X-Space: A Tool for Extending Mixed Reality Space from Web2D Visualization Anywhere

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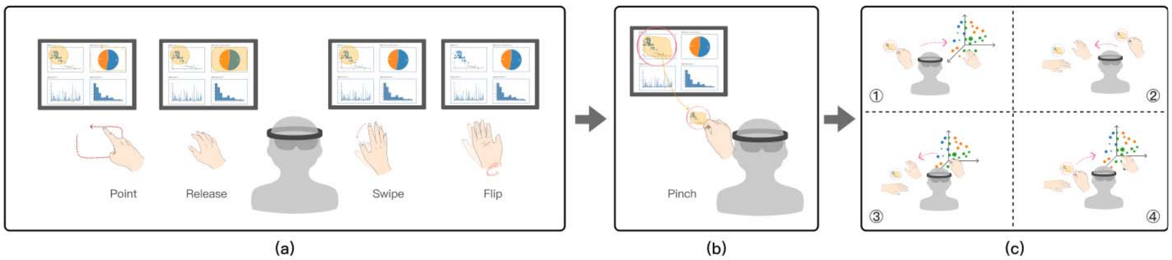

Figure 1: X-Space interaction stage. (a) 2D visualization selection, (b) Visualization data transfer, (c) ① Convert 2D visualization data into 3D visualization, ② Store 2D visual data to data storage box, ③ and ④ are the conversion of visualization data in 3D visualization and data storage box respectively.

Abstract

Mixed reality provides a greater visualization space and more intuitive means of interaction for data exploration. Numbers of works have focused on combining 2D visualizations with mixed reality. However, for a 2D visualization, it needs to implement a mixed reality 3D space on its own, and it is a challenge to build a mixed reality space for 2D visualization conveniently. Furthermore, it is also a challenge to provide mixed reality 3D space for many existing Web-based 2D visualizations. This paper presents X-Space, a tool based on HoloLens and Web bookmarks. It can extend Web2D visualizations into mixed reality 3D space anywhere and anytime. X-Space captures data bound in 2D visualizations, deconstructs them into a data stream, and then transfers them to mixed reality 3D space by freehand interaction. In addition, we equipped X-Space with a data API for existing tools for constructing 3D visualization. We show a series of cases to demonstrate the capabilities of X-Space. In the end, we discussed the current limitations of X-Space and future work.

Index Terms: Immersive and Virtual Environments; Mobile and Ubiquitous Visualization; Visualization System and Toolkit Design; Human-Computer Interaction; Manipulation and Deformation

1 Introduction

Multi-source mixed reality visualization is a visualization method that combines a 2D plane and immersive visualization. The Web is currently the leading platform for building and sharing 2D plane visualizations. As one of the most popular visualization toolkits, D3 [3] is widely used to create visualizations. The visualization community makes D3 visualizations to share interesting data information. And media workers use D3 visualizations to publish news. Compared to Web visualization, immersive visualization provides depth to show an additional abstract dimension. [11] [23] found benefits in using 3D scatter plots to understand multidimensional data structures. Immersive visualization also provides infinite 3D space, which allows users to freely arrange their views to think [4] [1]. Many studies have shown that users prefer 3D representations, even if they don't help with tasks[6]. MR technology brings more opportunities for immersive visualization. MR integrates virtual information with the natural world to ensure the current working habits of users [21], and can seamlessly integrate other surface devices [34] [16].

However, hybrid visualization systems are high-cost to build for three reasons. First, Web development and AR development are two different technical solutions that need to develop a diverse background to transmit data. Second, each hybrid visualization system is an independent application. The construction process is laborious and not reusable. Most importantly, for published Web2D visualizations, there is a lack of mixed reality 3D space extension tools that are reconfigurable and reusable.

In this paper, we implemented X-Space, a tool that can extend the mixed reality 3D space for Web2D visualization anytime and anywhere. The capabilities of X-Space are twofold. Firstly, it directly extends mixed reality to existing Web visualizations. The second is to provide a unified data transfer framework, so there is no need to customize the data transfer scheme for each 2D visualization.

The contribution of this paper is mainly in the following three aspects:

- A visualization method is proposed to expand mixed space anytime and anywhere.
- A tool X-Space, which can quickly transfer visualization running on the Web to 3D space;
- A set of freehand interactive methods for transferring data from 2D to 3D, helping users complete the data transfer process intuitively and naturally.

2 Related work

Our work involves data acquisition for Web-based visualization, mixed reality visualization for multi-source fusion, and freehand interaction.

2.1 Visualization data extraction

Web-based visualization can be divided into bitmap images and SVG-based technology. The most common approach for bitmap

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images is using computer vision and machine learning to extract the data. These technologies [13] [25] first extract image markers from images and then classify images according to these features. In Revision [28], graphic markers are further extracted from the classified images, and visualization data are provided. However, Revision has an accuracy rate of only 38% to 53%. The semi-automatic interactive method is adopted in ChartSense [15], which uses an interactive data extraction algorithm for the recognized chart type. ChartSense improves data accuracy to a certain extent. Recently, Zhang et al. [33] proposed Viscode to achieve high-precision data extraction. VisCode implicitly binds data to visualization and transfers data through a network of encoders and decoders.

For visualizations based on SVG technology, Interaction+ [19] extracts visual information (e.g., visual objects and visual mappings, etc.) from a visualization, providing a suite of interactions for users to facilitate the visual exploration. But it doesn't extract the underlying data bound to the visualization. The D3 deconstruction [12] approach proposed by Harper et al. allows the user to capture the underlying data of the D3 visualization and infer the data table structure. Our work adopts the data deconstruction work of Harper et al. Instead of modifying the D3 visualization style, and we integrate 3D space for D3 visualization through data transfer.

2.2 Combination of mixed reality and screen space

Due to the benefits of immersive visualization [23] [1], researchers are beginning to combine mixed reality environments with screen space to benefit from both. [20] [31] et al. have confirmed that mixed reality space can significantly increase users' ability to understand data. To better interact with the mixed space, researchers further explored the design space when the screen space of different flat devices such as mobile phones [34], tablets [16], and large screens [27] is integrated with the mixed reality environment.

However, due to the limitations of different technical solutions on the Web and mixed reality, the construction process of mixed space is difficult. Butcher et al. [5] came up with VRIA for creating immersive visualizations. VRIA is a Web-based framework that unifies visualization development on the Web and mixed reality. Chen et al. [8] adopted another method. They propose an authoring environment that seamlessly integrates design and deployment workflows to extend virtual content for static visualization. However, these methods require users to build a hybrid spatial visualization from scratch and do not apply to existing Web-based visualization.

A work with the same idea as this paper is that Araújo et al. [9] extracted data from bitmaps in the real world and reproduced the original visualization in mixed reality environment. Compared to their work, we offer a bridge to the architecture of mixed reality 3D visualization space. This provides users 3D tools to explore 2D visualizations freely.

2.3 Freehand interaction across devices

Freehand interaction can support seamless integration of multiple devices as a natural, intuitive and effective means of interaction. Chen et al. [7] proposed AirLink to realize file sharing among multiple mobile phones using hand movement. Users can transfer files between devices simply by waving from one device to another. MyoShare, implemented by Geronimo et al. [10], associates the gesture wave in a specific direction with the corresponding device for data sharing. Paay et al. [24] investigated four common gestures for information transfer between handheld and big-screen devices: pinching, swiping, swinging, and flicking. The results showed that one-handed and two-handed interaction did not affect task completion. The key that they suggest is that the selection gesture does not cause the pointing gesture to move during the selection part of the interaction.

In the process of combining screen space with mixed reality space, researchers often use a Pinch gesture to achieve data sharing across devices [34] [14] [26]. Wu et al. [32] also proposed a novel gesture interaction strategy that utilizes the existing physical support and space of everyday objects for intuitive interaction. They use metaphors in mixed reality and externalize abstract processes to facilitate interactive processes. These freehand interaction schemes across devices guide our data transfer gesture schemes.

3 X-Space System Design

3.1 Architecture and Pipeline

We created X-Space, a tool to help users quickly transfer 2D visualizations into 3D Space. X-Space aims to (1) help users deconstruct Web-based visualizations; (2) realize the natural and easy switch of visualization data from 2D to 3D space; (3) provide a mixed reality visualization 3D space.

As shown in Figure 2, X-Space consists of a Bookmarklet tool on a Web client, a HoloLens application on a mixed reality client, and a mobile server. It uses a client-server architecture. The mobile server is responsible for transferring information between client devices. While the Bookmarklet tool is accountable for deconstructing 2D visualization data, the HoloLens application serves as an interface for freehand interaction input and a vehicle for 3D visualization space.

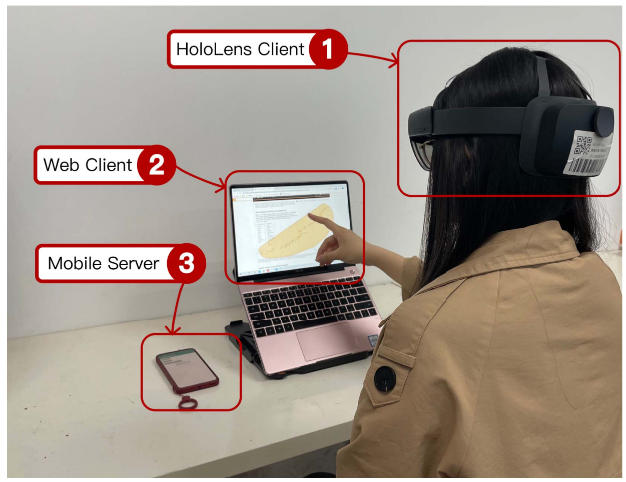

Figure 2: X-Space component.① HoloLens client is an interface for freehand interactive input and a carrier for 3D visualization, ② Web client is responsible for deconstructing 2D visualization, and ③ Moblie server transfers information between client devices.

The pipeline of X-Space is shown in Figure 3. Users first have to wear the Hololens device, install the Bookmarklet tool in the browser, complete 2D and 3D space calibration, and open the mobile server. When he finds an interesting visualization on a Web page and wants to explore it further in 3D space, he can select the visualization area using the freehand interaction of the HoloLens application. During the selection process, the HoloLens application sends the selection range data to the server in real-time. The server transmits the selected range to the Web, and the Bookmarklet tool activates the selected range within the Web page. Upon receiving a request from the server to transfer data, the Bookmarklet tool deconstructs visualization data within the selected area and sends it back to the server. HoloLens application receives the visualization data forwarded by the server and then renders and manipulates it in 3D space.

The initial input is a D3 visualization on the Web page during the entire data transfer process. Users complete the whole interaction process through freehand interaction. X-Space deconstructs and transmits data in the background. For final output, X-Space provides both a data ball and a visualization. This depends on the purpose of

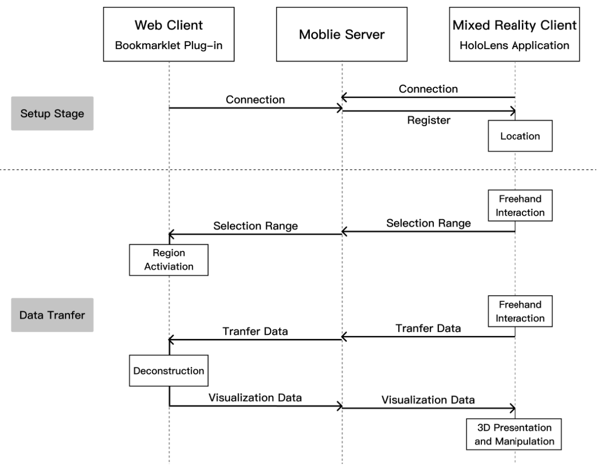

Figure 3: X-Space pipeline. In the setup phase, the user first opens the Web client and HoloLens client to establish a connection with the server. And HoloLens device is used to locate the Web client. Then it's time for the formal visualization transition. The Web client deconstructs the visualization according to the selection range from the HoloLens client and passes it back to the HoloLens client after receiving the transfer instruction.

users' interaction. On the one hand, when users need to observe the visualization in 3D space, the visualization data will be presented as an immersive visualization. On the other hand, when users need to store data temporarily, the visualization data will be presented as data balls. We provide data interfaces for various 3D information visualization building tools, and in this paper, we use DXR [29] as an example tool.

3.2 HoloLens Application (Mixed Reality Client)

The mixed reality client uses the HoloLens2 headset from Microsoft, which provides an excellent immersive experience. We use Unity 2019.4.8f1 for the HoloLens application.

Setup Stage: We use the ClientWebSocket class wrapped in c# to communicate with the server. Data is serialized and deserialized using the Newtonsoft library. HoloLens application then uses the Vuforia plug-in to locate the flat device. We assume that the flat device is in a fixed position. After Vuforia recognized the featured graph on the flat device, we placed a transparent object the same size as the screen. This defines spatial coordinates for screen space, which are used to realize coordinate conversion between screen space and mixed reality space.

Object manipulation: We set different object manipulation methods for the plug-in in 2D and 3D space. Objects in 3D space have independent 3D space morphology, so we allow direct manipulation. But for content in 2D space, we need to use the ray emitted between the eye and index finger to select regions.

Gesture recognition: HoloLens application provides static and dynamic gestures, as shown in Figure 4. The HoloLens application uses data about the position and rotation of hand joints to define these gestures. Static gestures have significant hand common characteristics, so the calculation of the distance between the joints of the hand is used for recognition. Dynamic gestures are the movement of the hand in a short period, and we employ start gestures and time variables to identify them. HoloLens recognizes the start gesture and determines whether the user has completed the corresponding hand movement within a certain period. If so, the dynamic gesture is activated.

Data storage: HoloLens application saves received visualization data as a local data JSON file, which is then presented to the user in

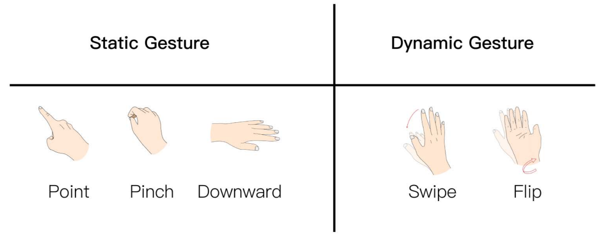

Figure 4: X-Space gestures. Static gestures include Point, Pinch, and Downward. Dynamic gestures include Swipe and Flip.

3D space as a data ball or an immersive visual form.

We pre-defined prefabs of 3D spatial objects in the HoloLens application. The data ball consists of an outer transparent light sphere and an inner image file. The visualizations use a DXR prefab made by Ronell et al.., which is a 3D construction tool that users can choose from. DXR is implemented by a syntax similar to Vega-Lite. It provides the basic visualization model. DXR prefab generates the corresponding visualization by reading local data files.

3.3 Bookmarklet Tool (Web Client)

The Bookmarklet tool works as a bookmark for the browser. It is a piece of code that starts with "javascript:". When clicked, it does something to the current page. We've packaged the functionality of the X-Space Web client into the Bookmarklet tool (Figure 5).

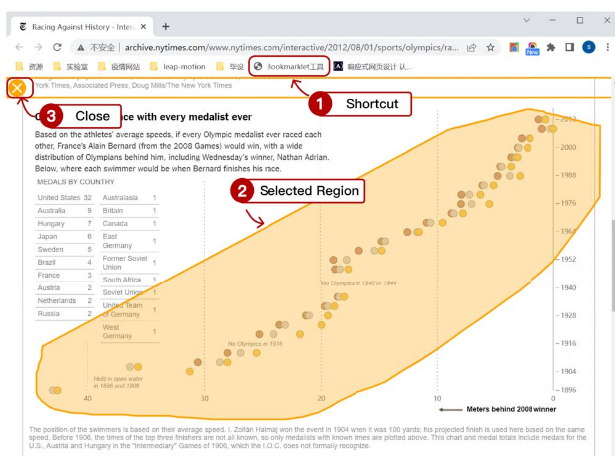

Figure 5: Bookmarklet tool interface. ① is a shortcut to the bookmark tool, ② is the visualization range selected by the user on the Web, and ③ is Used to exit the bookmark tool.

Setup Stage: Bookmarklet tool uses WebSocket objects to communicate with the server. The user instantiates a WebSocket object by entering the server IP when activating it. Then a featured image is loaded in the upper left corner of the Web page to identify flat devices. After the device is successfully identified, the Bookmarklet tool initializes a global object to record the visualization selection range, updating it based on the messages received from the server.

Region selection: When the user selects a visualization region, the Bookmarklet tool will add/remove the corresponding region track on the Web page in real-time. At the same time, if the Web page slides, the track position added in the Web page also needs to move the corresponding distance.

Data extraction: When the user transfers data, bookmarklet tool first retrieves visualization data within the selected region and then deconstructs it for transfer.

Specifically, the Bookmarklet tool first iterates through the DOM subtree to select all SVG nodes and extracts candidate SVG nodes that overlap with the selected region. Then the visual elements in candidate SVG nodes are traversed successively to determine whether their center position is in the selected region. Note that you need to restore the correct global location for embedded Web pages. Then we extract the visualization underlying data and image information of the selected region for transfer.

We use the method of Harper et al. to extract the underlying data of 2D visualization. Harper et al. took advantage of the D3 library, which binds data to element nodes. They retrieve the data and infer the data table by analyzing_data_ attribute of element nodes in visualization. But unlike the Chrome plug-in implemented by Harper et al., our Bookmarklet tool is more compatible and can be used across multiple browser platforms.

The html2canvas library intercepted visualization image data. We generate an image of the entire Web page, retrieve the visualization location of the selected area, and then crop that content across the whole page. Bookmarklet tool retrieves the image information and uses BAES64 encoding for data transfer.

3.4 Communication module design

X-Space server is an Android application developed in Java and installed on users' mobile phones. The mobile server uses Websocket protocol to realize real-time and bidirectional data transmission. Client instances of WebSocket are initialized to receive and send data on both Web and mixed reality clients. During the whole communication process, data is transmitted as a JSON file.

The mixed reality client sends gesture interaction data to the server. As shown in figure 6 left, gesture event data contains two types of information. GestureType indicates the type of gesture representing a specific interaction. GesturePosition records the screen space position when the gesture is operating.

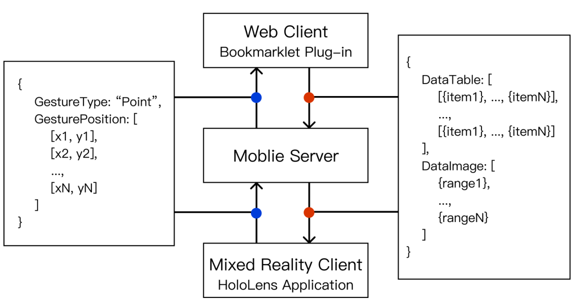

Figure 6: The data structure of the transmission. The HoloLens client sends interactive gesture data to the Web client, and the Web client sends visualization data to the HoloLens client.

The web client sends visualization data to the server. As figure 6 shows, the visualization data contains two types of information. DataImage stores the image information of 2D visualization data slices, and DataTable stores the data information bound to 2D visualization.

During communication, the mobile server only forwards data without any processing. The whole communication framework supports work in LAN and mobile hotspot network environments, ensuring that users can complete the data transfer work in various settings.

4 Interaction Design

The interaction design of X-Space follows the principle of reality-based interaction. It uses freehand gestures close to natural operation for visualization data transfer and manipulation to ensure the semantic and intuitive sense of interaction. As shown in figure 1, the whole interactive process can be divided into three stages : (1) 2D visualization selection, (2) Visualization data transfer, (3)Data storage box, and 3D visualization.

4.1 2D visualization selection

We treat a 2D screen as a canvas in 3D space, in which users can manipulate visualizations they are interested in as interactive objects.

Figure 7: Select 2D Visualization.The Point gesture activates the selection, and the Release gesture ends the selection.

Select 2D Visualization: Based on the brush + canvas metaphor, X-Space uses the "Point" gesture to point to the screen for selection. We provide visual feedback by highlighting selection areas most commonly used in 2D. When multiple objects are consecutively on canvas, we keep previously selected objects. Users can choose consecutively numerous visualizations or parts of a visualization (See Figure 7).

Remove 2D Visualization: X-Space removes the last selected area using the "Swipe" gesture with the eraser metaphor. The web client will remove the corresponding region trace(See Figure 8 left). X-Space allows the user to reset the state when objects on the screen become too cluttered. Similar to the canvas page-turning behavior, we introduced the "Flip" gesture to clear all selected regions on the screen(See Figure 8, right).

Figure 8: Remove 2D Visualization. The Swipe gesture clears the previous one, and the Flip gesture clears all selections.

4.2 Visualization data transfer

Visualization transfer is the process of 2D visualization to 3D space. We use the classic "Pinch" gesture to grab 2D visualizations(See Figure 1(b)). X-Space uses a transition animation to help users understand the process. During data transfer, X-Space first generates a red sphere of energy around 2D visualization. This wraps 2D visualization into a data ball to lock the user's interaction object. The data ball then moves autonomically to the user's interactive position, where the "Pinch" gesture interacts directly with 3D spatial objects. The data ball follows the user's hand until the user exits the "Pinch" gesture.

3D space data ball consists of two layers(See Figure 9): the inner layer is a selected visualization image, and the outer layer is a glowing spherical outline. The color of the spherical outline indicates the operating state of the 3D visualization object, as shown in figure 9. The Data ball contains context information of the selected area in 2D visualization, which can quickly wake up the memory of the selected visualization.

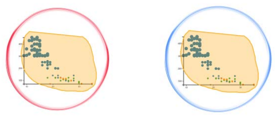

Figure 9: Data ball consists of an outer aperture and an inner picture file. The data ball on the left is active.

4.3 Data storage box and 3D visualization

X-Space provides a data storage box, allowing users to store visualization data that they don't need to explore at the moment. In the data storage box, visualization data is stored in the form of data balls to improve user understanding.

We use the drawer metaphor for the data storage box. X-Space uses a downward flip of the non-dominant hand (" Downward "gesture) to open the data storage box. As shown in Figure 1(c), the data storage box sits above and follows a non-dominant hand. When the user exits the Pinch gesture under the "Downward" gesture, visualization data enters the data storage box to form a data ball. The data balls are stored in a data storage box by spreading out layer by layer.

Users can directly save visualization data into the data storage box after selecting 2D visualization or select visualization in 3D space to save into the data storage box. Conversely, the user can also choose the data ball in the data storage box to generate a 3D visualization. 3D visualizations and data balls of 3D space can be converted into each other.

5 Use Cases

Figure 10-15 shows that we use X-Space to extract 2D visualizations from multiple sources and forms. Examples include scattering charts, thematic river charts, stack bar diagrams, bubble word clouds, heat maps, pie charts, etc. We extract and deconstruct the data bound in 2D visualization into 3D space. In 3D space, we use the DXR construction tool to generate a visual view directly. In this process, the user can select any dimension in the extracted data table for free mapping. 3D visualization dimensions in the following cases result from a free choice.

New York Times Chart (Figure 10). The initial visualization shows the distance relative to the finish line of each Olympic medalist in the men's 100m freestyle from 1896 to 2012 when France's Alain Bernard reached the finish line. Color maps the medal category. We transfer the entire visualization to 3D space and use the depth of 3D space to map categories of medals redundantly, thus reducing the occlusion of scattered points. We also changed the mark from a scatter to a bar, to show how far runners have to go. Original visualization from The New York Times [6].

Theme river map (Figure 11). The initial visualization shows the change of keywords from New York Times and Dynamic Topic Modelling when "climate change" and "global warming" are discussed. We move the visualization into 3D space in the form of a 3D scatter plot. XY axis mapping dimension is unchanged. Depth maps keywords and scatters height maps keyword proportion. Original visualization by Natemiller [22].

Stack bar diagram (Figure 12). The initial stacked bar chart shows the number of suicides in different Indian provinces from 2001 to 2013. We moved the visualization to 3D space in the form of space-time cubes. Depth maps time information. The height and size of the cube map the number of suicides. Original visualization by Vinod Louis [18].

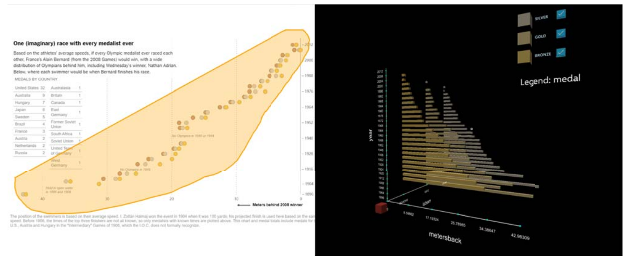

Figure 10: New York Times Chart (ScatterPlot Chart) data transfer.

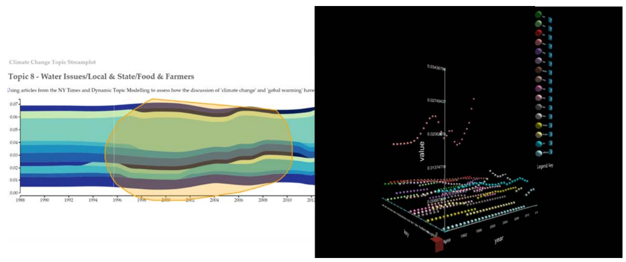

Figure 11: Theme river map data transfer.

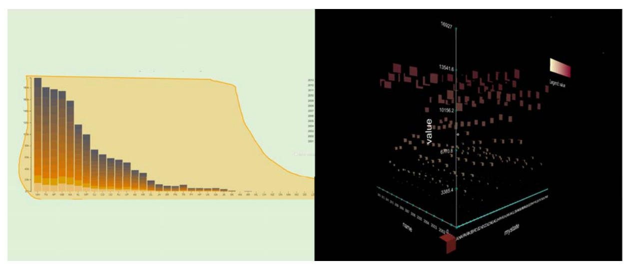

Figure 12: Stack bar diagram data transfer.

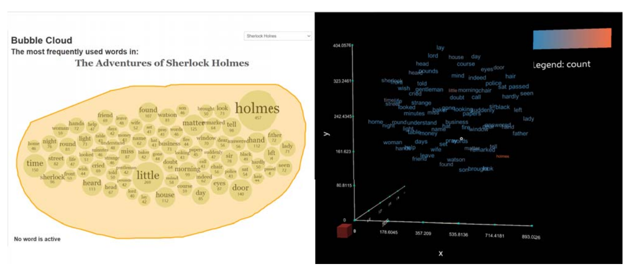

Figure 13: Bubble word cloud data transfer.

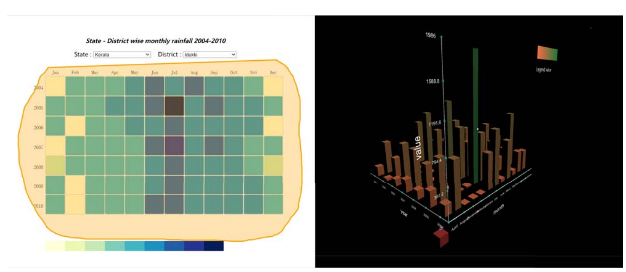

Figure 14: Heat map data transfer.

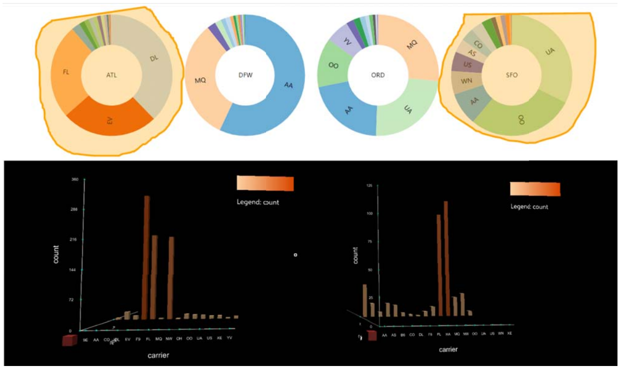

Figure 15: Pie chart data transfer.

Bubble word cloud (Figure 13). The initial visualization shows words that appear most frequently in Sherlock Holmes. We move visualization to 3D space. 3D space follows the 2D space layout in the XY plane. Depth and color map word frequency. Original visualization by Jim Vallandingham [30].

Heat map (Figure 14). The original visualization shows changes in precipitation in a region of India from 2004 to 2010. We move it into 3D space, which is added height to map precipitation based on 2D visualization—original visualization by Vinod Louis [17].

Pie chart (Figure 15). The initial nested pie charts show the number of flights by different airlines at four airports. Users can select the data they are interested in transferring. The 3D space generates a corresponding number of bar charts—original visualization by Mike Bostock [2].

6 Discussion

X-Space can successfully transfer 2D visualization data from the Web to 3D Space. Users can directly transfer visualizations shared by other users on the Web and visualizations built by themselves. X-Space integrates 3D analysis space for users to explore data on the Web. In this section. We discussed the limits of X-Space and future work.

6.1 Limitation of X-Space

Flat device recognition: X-Space uses fixed flat device positions, which does not affect fixed display devices such as large screens and desktops. But this can cause problems when users need to move flat devices. Because flat devices need to be repositioned every time after being moved, this interrupts user interaction. One possible solution is to use the spatial recognition capabilities of HoloLens to locate flat device movements in real-time.

Freehand gesture design: Based on the naturalness of gestures, X-Space uses a set of metaphor-based gestures to complete data transfer. We also look forward to conducting formal user experiments to evaluate the usability of this gesture interaction scheme or to obtain more gestures for data transfer interaction through heuristic design methods.

Visualization data extraction: At present, X-Space can complete the data deconstruction work of D3 visualization. X-Space cannot handle visualizations that also use SVG but do not bind data, such as infographics. The interaction provided in Interaction+ leverages visual information of visualization, which inspired the idea of transferring visual information of visualization. Furthermore, data extraction needs to apply computer vision techniques for a visualization based on Canvas technology. Previous work has used machine recognition techniques to analyze classical visualization models and extract data objects.

2D and 3D visualization styles: In the current 3D visualization generated by X-space, users need to use DXR's interaction panel to create different visualizations for data exploration. Then we can consider combining the view features of 2D visualization to provide reference suggestions for the visualization transferred to 3D space. For example, the scatter matrix diagram with clustering features can be transferred to 3D space and explored as a spatial scatter diagram. Furthermore, the design space of visualization transfer can be studied to seek the potential mapping relationship between 2D and 3D visualization.

User experimental evaluation: In Use Cases, we demonstrate the capabilities of X-Space by transferring multiple 2D visualizations. However, there is a lack of formal user experiments to determine whether the user's expectations are being met. We look forward to conducting formal user experiments to evaluate the effectiveness and usability of the overall visualization transfer process.

6.2 Future Work

Multi-device, multi-person collaboration: Visualization of complex, intensive data requires a team and cross-device capabilities. X-Space currently works in the context of visualization data transfer from single-user flat devices to mixed-space devices. The realization of data-free transfer requires further consideration of data transfer objects. Analyzing the device space (2D/3D) and users (single user/group user) of the data transfer object enables visualization data to be interconnected and shared among the users and devices.

Compatibility of 3D visual construction tools: We have configured the data interface of 3D visualization construction for X-Space so that it can connect with various 3D visualization construction tools. We will further verify X-Space compatibility in the future. At the same time, we will continue our efforts to package it into a complete toolkit to increase the flexibility of X-Space.

7 Conclusion

We proposed X-Space, a tool for transferring Web-based 2D visualization data to 3D space. It integrates 3D space for 2D visualization with freehand interaction. X-Space consists of a Web client, a mixed reality client, and a server. The server forwards data for the Web client and the mixed reality client. On the Web client, X-Space can currently extract and deconstruct D3 visualization data. On the mixed reality client, X-Space stores visualization data locally and provides an interface for 3D visualization construction tools. X-Space currently renders immersive visualizations through DXR.

Meanwhile, X-Space provides a data storage box for temporary data storage on a mixed reality client. We use a set of examples to demonstrate the capabilities of X-Space. Finally, we discussed the limitations and future work.

Acknowledgments

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