Immersive Visualisation of Geo-Temporal Narratives in Law Enforcement

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***Abstract*—Recent advances in virtual reality technologies enable high-fidelity exploration of data in immersive environments. This is advantageous for professional applications of high-dimensional datasets (such as geo-temporal narratives), as we can leverage all three spatial axes while immersing the user in the information itself. Geo-temporal narratives tell a story of entities, their movements, and as a result, their potential relationships, thereby defining the *who*, *what*, *where*, and *when* that define a story; everything except the *why*. This paper describes an immersive virtual reality system we have developed to convey these narratives, specifically focusing on the law enforcement domain. The system lets users not only view *who* was *where* and *when*, but also view explicit and implicit relationships between entities, repeated visits to recurring locations, as well as the crucial descriptive information supporting the *why*. We present the results of an expert review of the system from federal law enforcement and defence agencies that validate our approach.**

***Index Terms*—visualization, virtual reality, law enforcement**

I. Introduction

As part of the investigatory process, law enforcement agents are regularly required to internalise information involving the spatial, temporal, and abstract relationships of people and entities to build an understanding of potential criminal activity. Commonly, the information systems that support the agents focus on presenting the information as discrete artifacts, such as an individual witness report or a list of bank transactions, without contextualising what the artifact means within the broader case. It is up to the agent to internalise and contextualise these facts, which they do as a narrative [1]. This narrative encompasses the people of interest (POI) within the case, their motivations, their actions as a consequence of their motivations, as well as a temporal ordering of this information. Only towards the end of the case are these narratives externalised as briefs and shared between agents.

Insights within these data-driven narratives are often implicit and require piecing together disparate facts to build strong allegations of the POI's motivations and actions. Spatial locations and relationships, such as entity geo-collocation, must be understood. However, geo-located data is often sparsely available, especially in complex cases. Furthermore, abstract relationships between people and entities, such as telecommunications, need to be conveyed. Finally, the temporal dimension of the data is integral to conveying a narrative and implying causality. Insight requires correctly inferring connections between these dimensions that are not otherwise explicitly stated. Incorrect inferences from the data can lead to incorrect assumptions (influencing the investigation of a case) or worse, incorrect assertions (influencing the prosecution of a case). A frail understanding of the narratives constructed from the underlying data is a significant risk to the case.

Since its inception, visual analytics has been successfully employed in aspects of law-enforcement. Visualising criminal networks, for example, has been shown to provide insight into identity fraud [2]. Often, these intelligence systems visualise abstract and geospatial relationships between entities as separate but connected views through techniques such as linking or brushing [3]. Regardless of the views used, they must reduce the dimensionality of the data, which can potentially increase false positives and false negatives when understanding a case. We propose that by leveraging immersive technologies such as virtual reality (VR), we can increase the understanding of the complex relationships and spatial information in these cases. We are especially interested in exploring the affordances that a tracked view through a head mounted display (HMD) provides, which allows even minor head movements and rotations to help discern occlusions and communicate surface forms such as terrain [4].

In this work we present an immersive VR visualisation system that presents both the spatial and abstract relationships between entities over a period of time, in conjunction with additional descriptive information about the events of the case, collectively describing the *who*, *what*, *where*, *when*, and *why*. By utilising an immersive environment to show this information, we are able to view not just entities, their relationships and locations, but also the links between them as they develop over time. VR provides a natural method for representing both the abstract and spatial relationships along with the descriptive narrative. The result of this is a system that supports new insights into the entity networks and geo-temporal relations, and as a result, potentially supports a deeper understanding of the underlying narratives, aiding communication of the case. Users can i) view the social network as it develops over time ii) explore which entities are involved in events geographically, and iii) understand the actual events that took place.

The contributions of this paper are (a) identifying the requirements of understanding law enforcement narratives, (b)

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a prototype VR system that addresses these requirements, which presents the abstract and spatial relationships of a law enforcement narrative in a unified space, and (c) a validation of the immersive system approach from a review with domain experts.

The remainder of this paper discusses related work, requirements, the underlying data model we use to generate the visualisation and then a description of the visualisation itself. We then present an example use case with a review by domain experts, and conclude with future work.

II. Background

Narratives—being a communicable account of a set of meaningful, related events—are a powerful tool for transferring knowledge in a variety of professional and non-professional contexts. It is well regarded that narratives are not only used to communicate a law enforcement case, but in-fact form part of the mental model when comprehending such a case. Pennington and Hastie [1], [5], [6] have shown through repeated studies that when jurors piece together presented facts and evidence in court, they approach understanding and critical interpretation through a narrative mental model referred to as the "Story Model". More generally, agents in law enforcement build a "situational" mental model that describes how information is integrated into a mental representation [7]. One proposal for such a model is the event indexing model, where events are the basic building blocks of understanding that are mentally indexed on time, space, causation (what caused an event), protagonist (who or what was involved), and motivation (of the protagonists) [8]. Such a model is well supported by narrative discourse and helps to explain how visual communication is readily integrated through discourse, as both channels of communication (discourse and visual) are incorporated into the same model [7], [9].

A. Geospatial Narratives in Law Enforcement

Given the spatial nature of law enforcement narratives, the use of visualization to provide spatial context to narrative is essential. Approaching this problem from a purely geo-temporal perspective, such as [3], fails to take into account the greater narrative of what the data is actually telling us, i.e. the additional information that describes the story of the data over time is potentially ignored when the visualization designer's focus is solely on the space-time component and not on the actual narrative of interest. In the context of law enforcement, space and time are a critical in *supporting* the understanding of criminal narratives.

These narratives are compounded by a number of factors. Users need to analyse not just spatial relationships for a single object, but the relationships between them, creating more complex problems [10]. As we are no longer looking at a single trace [11], we must take into account what is being shown in space and time; vehicles [12], vessels [13], crime [14], or even object-agnostic events such as data from environment sensors [15]. All data forms part of the story which is identified by Peuquet [16] as referring to space (where), time (when) and objects (what). Such components support the interpretation of data as a narrative, consisting of the traditional *who*, *what*, *when*, *where*, and *why* structure.

While geo-temporal visualization is an established research topic, visualization tools to support the understanding of geo-temporal data for particular domains remains an open research problem [17]–[19]. Aigner et al. [20] surveyed current approaches, grouping them by their representation of time and data. Given the scope and continued research into this topic, it is clear there is no universal representation, an argument supported by Aigner, et al. Different analyses require different views. This includes selecting the correct view for the analysis and continually revising until the underlying story of the data is visible [21].

B. Visual Analytics Systems

Visual analytics (VA) is a well established field in law enforcement. Thomas and Cook [22] identified the requirements for visual analytics to "support production, presentation, and dissemination of analytical results". As part of the COPLINK project, Chen et al. [2] visualised criminal entity networks using multi-dimensional scaling and found positive results in detecting subgroups and between group interactions. The COPLINK project also investigated the use of linked views in the "spatio-temporal visualiser" [23], a system for visualising aggregate crime trends with a geospatial component.

Given the real world impact of tools for law enforcement, such research is not isolated to academia. Commercial platforms such as Palantir[1] offer users a plethora of tools to understand investigations. However, like COPLINK these tools tend to be data-focused, lacking the context provided by the narrative. Visualisations such as entity-link charts or geographic views are presented in isolation, separated from any representation of the core narrative of the case. As such, these tools primarily focus on the data itself, rather than on trying to identify, extract, and communicate the fundamental question: *why?*

C. Immersive Visualisation

With the advances in rendering technology, the third dimension has becomes accessible for visualization, enabling geospatial visualisation approaches such as the Space-Time Cube [24] and later implementations [25]–[27]. The Space-Time Cube has been extended to show discreet events [28] (a more completed level of question as defined by [24]), as well as to support the understanding of stories for data analysts, specifically explored in Eccles et al. [29].

Immersion should be considered when discussing three-dimensional visualisation. *Immersion* is the capability of a technology to deliver an illusion of reality [30]. Ware and Mitchell [31] studied the effects of various immersive cues in perceiving 3D graph projections and found a significant increase in the ability to trace graph paths when using these cues compared to 2D screens. The unique immersive properties provided by a tracked HMD allow a type of "vision

[1]https://www.palantir.com

based navigation" as the user moves and rotates their point of view in 3D space [32]. From Gibson's [33] theory of visual perception, this may be composed of "ambient vision", being head rotations, and "ambulatory vision", being head movement and rotations. As Islami [4] succinctly states of these properties in regards to understanding form:

> ... in the case of ambulatory vision, the observer is not apprehending a flat visual field composed of connected snapshots, rather a flowing array of visual cues that determine movement, direction, depth and so on. In other words, as the observer moves and scans the environment, the surfaces of objects emerge and recede, which together with an awareness of space and time, allows for a more comprehensive visual perception.

Chandler et al. discussed the potential impact of immersive environments on the engagement of people with data, and with each other, in data analysis and decision making, defining a research area they call *Immersive Analytics* [34]. This use of immersion has been used to improve narrative communication before, such as in work by [35] examining the influence of immersion in VR to persuade an audience. It is by combining the immersive properties of VR and visual analytics in our work, that we hope to improve engagement for both data analysis and decision making.

III. Requirements

We are primarily interested in exploring the potential insights immersive environments can bring to geo-temporal narratives in the law-enforcement domain. Deep insights in this domain occur through correct inferences from the data, which form the basis for allegations of criminal intent and action, both of which must be reasonably proven to charge an offence. Through a series of unstructured interviews with domain experts, we have defined the following set of requirements focused on building an understanding of potential criminal activity involving sparse geospatial data. These requirements are directly linked to the tasks that they perform.

R1 Communicate the descriptive elements of narrative: Criminal narratives can be full of complex behaviour and nuance that must be communicated.

R2 Communicate the abstract narrative relationships between entities: Abstract relationships, such as communications, form an important aspect of understanding a case. Intent to commit an offence is often represented by these abstract relations. From a narrative perspective, it is important to prioritise the actor (or subject) within these relationships to better represent agency and support understanding.

R3 Communicate the physical relationships between entities: Understanding the location of entities and the physical relationships, such as collocation, aids in determining the circumstances under which an offence actually took place.

R4 Help infer nature of sparse geospatial data: The geospatial data available in law-enforcement cases is often sparse. For example, CCTV footage could show a person of interest (POI) at location A, and witness statements later place the POI at location B, however, the POI's movements between these observations is completely unknown. Incorrectly inferring movements in-between this sparse data can be detrimental to the understanding the case. Even without new information, existing knowledge such as the location of main roads (for cars), and hills (for walking) can be taken into account.

R5 Support understanding the temporal ordering of events: Temporal ordering is the principle dimension in understanding causality.

IV. Data Model

The visualisation system presented here is part of a larger Integrated Law Enforcement (ILE) project being undertaken by the Data To Decisions Cooperative Research Centre. The ILE is focused on the use of novel technologies to improve every aspect of law enforcement, with the centre piece the development of a commercial information management system that forms the backbone and repository of an investigation. Under the banner of "data curation", aspects of this research use natural language processing and machine learning methods to create structured information from unstructured data. This includes extracting structured events and named entities from unstructured text such as witness statements or investigator reports [36], and linking entity mentions across unstructed text [37]. Although the use case data presented in this paper is primarily hand-encoded as an early concept demonstrator, the data model itself is motivated by real-world capabilities developed alongside this project.

We process elements of the data curation into a "narrative data model" suited to the visualisation present in this work. This data model is heavily influenced by situational models such as Dall and Donnelly's [38], while adding the concept of narrative segments. This allows us to focus on entities that have been charged or are "of interest", relationships such as X-degrees of separation from those entities, and narrative relationships in terms of who instigated an event versus who was a passive actor.

Formally, a narrative is a collection of events and entities, defined by the tuple $N = (E, \epsilon)$, where E is the set of event tuples and ϵ is the set of narrative entities. An event is a tuple (t_s, t_e, A); where t_s and t_e are a timestamp for the start and end of the event respectively, and A is the set of subject-verb-object *predicates* describing that event. Given the set of all entities in the narrative, a predicate is the tuple (S, O, d). Where S is the set of subject entities $\{s \in \epsilon\}$ of the predicate (the entities taking action), O is the set of entities $\{o \in \epsilon\}$ being acted upon, and d is a textual description of the action being performed.

A narrative may be split into *narrative segments* by splitting at the start and end periods of the events. Since events may potentially overlap, an event may exist within several segments, and, conversely, a segment may contain multiple events. By splitting the narrative into segments, we are able

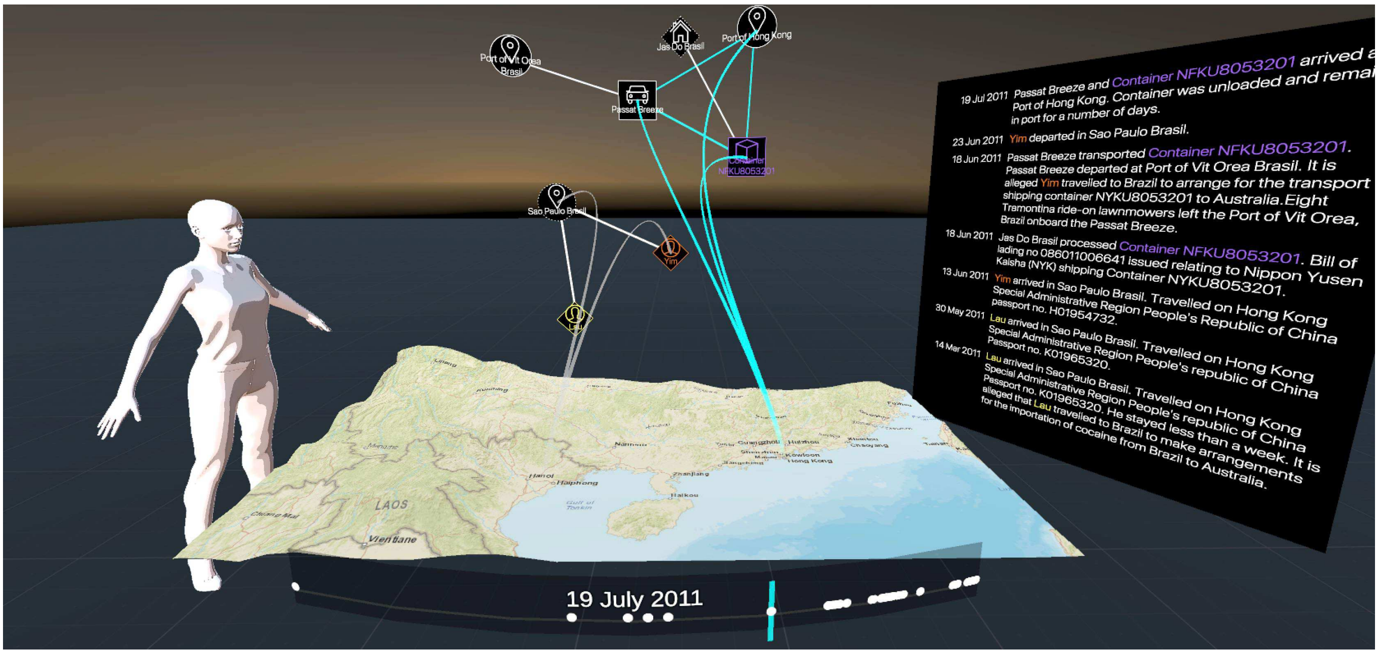


Figure 1. A screenshot of the immersive visualisation system we have developed to support law enforcement experts in comprehending narratives with sparse geospatial data. A human figure is provided to represent proportions with the visualisation at default scale. **Right:** the narrative view. **Centre-Top:** the entity-relationship graph. **Centre-Bottom:** The geospatial view. The entity-relationship graph is linked to geographic locations using bundled curved edges. Users are able to perceive the distinction between abstract and geographic links using the stereoscopic and depth cues proved by the VR technology.

to represent the narrative as a series of discrete state changes, which we use, for example, to animate the entity-relationship graph described in Section V-B.

V. VISUALISATION DESIGN

Our visualisation uses a HTC Vive VR headset, running at a consistent 90 Hz on a workstation with an i7 processor, Nvidia GTX 980 and 16GB of RAM. The visualisation system is composed of three distinct but complimentary visualisations of aspects of the current narrative: a narrative view, an entity-relationship graph view (often called a node-link diagram), and a geospatial view. These views are all linked and exist within a shared, fixed space. This allows the user to change their viewpoint by moving their head or physically walking around in the visualisation.

Our visualisations renders the narrative up to a user-controllable focus in time, as described in Section V-D.

A. Narrative View

Through informal discussions with experts during early design, we determined that a visualised narrative such as we are presenting requires a verbose communication of the descriptive elements within that narrative (addressing requirement **R1**). Despite the promises of more elaborate visualisations, the communication of narratives fundamentally requires a high-bandwidth discourse with the user (i.e., text). As such, the first visualisation component is a narrative view composed of the descriptive textual paragraphs of the events within the narrative (Figure 1, Right). We colourise a subset of named entities within the events using a optimally distinct colour palette generated using an open source project[2]. Up to eight entities of interest are assigned a distinct colour from the palette to provide a visual link to the entities in the entity-relationship graph and to aid identification when scrubbing through the narrative. The narrative is supported by a timeline component showing the date and time of current focus of the narrative, and the position of all the different narrative events that take place on that timeline (Figure 1, Bottom).

B. Entity-Relationship Graph

The entity-relationship graph (Figure 1, Top) uses a traditional spring embedder layout [39] to position entities in a two-dimensional plane in front of the user. Entities are rendered as labelled nodes with user-defined icons within the graph. Entities of interest are colourised using the same palette as described in Section V-A as a cue to visually link the two views. Edges in the graph show the relationships between entities that have occurred in the narrative. For every predicate within the narrative up to the focus, we draw an edge between every subject entity within S and every object entity within O. While we could have chosen to render the predicate as a clique containing the subjects and objects, the chosen rendering emphasises the agency and motivations of the subject (**R2**). The thickness of the edge is proportional to the number of occurrences of the relationship within the current narrative, i.e. the greater the number of events occurring between two entities, the thicker the line. Edges that represent relationships

[2]https://github.com/medialab/iwanthue

from the most recent event in the current narrative are highlighted blue, all other edges are coloured white.

To minimise movement of the graph, we pre-process the narrative, running the spring embedder on each narrative segment until the graph is settled and caching the resulting position of entities. When interacting with the system, the cache is used to determine the target location which entities will interpolate towards using an easing function.

Only entities that have been involved in the narrative up to the current focus are shown in the graph. This means that as the user either manually explores the narratives, or automatically plays through the case timeline, entities "pop" into view with the layout adjusting to accommodate.

C. Geospatial View

As previously highlighted, a key aspect of effectively communicating law enforcement narratives involves communicating sparse geospatial data. To achieve this, we present a geospatial view that provides spatial context by indicating the geospatial relationship between entities participating in consecutive events. The geospatial view is rendered as a map (including elevation data) positioned horizontally in front of the user. Entity locations are represented by visually linking the entities within the entity-relationship graph to geographic locations on the map using using curved edges (Figure 2). Elevation can be important for certain events, for example someone fleeing a scene will generally run down-hill, but not up. The use of 3D rendering assists in this context, and immersive technologies such as VR allow the user to position their view to see entities that may be occluded by elevation.

Entities participating in the same geo-located event are bundled together to indicate collocation (**R3**). While the system supports rendering all of the geospatial relationships in the narrative, through experimentation we have determined that showing only the two most recent events from the current focus produces an optimal solution for readability in most cases. The most recent event is highlighted blue while the second most recent event is provided to maintain context and is rendered in semi-transparent grey. The view automatically animates to optimise the zoom and position of the map to display geographical locations associated with the current focus within the narrative.

We have found the curved bundled edges to be an effective method for representing sparse geospatial relationships (**R4**). While we could have integrated entities within the geospatial view and presented their implied movements, the curved edge approach better represents the "unknowns" within the data and thereby reduces incorrect inferences. Coupled with the stereoscopic and depth cues provided by a VR Head Mounted Display (HMD), curved bundled edges provide a strong visual cue for differentiating the geographic links from the straight edges of entity-relationship graph. Feedback from users has supported this, as discussed in detail in Section VI.

By presenting a geographic map of locations of importance to the user's current context in the narrative, the user is able to rapidly discern not just the explicit current and past position of entities, but also collocated entities or groups acting together. This is especially advantageous when used with the entity-relationship graph, as we can easily identify if this is perhaps the first time entities have been collocated, or their association is a regular occurrence in the narrative. This would not be possible if the user was using a traditional map showing entity locations, but rather the power comes from the complimentary views in a shared space enabled by VR. Entity-association aside, we can also find out *why* those entities are co-located (or not, as the case may be) by utilising the narrative view. While there is no single ideal way to represent a case, by presenting complimentary data-specific views of the case, the user can not only understand the facts, but understand the reason.

D. Interaction

Interaction with the visualisation is two fold:

1. Controlling the narrative: Users can use the touchpad on the Vive in their dominant hand to navigate the focus of the timeline by moving their finger around the outside of the touchpad in a circular motion (emulating the "click-wheel" present in original iPods). The selected date/time can be viewed on the timeline, with each event that is present at the selected time causing a distinct "click" haptic vibration in the controller to tell the user there is an event at that point in time. Clicking the touchpad causes the timeline of the narrative to playthrough automatically at a fixed rate.

This interaction is the primary method for addressing requirement **R5**. The user is able to control time and observe the results interactively within the immersive environment, thereby understanding the causal effects within the narrative. Haptics are used to reinforce this understanding.

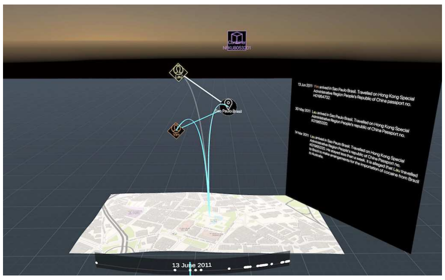
2. Map exploration: Using the Vive controller in the user's non-dominant hand, users can pan the map by swiping on the touchpad, and zoom in/out by clicking up/down on the touchpad. This allows the user to manually override the automatic zoom/pan performed by the system.

Enabled with these explicit interactions and using VR, the system affords an expressive platform for exploration. The user can adjust their temporal focus, their viewing focus, and scale. Being able to physically walk around and through the visualisation is an intuitive method to explore the data while maintaining spatial context.

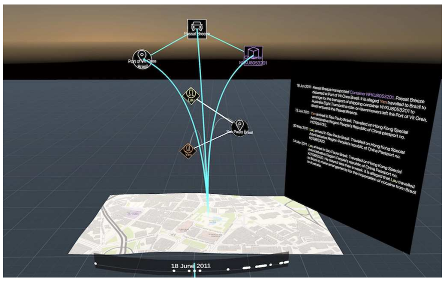
VI. Use Case

This section presents an example use case scenario demonstrating how our visualisation supports understanding sparse geospatial narratives within law enforcement domains, provides examples of the insights a user might gain from such visualisations, and presents expert feedback and observations of the system based on this scenario. The source data for the use case is a training criminal case from law enforcement partners.

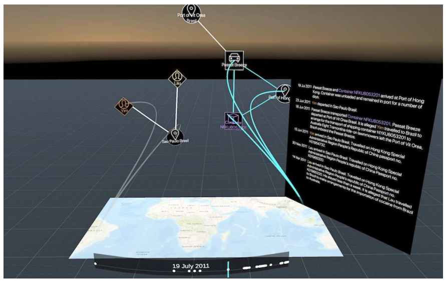
The scenario begins when our law enforcement agent wears the HMD and sees a world map observing the first event within the narrative, where our person of interest (POI) Yim arrives in Brazil. The agent scrolls forward on the Vive touchpad moving



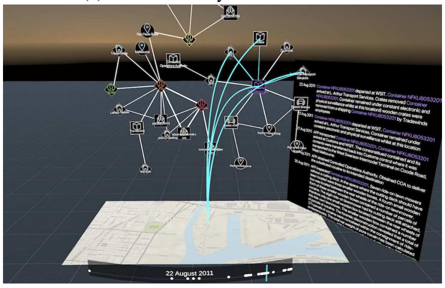
(a) Our POIs early in the narrative.



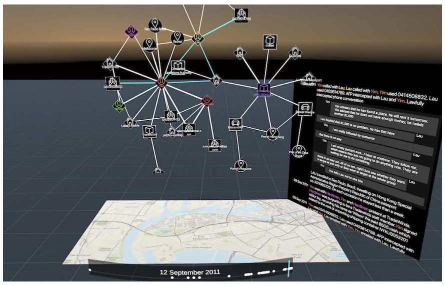
(b) Shipping container arrives at the same location.



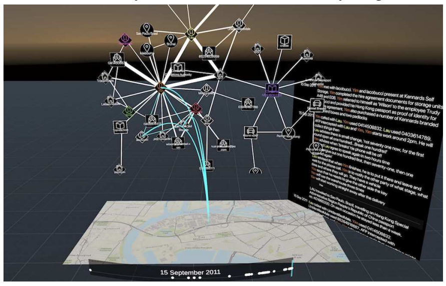
(c) Two storylines are clear at this early stage.



(d) Later in the narrative.



(e) The first event where the two storylines join.



(f) Late in the narrative.

Figure 2. The use case of an agent stepping through a realistic case scenario.

to the next two segments in the narrative, where another POI, Lau, arrives independently in the same location (Figure 2a) and a shipping container of interest also arrives in the same location as both Yim and Lau (Figure 2b). The agent gains the insight that, although there is no single event directly involving all three entities, they can infer some form collusion, as all three entities are collocated within a short period of time.

The agent advances the narrative and observes that two distinct storylines have formed (Figure 2c). The entity-relationship graph shows that the shipping container has split into one distinct storyline, while the POIs have split into another. Meanwhile, the geospatial view shows that these two storylines have also diverged geospatially. The agent expects both storylines to join at some point during the narrative to support causality. Later in the narrative (Figure 2d), the agent observes on the entity graph that Yim has made several phone and email communications (abstract relationships). Historical geospatial relationships are also represented in the graph view, such as the fact that Yim and Lau both were present in Brazil.

Advancing further, the two storylines finally merge (Figure 2e) as law enforcement intercept a phone call between Lau and Yim. Finally, the agent advances towards the end of the narrative (Figure 2f) and observes strong connections between the POIs.

A. *Preliminary Feedback from Domain Experts*

We presented our visualisation and use case to three experts within law enforcement domains that work with sparse geo-spatial narratives. All the experts had minor experience working with VR systems. We began demonstrating the system using a 2D projected display and a static camera placement within the scene. This provided a understandable baseline for explaining the visualisations. We then proceeded to step through the use case, describing to the experts what they were viewing. The experts noted that they appreciated the novel approach to visualising a spatial narrative and having a geographic map view integrated into a three-dimensional space. Potentially such a system could provide new or deeper insights into the narrative. Consistent colour-coding of the entities in both the narrative view and the entity-relationship diagram proved a good cue for visually linking the two facets.

We then asked each expert to wear the HMD and experience the system as an immersive visualisation, using the "thinking out loud" method to express their observations. After a brief orientation period, all experts received the visualisation positively. The experts commented that the geographic links are much more readable in the VR environment than viewing on a standard display. One expert described that the visualisation was "not as crowded in VR. . . and much more understandable", supporting our claim that the affordances of VR can more comfortably represent several linked views within the same space. Although primarily text, the experts found the narrative view more engaging in VR. Several experts chose to walk into the visualisations to physically immerse themselves in the narrative. One expert suggested making the system less prescriptive, and allow the user freely position facets of the visualisation, such as entities, as they see fit. This concept echoes our experience from previous immersive visualisation work. Overall, the experts considered this immersive approach an exciting method for gaining new insight into law enforcement narratives and worth further exploration.

VII. Limitations and Future Work

As noted in Section VI-A, domain experts expressed the need to be able to manually rearrange the workspace to suit their situation and process. Based on this feedback, we envisage direct manipulation methods to not only position and scale the visualisations, but to allow the user reach in and rearrange entities in the graph into a custom layout. Building upon these more advanced interactions, methods for search and filtering would help support larger or more complex datasets. Currently, the system represents the geospatial relationship of only the two previous events to maintain legibility; user-controlled filtering could potentially reduce visual complexity, and therefore may practically support more geospatial relationships to be rendered legibly.

VIII. Conclusion

Understanding the data-driven narratives in law enforcement is unique in that it requires determining the motivations of people based on insights from sparse data. This is complex, given real world events are the cumulative result of tens, hundreds, or thousands of pieces of individual information, touching from narrative, temporal, spatial, relational, etc., presenting information visualisation experts with a unique challenge when trying to develop systems to support understanding these events.

Given the recent advancements in VR, and the properties of such systems given their immersion, it is well positioned for unlocking new possibilities in understanding complex relationships within law enforcement datasets. However, the benefits of such immersion is not limited to law enforcement, as we see more and more domains exploring how to leverage VR. For our domain focusing on narratives with sparse geospatial data, we have presented our early work exploring the possibilities of immersive visualisation to this complex domain. Our system presents the first steps in not just visualising case data, but also exploring primitive narrative data-structures to enable their visualisation and navigation. The results of feedback from those working in the domain show definite promise for further development and exploration of systems in this area, not just in terms of gaining an understanding of the data, but encouraging interaction and exploration as the fundamental first step towards insight.

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