L-WiM: Collaborative Exploration in Immersive Environments

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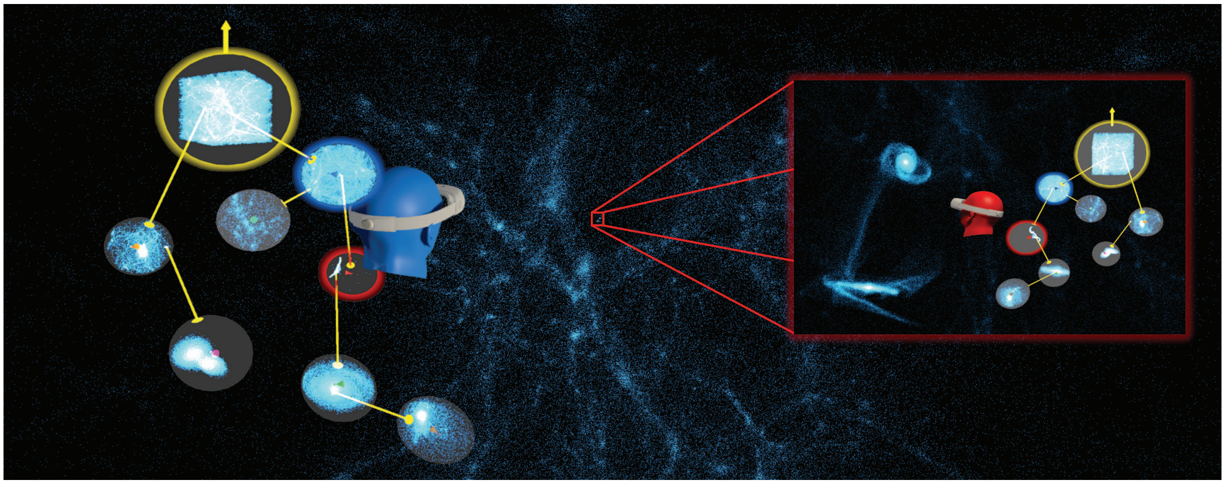

Figure 1: Seven users are exploring a large-scale simulation of astronomical data in the immersive virtual reality environment. Here we take two users (indicated by blue and red) as an example. The blue user possesses a larger scale, viewing the cosmic web while the red user is observing the galaxy in a relatively small scale. Each user is assigned a "World-in-Miniature" (WiM, highlighted by blue or red color) which shows a miniature of the virtual environment at the level of the scale. All the WiMs are connected in the L-WiM tree demonstrating the contextual information, relative position and scale relation among collaborators.

Abstract

An immersive environment provides multiple users a shared space for collaborative data explorations through head-mounted displays (HMDs). Effective collaboration is built based on different strategies, including the ability to focus on one's own tasks, be aware of others' location, orientation and scale, as well as share data/insights when needed. However, for astronomical data exploration, it might be the case that abundant information is distributed at multiple levels of magnitude. Therefore, it is difficult to observe others' contextual situations and exchange insights efficiently due to the reason that collaborators' avatars may be too far or even in different scales. In this work, we use World-in-Miniature (WiM) to show the virtual environment at the level of each user. Based on that, we propose L-WiM, a novel interactive user interface for collaborative astronomical data exploration that links multiple WiMs. Through L-WiM, collaborators can see their contextual information at a glance, such as the scales, spatial locations, view directions as well as the surrounding environment. Users are supported to communicate via voice messages and visual cues after they select other users' WiMs.

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms

1 Introduction

The immersive environment proposes new prospects for multi-user collaborative data exploration and information exchange in a shared space via Head-Mounted Displays (HMD) [29]. For instance, the use of immersive environments has applicable potential in the field of astronomy, helping scientists explore the unknown and verify research predictions. Through cosmological simulations, scientists predict that dark matter generates cosmic webs, and the filaments in the web deliver the energy and matter to the high-density cluster area such as galaxies. To discover patterns and confirm their prediction, scientists need to select and explore astronomical data, such as 3D cloud point data from the cosmological simulation [4, 6]. However, one of the inherent features of astronomical data is that these points are widely spread in enormous spatial ranges and contain abundant details at different levels of magnitudes. An immersive virtual reality environment can facilitate user engagement in the data exploration process so that the data can be examined at vastly different spatial resolutions to unveil interesting or unexpected patterns. Moreover, collaborative interaction in such an immersive environment shows great potential in strengthening teamwork and communication, allowing more holistic and efficient spatial exploration.

The *awareness* of collaborators plays a significant role in effectively exploring the immersive environment, including awareness of presence, location, actions and activities [34]. The awareness can influence the quality of collaborative work by allowing users to find and feel each other at any time. First, visualizing the location, actions and activities of their collaborators improves the user's *spatial and situational awareness*. It endows a sense of knowing where the user is, where other collaborators are, what other collaborators are doing and what is happening around them. Second, the opportunity to visualize collaborators within a shared virtual space prompts *insight sharing*. Insight sharing is one of the critical features of collaborative exploration, especially when the data is unknown and with exhaustive details.

The goal of our study is to design an intuitive and effective virtual reality (VR) interface that enhances collaborators' spatial awareness and supports them in sharing views and insights for astrophysical

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data exploration. For visualizing and representing collaborators, a common approach from the literature is using VR avatars, the virtual representations of users. However, when navigating a large-scale virtual environment, such as the simulation of the astrophysical universe, collaborators may focus on specific parts in different spatial scales and lose sight of the big picture and other collaborators' locations. More specifically, we identify three challenges as follows:

C1: Multi-scale. The astrophysical data often contains a large number of astronomical structures distributed on numerous scales in the Universe dominated mostly by emptiness. If the collaborators are represented as scaled avatars, visualizing other collaborators becomes challenging since their virtual avatars may look too large or too small in the user's scale of observation. Furthermore, in order to reach another user's location, they need to navigate across huge spatial scales.

C2: Large and empty space. On a specific scale, the astronomical data distributes widely, and empty spaces occupy most regions of the environment [30]. As a result, regions of interest (ROI) are spatially segregated from each other. Thus, in the exploration, users may not be able to see their collaborators if they are exploring different parts of the data.

C3: Communication and assistance. In order to identify ROI in the immersive environment, users may need assistance from a third-person point of view. However, sharing views and findings about the large-scale point cloud data in the immersive environment is extremely challenging due to the complex data environment.

In this work, we propose L-WiM (Linked World-in-Miniature), an intuitive and effective user interface for collaborative data exploration in an immersive environment. We used astrophysical data as an example of an application. With L-WiM, users can observe rendered images of other collaborators and their views, including *the contextual environment* and *the tasks being processed*. Users are aware of information about their collaborators' *locations* and *scales*. Furthermore, users can share and communicate their *insights* through interactions and visual cues.

2 Related work

This section reviews the recent work related to immersive visualization, collaborative exploration, and in particular, the World-in-Miniature technique in data exploration.

2.1 Immersive Visualization

In several domain studies and applications, including astronomy [2, 21, 35], biology [1, 28], medicine [41], urban planning [7], and other interdisciplinary sciences, immersive visualization has long been researched and employed. The advantages brought by immersive environments can be summarized from three aspects:

Immersion. The idea of "being a part of the data environment" can be used to describe immersion. Users' capacity to comprehend, manipulate, and explore complicated data is considerably improved by the immersive environment, which constructs a 3D virtual world where the investigators are able to observe closely and contact directly with 3D data representations. For instance, Nanotilus [1] employs a novel camera path planning method and an object sparcification management method to provide an immersive endoscopic inside-out experience in a dense environment. Quam et al. [36] proposed immersive biomedical simulations to promote the comprehension of clinical intervention risks through 3D patient data.

Engagement. Engagement can be regarded as "the emotional, cognitive and behavioral connection that exists, at any point in time and possibly over time, between a user and a resource" [3]. Wang et al. [41] presented a set of non-contact gesture-based interaction techniques for volume data, which enhanced users' cognitive capability in the exploratory tasks. Lubos et al. [32] proposed a hand-tracking-based user interface to support interactions with point cloud data in the immersive environment, such as selection, annotation, and segmentation activated by voice or VR controller.

Awareness. The awareness from an immersive environment can be understood from two aspects: 1) understanding of what has been changed / is changing in the context, and 2) understanding of people's actions and reactions. For instance, Freser et al. [23] proposed a method to increase the awareness of the manipulation process to the objects. They leveraged the wire-frame to represent the object being moved by the user. In terms of the awareness of the collaborators, many techniques were developed to improve the awareness of position, facial orientation, field of view, and the actions of other collaborators, including the visualization of wire-framed frustum [23], World-in-Miniature [38], and bird's eye view [16], etc.

2.2 Collaborative Exploration

Collaborative exploration is an effective approach for analyzing huge and complex datasets [17]. It supports a group of users to perceive, observe, and manipulate the data in a shared space [25]. Users are supported to collaborate in two main ways: 1) in the same physical space (co-located collaboration) with distinct virtual avatars in the shared, cognitive and physical space, communicating via discourse, gestures and gaze or 2) link to the same immersive environment via different hardware in multiple physical locations (remote collaboration).

The CAVE Automatic Virtual Environment (CAVE), the responsive workbench [26] and Fishtank [31] were a few of the earliest immersive techniques for co-located collaborative data exploration [13]. Later, the new generation of the CAVE style product CAVE2 was developed [20] and the use cases were proposed by Marai et al. [33]. However, the CAVE-style immersive environment requires multiple screens projected on walls in a large room, which can be costly. In addition, only one tracked user can receive accurate stereoscopic vision, which makes it even less cost-effective.

In recent years, VR head-mounted displays (HMDs) have been gradually employed in immersive collaborative data exploration. Users connect to the shared virtual space via different hardware and possess a unique view. Previous research has studied the relative merits of VR HMDs for collaborative work. The results indicated that VR HMDs achieved the same level of accuracy as CAVE-based systems while being more portable and affordable in the meantime [12]. Hence, VR HMDs have been utilized in many collaborative system designs. Several notable designs are iVIZ [18], an internet-based collaborative platform for immersive visualization that works with the Oculus Rift, Telearch [27], a collaborative and interactive archaeological exploration platform and MICA [15], a collaborative system for astrophysical data analysis. The recent work FIESTA [29] concentrated on the group collaborative pattern in a free-organizing co-located immersive environment with multiple users.

2.3 WiM (World-in-Miniature)

World-in-Miniature (WiM) [38] is a technique that provides a scaled-down version of the whole or a part of the virtual environment. The technique has been effectively applied to architecture [5, 9, 24], augmented reality [19], and medical visualization [10]. More recently, Danyluk et al. [14] defined WiM as "a scale replica within and linked to the original region through virtual feedback or interaction". When a user manipulates objects through a WiM, the changes to the WiM will be synchronized into the original world. Similarly, modifications to items from the original world will be reflected in WIM objects. Users can utilize WiMs to edit items that are out of reach. Furthermore, WiM can also be utilized as a navigation tool [11, 40]. A limitation of WiMs is that the data visualized with a broad scope (large-scale) contains many invisible details. Li et al. [30] proposed SWiM to support fast scale transition in an astronomical environment based on the Power-law spatial scaling method. They leveraged logarithmical mapping approach to visualize the miniature spaces, providing an overall view of the whole astronomical spreading on a wide range. Wingrave et al. [42] introduced SSWIM to overcome the large-scale problem in city simulated data. SSWIM allows the WiM to show parts of the whole data with a user-defined visualization scale and region, supporting the navigation and manipulation of the buildings in a vast city in an immersive environment. Although the exploration of large-scale data via WiM has been investigated, a relatively small body of literature is concerned with collaborative application with WiMs [14]. Stafford et al. [37] proposed "god-like collaborative interaction" in which the user indoor manipulates a WiM projected by a tabletop display system, while the user outdoor observes the reconstructed model reflected from the indoor WiM via a mobile augmented system. Chheang et al. [8] developed the group WiM (GWiM) system, which provided a team navigation method via WiM guided by a leader. The WiM technique in collaborative large-scale data exploration has not been studied. A single WiM is able to display the contextual information and support interactions that are out of reach. We believe WiMs combined with small multiples [39] is an effective technique for collaborating with partners in large-scale data. In our work, we aim to investigate how multiple WiMs can be linked for collaborative exploration in an immersive environment.

3 Design Considerations

In this section, we introduce the design considerations. The system aims to enhance the collaborator's context, position, and scale awareness in immersive exploration work. Therefore, we summarize four design considerations (DCs) to guide the design.

DC1 Context Awareness: Illustrate the virtual environment at the user's level of scale. The main idea of the WiM metaphor is to offer a dynamic view through a miniature of the virtual environment so that the users are aware of the surrounding data. Therefore, it is critical to provide contextual information in the WiM, including the surrounding virtual environment, the user's position and orientation in that environment.

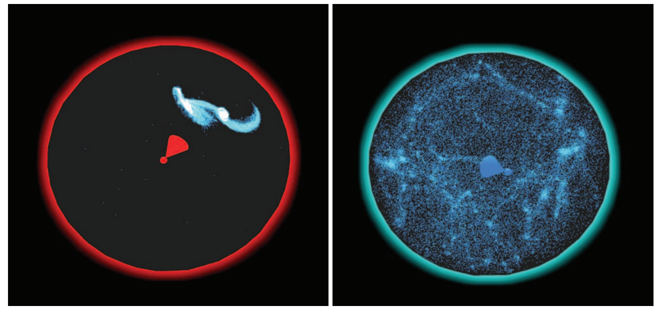
DC2 Position Awareness: Demonstrate the relative positions among the collaborators. The relative positions of collaborators are vital for collaborative exploration, especially when exploring multi-scale data in the immersive VR environment. Thus, it is important to display all users' WiMs in one view so that people will know where their partners are or how to find them.

DC3 Scale Awareness: Indicate the level of scales among collaborators. The unique feature of exploring multi-scale astrophysical data in the immersive environment is that people can navigate through different scales and focus on the data in different regions. Thus, the system should indicate users' scales in the view and display what people are looking at from their positions.

DC4 Collaboration: Support communication and information sharing. There are many ways to achieve communication and information sharing, for instance, co-located and synchronous sharing through voice messages, visual highlights, viewpoints sharing. To ensure effective collaboration, the system should provide an optimized way to support people 1) focus on their own data analysis, and 2) exchange their insights and share their findings when needed.

4 L-WiM (Linked World-in-Miniatures)

In this section, we introduce the L-WiM system, an intuitive interface for collaborative exploration in an immersive VR environment. The idea of L-WiM is that every user in the collaborative work has a WiM and all WiMs are linked together through a thread, constituting an L-WiM tree. The L-WiM tree provides an all-knowing third-person perspective of all collaborators' observations. Therefore, the L-WiM tree is presented in every user's view, in addition to the first-person perspective view of 3D particle data visualization (see Fig. 1).



(a) WiM of the red user (b) WiM of the blue user

Figure 2: The WiMs of (a) the blue user and (b) the red user are shown. The user-centered WiM demonstrates the virtual environment at the corresponding level of scale.

First, we will introduce the "size" and "scope" concepts used in the L-WiM system. Danyluket al. [14] explains these two terms, where "size" refers to the spatial size of a WiM, and "scope" refers to the range of miniature data visualized by the replica. For instance, a cube-shaped WiM (size: 1 meter on each edge) in the immersive environment holds a replica of the milky way galaxy with a radius of 520 thousand light-years (scope).

4.1 WiM

To address **DC1**, every user is assigned a WiM that miniaturizes the virtual environment at the level of scale where the user is. Immersed in astronomical data that span multiple orders of magnitudes, users can traverse multiple scales and explore different regions. Through the WiM, the user can see a scaled-down copy of the contextual environment, where the user perceives their location, view direction, surroundings, as well as other collaborators' avatars if they are on the same scale.

We constructed the user's surrounding environments using a spherical WiM (see Fig. 2). Within the spherical WiM, the user's location is represented as a cone, and the user's view direction is illustrated by the opening (base) of the cone. For ease of visualization, the user is always placed in the center of the WiM sphere. Note that the WiM only highlights data that is within the visible scope of the user. The scope of the visualization is computed by $c \cdot s_{user}$, in which s_{user} refers to the size of the user and c is a user-defined constant factor (for our use case, the value is set to 5). We calculate the distance between the datapoints and the user (located in the center of the WiM)

$$||p_{user} - p_{particle}|| < c \cdot s_{user} \quad (1)$$

where p_{user} is the position of the user and $p_{particle}$ is the position of each particle in the dataset. The particles located within the scope are visualized in the WiM.

4.2 L-WiM

To address **DC2** and **DC3** and guide the design of the L-WiM tree, we propose the following design principles:

DP1 If a user (U_i) travels to a different scale and appears in another user's (U_j) virtual environment, i.e., if U_i is located within the scope of the U_j's world, the two WiMs are connected directly.

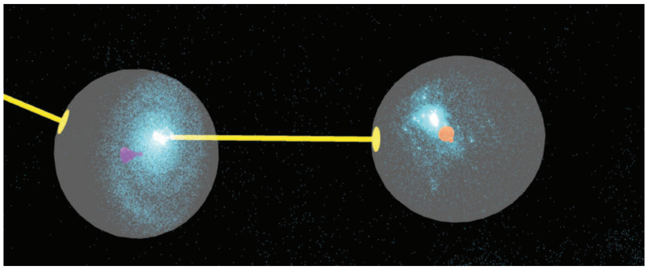


Figure 3: The father node (WiM with the purple user) and the child node (WiM with the orange user) are connected through the yellow thread. The endpoint of the thread located within the father node illustrates the relative position of the orange user to the purple user in the purple user's world.

DP2 If two WiMs are connected through a thread, the user can learn the relative position of the other user by looking at the endpoints of the thread.

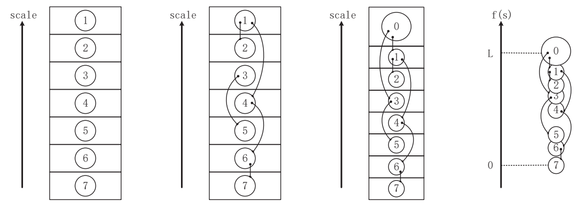
DP3 The position of WiM in the tree along a pre-defined axis indicates the user's level of scale compared to other users.

To address **DP1** and **DP2**, we leverage a father-child relation to demonstrate the relative position among collaborators. We define WiM W_2 as the father node of WiM W_1 if W_1 is located in the scope of W_2 and has a smaller scale than W_2, i.e.,

$$\begin{cases} ||p_1 - p_2|| < c \cdot s_2 \\ s_1 < s_2 \end{cases} \tag{2}$$

where p_1 and p_2 are the positions of W_1 and W_2. s_1 and s_2 are the scale of W_1 and W_2. If such a father-child relation holds, the two WiMs can then be connected by yellow threads (see in Fig. 3). The thread's endpoint in the father node indicates the relative position of the child node to the father node. However, in some cases, one WiM may have multiple father nodes or none. In order to obtain an intuitive and clear hierarchical L-WiM tree, we determine the father node for each WiM by the following steps. We first sort the n WiMs based on the corresponding user avatar scale from the largest value to the smallest, where n represents the number of the WiMs, and create a WiM list (see in Fig. 4a). Then, we pick one WiM W_i from the list. Following a bottom-up order from the list, we search for its father node W_j which meets two requirements: 1) user i's avatar appears within the scope of W_j and 2) W_j's avatar has a greater value of scale than W_i until we find the first satisfied WiM. We perform this bottom-up search on every WiM in the list and eventually obtain the hierarchical relationships among the WiMs (see in Fig. 4b). Note that, not all WiMs in the list can be connected in the same branch, and some WiMs may have no father node because they do not belong to any scope of the other WiMs. For instance, node #3 and node #5 are isolated from the main tree without connection. Finally, in order to link all the WiMs to the tree, we add a node #0 at the top of the L-WiM tree (see in Fig. 4c). The node #0 illustrates the replica of the whole environment to ensure all WiMs are eventually included in the tree. It is highlighted in yellow (see in Fig. 1) and has a larger size than the other WiMs.

To address **DP3**, initially we attempted to map the scale information to the size of the WiMs, i.e., users observing at a larger scale owns a bigger WiM. However, visual depth perception in immersive environment influences the judgement of the WiM size. A large size WiM located far away might look smaller than a nearby WiM with a small size. Therefore, we decide to illustrate the spatial scales through the vertical organization of the individual WiMs in the L-WiM tree. We leverage an additional axis to map the uses' scale



(a) Sorting (b) Linking (c) Adding node #0 (d) Mapping

Figure 4: The building process of the L-WiM tree

information. In other words, the WiM projected on a higher-up position in the tree along the axis indicates that the user is at a larger level of scale of observation. To implement this, we first set the position of the node with the minimum scale (node #7) as $(P_{x_{min}}, P_{y_{min}}, P_{z_{min}})$ in the virtual view, the direction of the scale axis denoted by the unit vector $\overrightarrow{n}$ and a total length L for the L-WiM. Next, we map the user scale interval (s_{min}, s_{max}) to the range $(0, L)$ based on the function

$$f(s) \in (0, L), s \in (s_{min}, s_{max}), f(s_{min}) = 0, f(s_{max}) = L \tag{3}$$

and it also satisfies

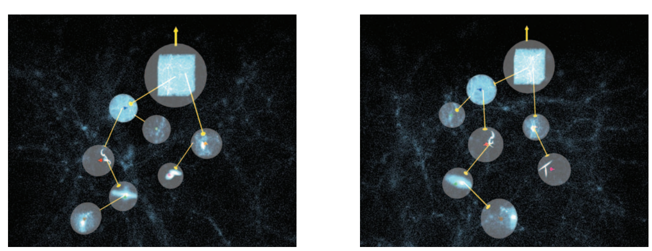
$$s1 \in (s_{min}, s_{max}), s2 \in (s_{min}, s_{max}), s1 < s2, f(s1) < f(s2) \tag{4}$$

In terms of the design of $f(s)$, we considered the situation that many users may explore data at a similar scale. Thus, to avoid clustering of WiMs within a small scale range, we use the non-linear $f(s)$. In our design, the first derivative of $f(s)$, denoted by $f(s)'$, is related to the WiM distribution density spread in (s_{min}, s_{max}). In a dense distributed region, $f(s)'$ has a large value. This way, if many WiMs have similar scales, bigger range along the scale axis will be preserved and these WiMs with similar user scales will distribute sparser. The position of WiM along the scale axis $(P_{xaxis_i}, P_{yaxis_i}, P_{zaxis_i})$ is calculated as:

$$(P_{xaxis_i}, P_{yaxis_i}, P_{zaxis_i}) = (P_{x_{min}}, P_{y_{min}}, P_{z_{min}}) + f(s_i) * \overrightarrow{n} \tag{5}$$

Subsequently, the WiMs are ranked vertically along the scale axis so that the higher-up WiM possesses a bigger scale (see in Fig. 4d). Furthermore, to avoid the overlapping issue and maintain the correct scale information, we push the WiMs one by one to the sparse area in the direction perpendicular to the scale axis denoted by the unit vector $\overrightarrow{v_i}$ until they do not overlap and are separated by a certain distance away from each other. The final position of the WiM $(P_{x_i}, P_{y_i}, P_{z_i})$ is:

$$(P_{x_i}, P_{y_i}, P_{z_i}) = (P_{xaxis_i}, P_{yaxis_i}, P_{zaxis_i}) + r_i * \overrightarrow{v_i} \tag{6}$$



(a) L-WiM tree (b) L-WiM tree (90°rotation)

Figure 5: The structure of L-WiM tree in a front view (a) and side view (b). The yellow arrow on top of node#0 indicates the positive direction of the scale axis.

where r_i is an adaptive constant representing the distance being pushed and $\overrightarrow{v_i}$ is an adaptive unit vector indicating the most sparse direction at $(P_{xaxis_i}, P_{yaxis_i}, P_{zaxis_i})$ perpendicular to $\overrightarrow{n}$:

$$\overrightarrow{v_i} \cdot \overrightarrow{n} = 0 \tag{7}$$

The interface is shown in Fig. 5. To demonstrate the direction of spatial scale, we provide an additional yellow arrow on top of the #0 node showing the direction of increasing scale.

4.3 Communication and information sharing

To address **DC4**, we design a direct approach to support users to "visit" others' WiMs (sharing findings, observing data, offering guidance) through visual cues and voice messages. We consider the key principles of communication and information sharing in collaborative exploration from two aspects.

DP4 The user should be able to decide if they want to be observed or visited by others.

DP5 The user can visit their collaborators' WiMs whenever they want if it is allowed.

DP4 is proposed for personal focus and productivity. The users should be able to focus on their own work without being disturbed. Thus, they should have the option to decide if they would like to receive messages and allow others to see what they are doing. To achieve DP4, our L-WiM provides a switch-like functionality. By default, all WiMs can be visited. However, if a user chooses to disable visitor view permission by turning off the switch, the user's WiM is rendered invisible in other's view (the grey WiM in Fig. 6).

DP5 is proposed because users should be provided with direct and instant communication whenever they need it. The users can also click on other WiMs on the L-WiM tree to set up communication. The selected WiM will be highlighted, and a copy of the WiM will be attached to the left VR controller (see in Fig. 6b). After that, the users are able to communicate with the hand-held WiM through,

voice messages. The voice messages will be received by the selected WiM and played in the air.

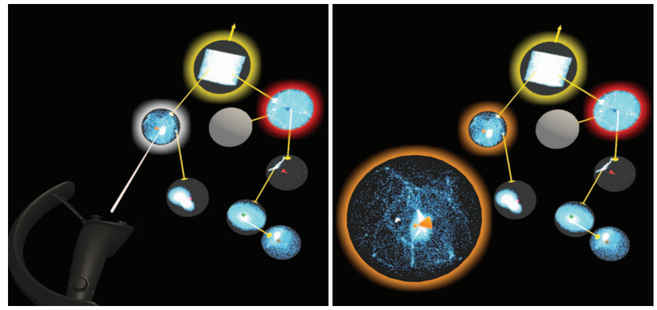
observation. Users can travel to the selected WiM by setting a destination directly in the hand-held WiM. After that, the virtual camera moves continuously to the destination, and the scale will also be adjusted accordingly.

4.4 Interactions

Our prototype supports the manipulation of the L-WiM and the individual WiMs. We leverage the "World grab" metaphor [22] for manipulating the L-WiM. By holding the trigger button on the right VR controller, users can drag, push and rotate the L-WiM in the view. Users can also use the left-hand VR controller to select and manipulate an individual WiM through the Ray-casting pointing method by the white ray. The boundary of the WiM being pointed will be highlighted in white when the ray moves over (see Fig. 6a). Users can press the trigger button to select the WiM. The selected WiM will be highlighted in the same color as the corresponding user, and at the same time, it will be copied and attached to the virtual left-hand controller (see Fig. 6b). Users can manipulate the controller to get a closer look at the selected WiM from different directions. The WiM can be deselected and detached from the left-hand controller by pressing the trigger button again.

5 Conclusion

In this paper, we propose a novel interface for location and information sharing in the immersive VR environment. We focus on the large-scale 3D point cloud data which are very commonly used in scientific domains, such as astronomical and physical simulations. For such datasets, domain experts need to examine and explore data in different scales, and share insights and questions whenever needed. Our interface is designed as a virtual platform that bridges the communication of collaborators. Using our design, collaborators can see each other's location and level-of-scale, share findings, and setup visual and voice communication. However, at the moment, a user study verifying the effectiveness of our design has yet to be completed. Moreover, a more general understanding of specific needs of collaborative exploration in different research domains is required. Future work can focus on expanding our design to broader collaborative research topics where large-scale datasets are involved. We hope that our design will inspire more thinking about the effect of spatial awareness in immersive collaboration, as well as how information can be shared in different exploration tasks.



(a) Pointing to the WiM (b) Selecting the WiM

Figure 6: (a) The WiM is highlighted in white when the user is pointing at it with the write ray. (b) a copy of the selected WiM is attached to the left hand by clicking the "trigger". After that, both the WiM in the L-WiM tree and the copy will be highlighted with the same color of the corresponding collaborator. The grey opaque WiM is inaccessible.

Acknowledgments

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References

[1] R. Alharbi, O. Strnad, L. R. Luidolt, M. Waldner, D. Kouril, C. Bohak, T. Klein, E. Groeller, and I. Viola. Nanotilus: Generator of immersive guided-tours in crowded 3d environments. *IEEE Transactions on Visualization and Computer Graphics*, 2021.

[2] K. K. Arcand, E. Jiang, S. Price, M. Watzke, T. Sgouros, and P. Edmonds. Walking through an exploded star: rendering supernova remnant cassiopeia a into virtual reality. *arXiv preprint arXiv:1812.06237*, 2018.

[3] S. Attfield, G. Kazai, M. Lalmas, and B. Piwowarski. Towards a science of user engagement (position paper). 01 2011.

[4] J. Bechtold. The Lyman-Alpha Forest near 34 Quasi-stellar Objects with Z 2.6. , 91:1, Mar. 1994. doi: 10.1086/191937

[5] A. Bluff and A. Johnston. Don't panic: Recursive interactions in a miniature metaworld. In *The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry*, pp. 1–9, 2019.

[6] J. Bond, L. Kofman, and D. Pogosyan. How filaments of galaxies are woven into the cosmic web. *Nature*, 380:603–606, 04 1996. doi: 10.1038/380603a0

[7] S. Chen, F. Miranda, N. Ferreira, M. Lage, H. Doraiswamy, C. Brenner, C. Defanti, M. Koutsoubis, L. Wilson, K. Perlin, et al. Urbanrama: Navigating cities in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 2021.

[8] V. Chheang, F. Heinrich, F. Joeres, P. Saalfeld, B. Preim, and C. Hansen. Group wim: A group navigation technique for collaborative virtual reality environments. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 556–557, 2022. doi: 10.1109/VRW55335.2022.00129

[9] L. Chittaro, V. K. Gatla, and S. Venkataraman. The interactive 3d breakaway map: A navigation and examination aid for multi-floor 3d worlds. In *2005 International Conference on Cyberworlds (CW'05)*, pp. 8–pp. IEEE, 2005.

[10] D. Coffey, N. Malbraaten, T. Le, I. Borazjani, F. Sotiropoulos, and D. F. Keefe. Slice wim: a multi-surface, multi-touch interface for overview+ detail exploration of volume datasets in virtual reality. In *Symposium on Interactive 3D Graphics and Games*, pp. 191–198, 2011.

[11] D. Coffey, N. Malbraaten, T. B. Le, I. Borazjani, F. Sotiropoulos, A. G. Erdman, and D. F. Keefe. Interactive slice wim: Navigating and interrogating volume data sets using a multisurface, multitouch vr interface. *IEEE Transactions on Visualization and Computer Graphics*, 18(10):1614–1626, 2011.

[12] M. Cordeil, T. Dwyer, K. Klein, B. Laha, K. Marriott, and B. H. Thomas. Immersive collaborative analysis of network connectivity: Cave-style or head-mounted display? *IEEE transactions on visualization and computer graphics*, 23(1):441–450, 2016.

[13] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti. Surround-screen projection-based virtual reality: the design and implementation of the cave. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pp. 135–142, 1993.

[14] K. Danyluk, B. Ens, B. Jenny, and W. Willett. A design space exploration of worlds in miniature. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–15, 2021.

[15] G. Djorgovski, P. Hut, R. Knop, G. Longo, S. McMillan, E. Vesperini, C. Donalek, M. Graham, A. Mahabal, F. Sauer, C. White, and C. Lopes. The mica experiment: Astrophysics in virtual worlds. 01 2013.

[16] T. J. Dodds and R. A. Ruddle. Using teleporting, awareness and multiple views to improve teamwork in collaborative virtual environments. In *Virtual Environments 2008*, pp. 81–88. Eurographics Association, 2008.

[17] C. Donalek, S. G. Djorgovski, A. Cioc, A. Wang, J. Zhang, E. Lawler, S. Yeh, A. Mahabal, M. Graham, A. Drake, et al. Immersive and collaborative data visualization using virtual reality platforms. In *2014 IEEE International Conference on Big Data (Big Data)*, pp. 609–614. IEEE, 2014.

[18] C. Donalek, S. G. Djorgovski, A. Cioc, A. Wang, J. Zhang, E. Lawler, S. Yeh, A. Mahabal, M. Graham, A. Drake, et al. Immersive and collaborative data visualization using virtual reality platforms. In *2014 IEEE International Conference on Big Data (Big Data)*, pp. 609–614. IEEE, 2014.

[19] T. Drey. Data visualisation using augmented reality with a focus set on head mounted displays and collaborative tasks. 2018.

[20] A. Febretti, A. Nishimoto, T. Thigpen, J. Talandis, L. Long, J. Pirtle, T. Peterka, A. Verlo, M. Brown, D. Plepys, et al. Cave2: a hybrid reality environment for immersive simulation and information analysis. In *The Engineering Reality of Virtual Reality 2013*, vol. 8649, pp. 9–20. SPIE, 2013.

[21] G. Ferrand, J. English, and P. Irani. 3d visualization of astronomy data cubes using immersive displays. *arXiv preprint arXiv:1607.08874*, 2016.

[22] A. Fonnet and Y. Prie. Survey of immersive analytics. *IEEE transactions on visualization and computer graphics*, 27(3):2101–2122, 2019.

[23] M. Fraser, S. Benford, J. Hindmarsh, and C. Heath. Supporting awareness and interaction through collaborative virtual interfaces. In *Proceedings of the 12th annual ACM symposium on User interface software and technology*, pp. 27–36, 1999.

[24] C. Hull and W. Willett. Building with data: Architectural models as inspiration for data physicalization. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 1217–1264, 2017.

[25] P. Isenberg, N. Elmqvist, J. Scholtz, D. Cernea, K.-L. Ma, and H. Hagen. Collaborative visualization: Definition, challenges, and research agenda. *Information Visualization*, 10(4):310–326, 2011.

[26] W. Krüger, C.-A. Bohn, B. Fröhlich, H. Schüth, W. Strauss, and G. Wesche. The responsive workbench: A virtual work environment. *Computer*, 28(07):42–48, 1995.

[27] G. . i. e. j. Kurillo and M. Forte. Telearch–integrated visual simulation environment for collaborative virtual archaeology. *Mediterranean Archaeology and Archaeometry*, 12(1):11–20, 2012.

[28] D. Kutak, M. N. Selzer, J. Byska, M. L. Ganuza, I. Barisic, B. Kozlikova, and H. Miao. Vivern a virtual environment for multiscale visualization and modeling of dna nanostructures. *IEEE Transactions on Visualization and Computer Graphics*, 2021.

[29] B. Lee, X. Hu, M. Cordeil, A. Prouzeau, B. Jenny, and T. Dwyer. Shared surfaces and spaces: Collaborative data visualisation in a co-located immersive environment. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1171–1181, 2020.

[30] Y. Li, C.-W. Fu, and A. Hanson. Scalable wim: Effective exploration in large-scale astrophysical environments. *IEEE Transactions on Visualization and Computer Graphics*, 12(5):1005–1012, 2006.

[31] J.-C. Lombardo. A virtual reality environment for macromolecules exploration. In *Proc. Laval virtual, First International Virtual Reality meeting*, pp. 1–10. Citeseer, 1999.

[32] P. Lubos, R. Beimler, M. Lammers, and F. Steinicke. Touching the cloud: Bimanual annotation of immersive point clouds. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 191–192. IEEE, 2014.

[33] G. E. Marai, A. G. Forbes, and A. Johnson. Interdisciplinary immersive analytics at the electronic visualization laboratory: Lessons learned and upcoming challenges. In *2016 Workshop on Immersive Analytics (IA)*, pp. 54–59. IEEE, 2016.

[34] T. T. H. Nguyen and T. Duval. A survey of communication and awareness in collaborative virtual environments. In *2014 International Workshop on Collaborative Virtual Environments (3DCVE)*, pp. 1–8. IEEE, 2014.

[35] S. Orlando, I. Pillitteri, F. Bocchino, L. Daricello, and L. Leonardi. 3dmap-vr, a project to visualize 3-dimensional models of astrophysical phenomena in virtual reality. *arXiv preprint arXiv:1912.02649*, 2019.

[36] D. J. Quam, T. J. Gundert, L. Ellwein, C. E. Larkee, P. Hayden, R. Q. Migrino, H. Otake, and J. F. LaDisa Jr. Immersive visualization for enhanced computational fluid dynamics analysis. *Journal of Biomechanical Engineering*, 137(3):031004, 2015.

[37] A. Stafford, W. Piekarski, and B. H. Thomas. Implementation of god-like interaction techniques for supporting collaboration between outdoor ar and indoor tabletop users. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality*, pp. 165–172. IEEE, 2006.

[38] R. Stoakley, M. J. Conway, and R. Pausch. Virtual reality on a wim: interactive worlds in miniature. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 265–272, 1995.

[39] S. van den Elzen and J. J. van Wijk. Small multiples, large singles: A new approach for visual data exploration. *Computer Graphics Forum*, 32(3pt2):191–200, 2013. doi: 10.1111/cgf.12106

[40] E. Vote, D. A. Feliz, D. H. Laidlaw, and M. S. Joukowsky. Discovering petra: Archaeological analysis in vr. *IEEE Computer Graphics and Applications*, 22(5):38–50, 2002.

[41] S. Wang, D. Zhu, H. Yu, and Y. Wu. Immersive wysiwyg (what you see is what you get) volume visualization. In *2020 IEEE Pacific Visualization Symposium (PacificVis)*, pp. 166–170. IEEE, 2020.

[42] C. A. Wingrave, Y. Haciahmetoglu, and D. A. Bowman. Overcoming world in miniature limitations by a scaled and scrolling wim. In *3D User Interfaces (3DUI'06)*, pp. 11–16. IEEE, 2006.