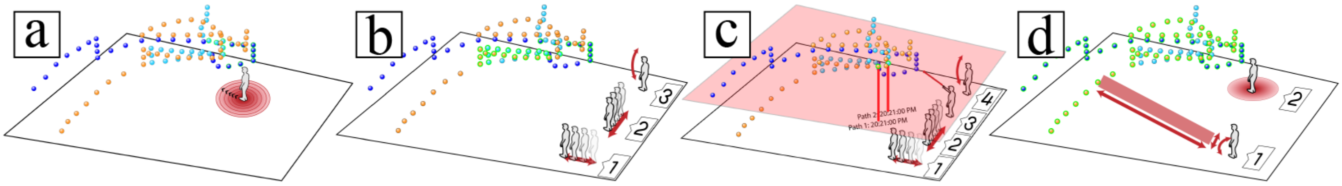

Figure 2: *Four interactive filters of the data implemented in the tool with their interaction techniques: (a) region of interest (ROI), (b) period of interest (POI), (c) measurement plane, and (d) trajectory path selector. When filters are being adjusted, the selected data points are highlighted in green. Upon finalizing the filter, these data points will remain within the visualization.*

lates the time slider movement. If the user walks backwards or to their right, the green shader moves backwards on the timeline. Conversely, moving forwards or to the left moves the shade forwards on the timeline. The Measurement Plane also uses Proximity interaction. Furthermore, Proximity's Path filter lets users pick single or multiple trajectories. Proximity, Path filter, and interpersonal zone radius are required to select a path. Once the visual interpersonal zone is created, users can move it to intersect with any datapoint on any trajectory. The interpersonal zone intersects any trajectory, highlighting it with a green shader.

Orientation: The body or head orientation utilizes the body and head's facing direction for interaction. In our prototype, the head was oriented to the Earth's vertical and horizontal axes. To make head movement more natural and convenient, we limit vertical head rotation to 20° above the Earth-vertical and 30° below the Earth-vertical. Similarly, the horizontal head rotation range was 30° above and below the Earth-vertical. In addition, POI, Measurement Plane, and Path Selector filters support orienting. The vertical head rotation for POI and Measurement Plane filters allows movement of the selected time period or plane up and down the time axes. In this case, a solid line is projected from the area of interest to the floor, with the data point's information placed on the floor. The Path Selector uses visible raycasting [HRK16] to allow users to select paths that intersect the raycast. This filter creates a raycast from the user's location, which can be adjusted in width and length for trajectory selection. Users can rotate their heads to rotate the raycast. The user can also move the raycast to a different location. The green colour indicates paths that cross the ray-cast area (i.e. *width* x *length*). Only selected trajectories will be shown to users after confirmation. A raycast trajectory path with a data point will be highlighted after filter confirmation.

Mid-Air Gestures: We refer to the mid-air gesture interaction in our prototype as Pointer. Pointer adjusts the Measurement Plane filter. The user points at the plane, pinches it, and then moves their hand up and down to move it along the time axis. [ARH*15, FFN19] found that when movement data is shown, the pointer interaction allows quick access to detailed information (tooltip). Pointing at a data point shows it as a green sphere. A single pinch gesture then displays a tooltip for data exploration. Repetition of the same gesture on the same data point hides the details.

4 Discussion

We present SSCA, a prototype which combines situated spatio-temporal visualization and in-situ data exploration activities through proxemics and embodied interactions. We note that current limitations of our prototype include the HMD's limited field of view, which may restrict how information is displayed and explored. Consequently, more head orientation and body movement might be required. This may impact: 1) the duration for the data analysis, and 2) the user's physical comfort level. We implemented proxemics and embodied interaction to support in-situ data analysis. However, these interactions have not been user evaluated and thus it is not clear the limitations they and our prototype may need to overcome for and during in-situ data analytic tasks. Furthermore, while we use STC in a geographic space covering a large physical area (i.e., a building atrium or soccer field), due to the current HWD technical challenges (i.e. limited HMD computational power), the scalability of our tool may not accommodate extremely large spaces (e.g. a district or city) to create complete immersive data analytic experiences. We acknowledge that SSCA will likely require training, when the user does not have any prior knowledge of STC, situated visualization and analytics, or these interaction types. Through future user studies with our SSCA prototype, we aim to explore how, when, and why situated analytics can take place as well as users' analytical processes and strategies through the use of filters, interactions, and analytic modes to accomplish varying degrees of data analytic tasks.

Through our SSCA prototype, we envision many potential use cases. As example, this can include use by professional athletes and coaches. Here, typically video data is viewed post-game on screens that are away from the environment it was captured. By being in-situ, players and coaches may be able to take advantage of SSCA's in-situ nature and embodied interactions to further take meaning, and to create actionable strategies within the respective environment that the spatio-temporal data was captured. Furthermore, other applications include the in-situ inspection of accident scene data taken from spatio-temporal data captured within vehicles or in-situ spatio-temporal personnel data viewed within a workplace or factory to maximize efficiency.

5 Conclusions

This paper offers an early situated space-time cube analytics (SSCA) prototype. SSCA can visualize spatio-temporal data, through STC visualization, and projects it into the environment where the data were captured using AR technologies. Our prototype demonstrates intuitive 3D input modalities using proxemics and embodied interaction for in-situ data exploration, interaction, and filtering. Through our prototype, we further the boundaries of information visualization paradigms, leveraging a new generation of HWDs to explore the potential for situated STC analytics.

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