Synthetic Visualizations in Web-based Mixed Reality

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ABSTRACT

The way we interact with computers is constantly evolving, with technologies like Mixed/Augmented Reality (MR/AR) and the Internet of Things (IoT) set to change our perception of informational and physical space. In parallel, interest for interacting with data in new ways is driving the investigation of the synergy of these domains with data visualization. We are seeking new ways to contextualize, visualize, interact-with and interpret our data. In this paper we present the notion of *Synthetic Visualizations*, which enable us to visualize *in situ*, data embedded in physical objects, using MR. We use a combination of established 'markers', such as Quick Response Codes (QR Codes) and Augmented Reality Markers (AR Markers), not only to register objects in physical space, but also to contain data to be visualized, and interchange the type of visualization to be used. We visualize said data in Mixed Reality (MR), using emerging web-technologies and open-standards.

Keywords: Immersive Analytics, Mixed/Augmented Reality

Index Terms: H.5.2 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities.

1 INTRODUCTION

Researchers, developers and technology enthusiasts strive to develop new ways to make sense of our data, as the latter becomes more pervasive in our lives. There are many opportunities that are now becoming possible because of recent technological advances in interface and display technologies. In particular, through the advent of the smartphone and powerful tablets, technologies such as Virtual Reality (VR) and MR/AR have become more accessible, personalised and allow new forms of interaction [2]. Researchers are, gradually, taking steps away from the desktop environment into a MR world of ubiquitous, data-driven information [22]. A vision of this MR world is portrayed by Vernor Vinge, in *Rainbows End* [24], where almost every object is networked, humans are wearing context-aware clothing and mediated-reality technology is everywhere.

MR as a data-investigation and sense-making environment presents an interesting prospect. Contrary to VR, MR allows data to be placed *in situ* into the physical world, while the latter is still perceivable, adding context and meaning, both to the data itself but also to the analytical and sense-making process. Barba et al. [2] and Roberts et al. [22] revisit the definitions of MR, by Milgram and Kishino [18], and Augmented Reality (AR) by Azuma [1], and discuss the evolution of these domains, which began as a collection of display and graphics technologies and has evolved in a hybrid notion, bringing together the concepts of '*perception*', '*place*' and '*capabilities*'. Like Roberts et al. [22], we also believe that this expanded version of perceptualization will be intrinsic to the future manifestation of visualization.

For this work though, we draw inspiration from a less popular definition of AR, from Mackay [17], which extends the aforementioned ones. Mackay focuses on user experience and describes a notion of augmenting the environment through interactive, networked objects, approaching Weiser's [25] notion of Ubiquitous Computing, often regarded as the antithesis of VR. We also look into the emergence of the Web, especially mobile, as the de-facto interconnecting platform that has the potential to make Weiser's vision possible. Our motivation is shared by Elmqvist and Irani [8] who describe the notion of ubiquitous analytics, as an ever-present, always-on computing paradigm for interacting, manipulating, and analyzing data. Inspired from these visions, we investigate ways to synthesize physical artefacts, with data embedded in them, and computer-driven visualizations, in MR. We call these *synthetic visualizations*.

In this paper we present a prototype application based on the notion of embedding interactive, MR visualizations, and data, in physical markers commonly used for MR/AR and quick response. We depict the visualizations *in situ*, using open-standards web-technologies as these: (i) support a variety of popular libraries for data binding and manipulation, such as D3.js, and (ii) allow us to use the Web (including mobile) as deployment platform, thus converging to Weiser's vision of ubiquitous computing. In addition, through web-technologies our depictions are accessible from a variety of interfaces, such as smartphones, Head Mounted Displays (HMDs), etc. Our application can be used to embed data in physical objects, such as a business card or the cover of a technical report, which can then be placed on physical place-holders, such as a desktop mat, which in turn determine the type of *in situ* visualization of said data.

The structure of the paper is as follows: In Section 2 we review related work and highlight our motivation and inspiration for some of our design and implementation decisions. In Section 3 we present our prototype application, detailing marker design, data binding and visualization depiction. In Section 4 we discuss future work and ideas, and in Section 5 we conclude.

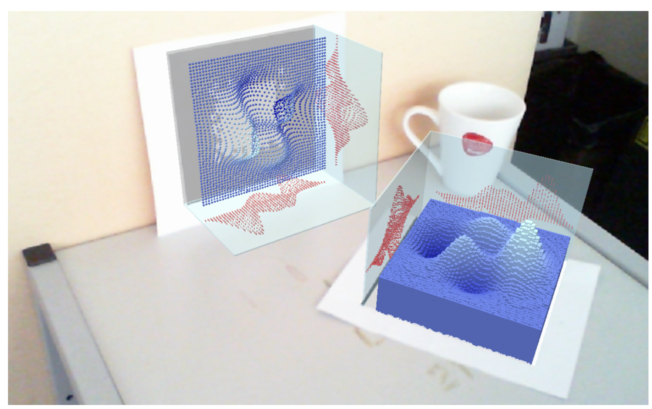

Figure 1: Exploring synthetic visualizations in MR. Our prototype uses popular MR tracking mechanisms, QR-codes, open-standards web technologies and D3.js.

2 RELATED WORK

Our review of related work for this research is twofold: (i) we look into the theme of immersive analytics, as the emerging domain that investigates the synergy between immersive technologies and data visualization, and (ii) we discuss open-standards Web technologies that enable interoperable MR/AR.

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2.1 Immersive Technologies and Data Visualization

The interest to fuse VR and MR/AR with visualization dates back to the previous decade, e.g., Slay et al. [23] and Casseb et al. [6]. A recent incarnation of this interest is the emerging research theme of Immersive Analytics (IA). IA seeks to investigate the use of novel display and interface technologies in analytical reasoning and decision making [4]. Although the term 'Immersive Analytics' was only recently coined by Chandler et al. [4], fundamental aspects of beyond-the-desktop visualizations have been discussed in a number of publications. For example, Lee et al. [14] discuss post-WIMP (Window-Icon-Mouse-Pointer) interactions, Elmqvist et al. [9] explore fluid, natural interactions for information visualization, Panëels et al. [19] explore haptic data visualizations, Jansen and Dragicevic [12] propose an interaction model for beyond-the desktop and Willet et al. [26] discuss situated data representations.

With regards to immersive technologies, most recent efforts focus on VR systems. Donalek et al. [7] write about "immersive and collaborative data visualization", highlighting that VR opens new avenues for data exploration. Chandler et al. [4] discuss usability issues of immersive environments intended for data analytics, pinpointing the multifaceted nature of the field, bringing together several research communities. Cordeil et al. [5] compare HMD-based and CAVE-style immersive environments, for collaborative analysis of network connectivity. Kwon et al. [13] investigate the use of immersive, 3D visualizations for information visualization, looking into spherical graph layouts, edge bundling and techniques for interactive highlighting. Focusing on MR/AR, ElSayed et al. [10], investigate how to link visual information and objects in physical space using MR, and a model of *"details first, analysis, then context-on-demand"*. Lu et al. [15] review the current state of mobile immersive environments, using VR and AR, that are relevant to the field of big data and data visualization. Luboschik et al. [16] investigate the effect of spatial cues for data visualization, arguing for the need of adaptation of existing, non-data related VR and AR approaches, if these are to be used in data visualization scenarios.

In addition to academic-led approaches, enthusiasts, developers and organisations have explored the notion of IA. Masters of Pie (`www.mastersofpie.com`), a UK-based studio, explores big data visualization in VR with Valve Academic Research Consortium (VARC), which renders data points onto a spiral, arched over the user. VR Nasdaq (`http://graphics.wsj.com/3d-nasdaq/`) uses Three.js an D3.js to present a guided tour of 21 years of the Nasdaq in VR, for Wall Street Journal. Virtualitics (`https://www.virtualitics.com/`) uses Virtual/Augmented Reality (VR/AR) along with machine learning and natural language processing to devise immersive data exploration tools.

2.2 Interoperable MR on the Web

Mackay's [17] vision of an interconnected MR/AR world implies the need for interoperable systems. In the field of MR/AR, there has been significant efforts to promote standardisation towards interoperability [21], endorsed by organisations such as IEEE and W3C. Many of these established and emerging standards are suitable for use on the Web, and therefore fit our motivation and requirements. Likewise, popular toolkits, such as ARToolkit[1] have been ported with an intention to bring their functionality on the Web. These tools enable us to create content for VR and MR with effectively the same mechanisms as non-Web systems. Moreover, these tools are interoperable as they are built to use the HTML DOM. Examples of such toolkits include AWE.js, AR.js (used in this paper) and Argon.js. These libraries provide variation of the same theme — a composite view of the world, with 2D/3D graphics superimposed and anchored on a location (marker-based, geo-located etc.) These toolkits run on browsers that support WebGL and WebRTC. The latter is an open project supported by Google, Mozilla and Opera, that provides browsers and mobile applications with real-time communications (RTC) capabilities. WebRTC essentially provides web pages with plugin-free access to the video stream (amongst other protocols).

As far as 3D graphics on the Web are concerned, the recent popularity of the neighbouring field of VR has had significant impact in the development and constant refinement of suitable tools. Examples of such standards include WebGL, ARML, X3DOM and the more contemporary WebVR. The latter in particular has been a major driver in the development of web frameworks that make use of VR interfaces such as the Oculus Rift, HTC's Vive, and Google's Daydream. In this work we use A-Frame (`https://aframe.io/`), an entity component framework that provides declarative, extensible, and composable structure to Three.js. A-Frame is currently the most powerful way to create WebVR content.

More importantly though, as the aforementioned frameworks make use of the HTML DOM, they have the potential to work seamlessly with already established libraries used in Information Visualization and Visual Analytics. We believe this is a prime opportunity for exploring this synergy, as libraries such as D3.js provide powerful mechanisms for data binding, node manipulation etc., and are familiar to a number of visualization developers. We have already began investigating this potential in VR [3] and we have extended our efforts towards MR/AR [20], as we believe that the combination of powerful visualization libraries, interoperable web-based MR toolkits and the pervasiveness of the Web is the best route towards realizing Mackay's vision.

3 Synthetic Visualizations

In the context of this paper, the purpose of synthetic visualizations in MR is to fuse physical and digital elements into a spatially registered 3D data visualization representation. In broader terms, 2D representations could be also used — e.g., an *in situ* glyph that depicts some information about that particular location. We opt for 3D as these pose challenges and opportunities of their own, such as devising suitable data mappings, or requiring particular interaction mechanisms. Moreover, for synthetic visualizations beyond the flavour presented here, the proportion of physical and digital is very much dependent on the registration mechanics and intended depictions. For example, projection-based systems may work better in 2D, whereas holographic displays are 3D etc.

Our prototype application consists of three sub-components;

i) a Quick Response (QR)-reader, that detects data embedded in the QR Code (ISO/IEC 18004:2015) [11], in the form of JSON or a URL reference to a hosted dataset,

ii) a registration mechanism that uses the AR.js (`https://github.com/jeromeetienne/AR.js`), the Instascan.js (`https://github.com/schmich/instascan`) libraries and modified AR markers (we call them 'ring' markers) to determine the 3D visualization type and spatial placement, through a WebRTC-compliant browser, and

iii) a web-based system that uses D3.js and A-Frame for depicting *in situ* 3D visualizations.

3.1 Composite Markers

We use the composite markers shown in Figure 2 for data inclusion and retrieval, visualization type determination and spatial registration. Different datasets can be visualized by interchanging the QR Code 'data core', whereas different visualizations can be displayed by interchanging the 'ring' marker.

At present, our system is capable of reading two types of QR Codes: an entirely text-based QR Code containing a JSON file, or a URL with the data appended as a query string containing the JSON. Encoding the data directly as a QR Code poses limitations in terms of the size of the data that can be included, dependent on the

[1] See `https://archive.artoolkit.org/` for history, and latest and archived versions.

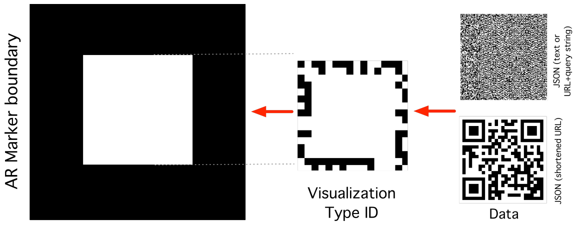


Figure 2: Composition of a Composite Marker with Embedded Data in QR Code format. The Visualization type is encoded in the inner ring of the marker, surrounding the QR-code. Interchanging the visualization ring and the data core allows the rendering of different visualizations and datasets. The QRs in the figure containing 2000 character long URLs with 639 data-points.

version of the QR Code used (1 to v.40). We currently use version 10 (~170 characters with 30% correction capability). Higher versions are also physically larger, posing limitations in marker size that can be practically usable. In the case of embedding a URL in a QR Code, we can link to a MR-viewer page without passing any data, which can then be loaded from the QR Code. Alternatively, data can be passed to the viewer page directly as a query string, appended to the viewer's base URL. In this case, the amount of data that can be passed in a query string is limited due to the maximum length of a URL (~2000 characters, depends on browser).

The MR/AR markers are based on the venerable ARToolkit, whose markers must be square, have a continuous black or white border that is by default 25% as wide as the main marker body's width, and must not be rotationally symmetric. Version 2.x of ARToolkit is using $N \times N$ pattern files as representations of the image in the markers 'core'. Our modified markers are generated in the same fashion as the standard $N \times N$ markers, with the option of removing pixels from the centre of the marker except for an outer X pixel-wide perimeter, where $X > 2$ elements (squares). The $X > 2$ limit is imposed to give pixel-pixel contrast between pixel in both the parallel and perpendicular direction to the nearest edge, and therefore improve registration. Different QR-Codes correspond to different visualization types.

3.2 3D Visualization and Data Mapping in MR

For the 3D graphics we use A-Frame, whereas data binding and manipulation is provided by D3.js. Our prototype is essentially a series of public-facing web pages. Once visited, via a WebRTC compliant browser, and used to scan the aforementioned composite markers, our prototype will superimpose on the composite marker a 3D visualization of the data embedded in the QR 'core'. Each pattern file is effectively matched with an A-Frame element in the DOM, which in turn corresponds to a different 3D visualization. An overview of our prototype is shown in Figure 3.

Once the QR-code is read, the detected data-sets are passed as objects to the data-mapping logic, which is specific for each 3D representation. This initiates the MR/AR functionality of AR.js and renders the 3D depiction in place. We found that the sequence of these actions is essential, as once the tracking mechanisms is initiated the QR Code can not be read. At the moment changing datasets requires a page refresh.

We have devised simple data-mappings for two types of visualizations, a 3D bar chart and a 3D scatter plot. We have experimented with various stylistic differences, including density of the grid, value-projections on side-walls, 3D object coloring based on value (via a D3.js linear scale), different coloring schemes etc. Modifying the visualizations, in terms of aesthetics can be done using A-Frame, whereas for more advanced requirements override calls to Three.js API can be used. At the moment, our interaction with the 3D depictions is limited as we only allow inspection by moving the physical

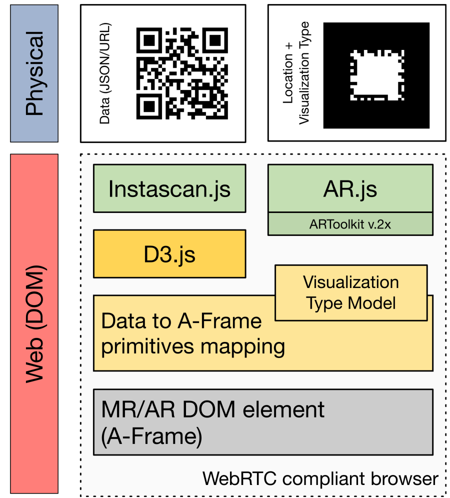


Figure 3: Anatomy of our prototype, bringing together a number of open-standards to provide a web-based, marker-based MR data visualization demonstration in WebRTC compliant browsers. The standard that binds together everything is the HTML DOM.

marker. Nonetheless, by using A-Frame we can use modern HMDs (modified to view the physical world, for MR) and their handheld controllers, to investigate different interactions with data in MR.

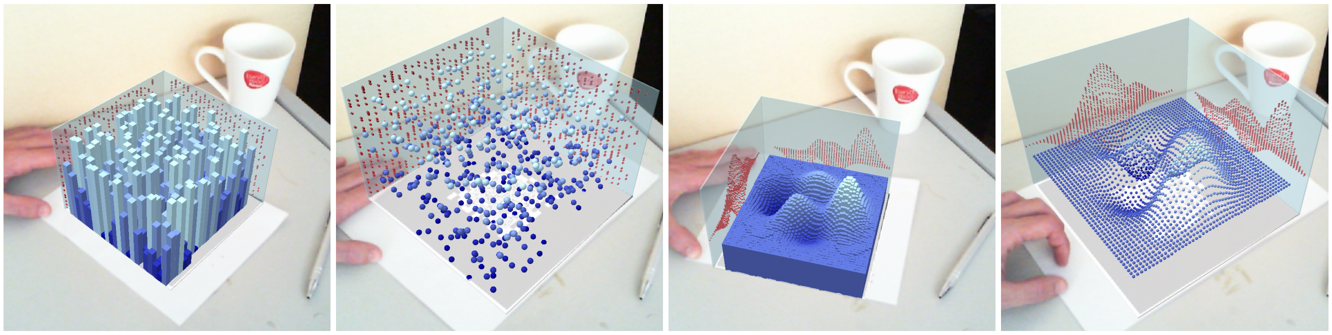
4 Reflection & Future Work

Currently, our prototype provides a proof of concept, but also highlights a number of challenges that need to be addressed to increase its potential, in terms of interoperability and practicality. At the moment, our 3D visualizations are fairly basic, and although sufficient for investigating the systemic integration of different frameworks, equivalent 2D visualizations may give a more clearer representation of the data. Furthermore, it is evident from our implementation (see Figure 4) that in addition to the limited interaction, challenges such as occlusion, rendering speed, and registration stability affect the overall user experience associated with these representations.

There are many opportunities for creating more effective mapping and displaying mechanisms, allowing greater level of flexibility, both in terms of the depictions themselves, as well as the datasets that can be accommodated. We are currently working on a library of more generalizable mappings and their corresponding 2D/3D spatially-registered visualizations, suitable for MR. It is also important to think about potential analytical tasks, collaborative or not, that can be carried out in MR context. The outcome of this process will, ideally, be a visual vocabulary for IA in MR. We believe that such a vocabulary will assist in the development and concise evaluation of future MR data visualization systems.

Moreover, there is much potential in combining several web technologies, for building such systems, as these provide a future-proof development platform. In the next few years, we expect to see an increase of practical web-based MR implementations, aided by the emergence and establishment of open-standards. Therefore, there will be more opportunities to create synthetic visualizations in MR using the Web, especially as the adoption of enabling technologies becomes broader, such as with the recently announced support of WebRTC in future Apple iOS versions.

Finally, beyond refining the current marker-based solution, we are very much interested in exploring alternative registration mechanisms, such as SLAM-based (Simultaneous Localization and Mapping) systems. These will allow us to explore *in-situ* synthetic visualizations in more contexts, and with deeper integration with the physical space and objects.



(a) (b) (c) (d)

Figure 4: Embedding visualizations in MR/AR markers. Data is encoded in JSON format and embedded in a QR Code. A modified AR Marker provides visualization-type identification via the pattern in the inner rim of the marker. Identification of the QR Code triggers the MR/AR component which 'places' the visualization on the marker, rendering the data from the JSON in the QR. The image pairs (a),(b) and (c),(d) show the same data set. The image pairs (a),(c) and (b),(d) show the same visualization, a 3D bar chart and a scatter-plot respectively.

5 Conclusion

In this preliminary investigation, we have explored the concept of synthetic visualizations in mixed reality. Our prototype uses a combination of AR markers and QR Code for reading data and superimposition on the physical world. We use open-standards web technologies, as we investigate the use of the Web as a platform for ubiquitous and ever-present analytics in MR. This approach allows us to use AR.js, an ARToolkit-based library for MR/AR on the web, along with the data binding and manipulation capabilities of D3.js, and A-Frame, an emerging framework for 3D graphics. We plan to further explore these synergies in web-based MR, by investigating interactions using mobiles/wearables, devising generalizable data mappings, a 3D visualization vocabulary, and incorporating alternative spatial registration mechanisms.

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