Immersive Analytics

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***Abstract*—Immersive Analytics is an emerging research thrust investigating how new interaction and display technologies can be used to support analytical reasoning and decision making. The aim is to provide multi-sensory interfaces that support collaboration and allow users to immerse themselves in their data in a way that supports real-world analytics tasks. Immersive Analytics builds on technologies such as large touch surfaces, immersive virtual and augmented reality environments, sensor devices and other, rapidly evolving, natural user interface devices. While there is a great deal of past and current work on improving the display technologies themselves, our focus in this position paper is on bringing attention to the higher-level usability and design issues in creating effective user interfaces for data analytics in immersive environments.**

I. Introduction

We are living in the era of big data [1], [2]. The amount and complexity of the data available for analysis in the physical-, life- and social-sciences—as well as that available for guiding business and government decision making—is growing exponentially. Several overlapping research fields are concerned with the development of methods to support the analysis of such data; particularly: information visualisation, scientific visualisation, machine learning, data mining, data science, human computer interaction and visual analytics.

Visual Analytics was introduced a decade ago as *"the science of analytical reasoning facilitated by interactive visual interfaces"* [3]. Techniques and practices developed by this discipline are now common-place in (for example): business intelligence; transport and logistics; scientific applications including astronomy, biology and physics; environmental monitoring and personal information management. It is now a key technology for dealing with big data [4], and there is massive potential for its use in further emerging application areas like health informatics and many others.

The definition for visual analytics given above is agnostic of the actual interface devices employed by visual analysis systems. Nevertheless, the affordances of display and input devices used for analysing data strongly affect the experience of the users of such systems. It is now well understood that user experience in interactive systems strongly affects their degree of engagement and, hence, productivity [5]. Ultimately, therefore, it affects the adoption and ubiquity of data analysis tools. For practical visual analysis tools used in the industry and areas of data science described above, the platform for interaction is almost always a standard desktop computer: a single average-sized display, keyboard and mouse.

In recent years we have seen significant advances in the development of new technologies for human-computer interfaces. On one hand, we have seen the development of expensive bespoke technologies mainly for scientific visualisation. For example, immersive environments like a Cave Automatic Virtual Environment (*CAVE*) [6] can make use of ultra-high resolution technology, and combine 2D and 3D visualisations to allow users to immerse themselves in computer generated scenes. A classic use-case for the CAVE is "walk-throughs" of human-scale architectural and engineering models [7].

On the other hand, we have also seen the development of inexpensive commodity technologies—such as the Leap Motion[1], Kinect[2], Oculus Rift[3] and (soon) Microsoft HoloLens[4]—for providing natural user interfaces, virtual and augmented reality. Industry—in particular the entertainment industry—has driven this development and it has progressed rapidly, providing engaging and immersive experiences for a fraction of the cost of the CAVE. As a consequence, voice- and gesture-based control as well as 3D visualisation are becoming more and more a part of everyday life, and corresponding devices are becoming available and affordable for small businesses and the general public. The amount of new, low-cost interaction technology hitting the market is unprecedented, and given the rise of new manufacturing technologies (additive manufacturing) and business models (crowdfunding, etc.) the number of new and affordable display and interaction devices is only going to increase.

Visual analytics and information visualisation researchers sometimes publish studies exploring various data visualisation applications in 3D, for example [8]. However, this has never been a core topic in information visualisation. Meanwhile, the rise in popularity of consumer touch-screen devices has, arguably, led to an explosion in research visualisation tools incorporating multitouch interaction. In other words, touch is an example of a recent natural user-interface technology reaching maturity and acceptance in the information visualisation community, for example, a compelling research agenda on this topic is put forward by Isenberg et al. [9]. Yet, to date, 3D user interface researchers have tended to focus more on the lower-level challenges such as making gesture recognition, head-tracking and rendering techniques robust and reliable. This is understandable, given the significant algorithmic and

[1] http://www.leapmotion.com
[2] https://www.microsoft.com/en-us/kinectforwindows/
[3] https://www.oculus.com
[4] https://www.microsoft.com/hololens

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(a) (b)

Fig. 1. A use-case to be explored by immersive analytics: collaborative data analysis in augmented and virtual reality. (a) Wearable display devices that can augment the world around us with arbitrary text and graphics enable a new degree of flexibility in data analysis. A concept sketch, two people in the same room (Peter and Sarah) discuss complex data. They can summon visual representations into one another's field of view with a simple hand gesture or voice command. Just as information graphics can be overlaid on their environment, a third person (John) can join the meeting and be given a virtual presence. At John's end, he also sees Peter and Sarah as if they are physically in the same room, together with the data visuals. The devices to at least prototype such experiences are now cheap and reliable enough that we can focus on the application and ergonomics rather than the underlying technologies such as motion tracking and image registration. (b) Wearable VR headsets can immerse us into our data. A prototype using the Oculus Rift that we are building to try and realise this scenario.

hardware challenges involved. The higher-level concerns of applications and effective user experience, let alone the use of this technology in data analysis applications, has lagged behind. Therefore, a systematic approach to develop practical visual analysis tools in immersive environments is lacking.

We propose a new facet of data analytics research that seeks to unify these efforts to identify the most enabling aspects of these emerging natural user interface and augmented reality technologies for real-world analysis of data. We call this new research thrust *Immersive Analytics*, a topic that will explore the applicability and development of emerging user-interface technologies for creating more engaging and immersive experiences and seamless workflows for data analysis applications.

Immersive Analytics builds on technologies such as large touch surfaces, immersive virtual and augmented reality environments like Oculus Rift and CAVE2 [6], and tracking devices such as Leap Motion and Kinect to provide environments beyond the classical monitor, keyboard and mouse desktop configuration [10]. The environments we envision will be developed by immersive analytics researchers, will be usable by experts and analysts to help in the detailed analysis of complex, big data sets. However, they will also be accessible to decision makers—that is, the managers who spend more time working face-to-face with others than in front of a desktop computer—and to the everyday public to help them in tasks like shopping, understanding public transport and social and political issues affecting their lives.

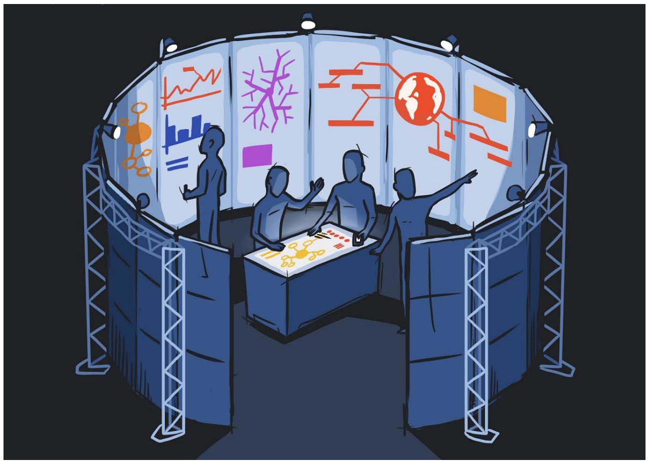
In this position paper, we first give examples of the current state of main stream research into visual analytics, virtual reality and collaboration. We then present immersive analytics by describing near-future scenarios and a number of projects that are currently being developed by the Immersive Analytics research group at Monash University[5]. These projects are all striving to move beyond traditional desktop visualisation and provide a much richer, more immersive experience. We finish by presenting a number of research questions that we feel this new field should address.

II. Background

Research on immersive analytics comprises the development and evaluation of innovative interfaces and devices, as well as the corresponding interaction metaphors and visualisations that allow these to be used for understanding data and for decision making. Immersive analytics is therefore inherently multi-disciplinary and involves researchers from human-computer interaction, visual analytics, augmented reality, and scientific and information visualisation. Relevant conferences include, for instance, HCI[6], 3DUI[7], VR[8], AR[9], CSCW[10], TableTop[11], Vis and InfoVis[12] and VAST[13]. At some of these conferences we are already seeing workshops and special sessions that address aspects of immersive analytics: e.g. "Death of the Desktop"[14], "3DVis"[15], etc. However, at this stage there is no coordinated exploration of immersive analytics.

During the last three decades, research in Virtual Reality Environments (VRE) has been focused on the use of head

[5] https://immersive-analytics.infotech.monash.edu.au/
[6] Human Computer Interaction www.sigchi.org
[7] 3D User Interfaces www.3dui.org
[8] Virtual Reality www.ieeevr.org
[9] Augmented Reality www.ismar.vgtc.org
[10] Computer Supported Cooperative Work www.cscw.acm.org
[11] Interactive Tabletops and Surfaces www.its2014.org
[12] (Information) Visualization www.ieeevis.org
[13] Visual Analytics Science and Technology www.vacommunity.org
[14] http://beyond.wallviz.dk
[15] https://sites.google.com/site/3dvisieeevis2014/



(a)

(b)

(c)

Fig. 2. “Immersing people in their data” does not necessarily involve 3D or stereo display. (a) In this concept, analysts work in a purpose-built, collaborative data analytics room. Interaction technologies such as pen, touch and gesture control allow them to interact directly with their data and collaborate in a more egalitarian way than keyboards and mice, which tether individual users to a desktop. Immersive analytics will systematically research how many kinds of emerging interaction technologies can be harnessed to engage and enable people to work together to better understand data. (b) The figure shows a prototype that we are building using the Monash CAVE2 immersive visualisation facility to try and realise this scenario. (c) Ultimately, the so-called “ContextuWall” project is intended to enclose a natural space where people can work collaboratively, their discussions supported by the contextual display of information at high-resolution on the CAVE2 wall.

mounted displays (HMDs) and CAVEs to immerse users into data graphics. VREs have proven their effectiveness in many scientific applications such as brain tumour analysis [11], archaeology [12], [13], geographic information systems [14], geosciences [15], [16] or physics [17]. These studies focused on the perception of abstract data visualisation for a single user. VREs have also been studied to support collaborative work. VRE have shown benefits to support collaborative tasks such as puzzle solving [18], navigation with individualized views [19], or complex manipulations such as moving a ring on a U-shaped hoop [20]. Szalavri et al. [21] developed a collaborative augmented reality system with see-through HMDs in order to support collaborative scientific visualisation. They observed that their system seems to be superior to a classic desktop environment, but did not provide formal results.

Huang et al. [22] investigate *Personal Visual Analytics* (PVA), Visual Analytics used within a personal context, but not restricted to personal data. They describe a design space for PVA and present a literature survey on the topic. This application is a natural fit for augmented reality as headsets become lighter and less obtrusive.

Collaboration can play an important role in information visualisation by allowing groups of humans to make sense of data [23], [24]. Collaboration might also be the key feature to successfully understanding big and complex data [6], [25]. Yet little research has focused on collaborative and immersive environments for abstract visualisation. Mahyar and Tory explored how communication and coordination can be supported to facilitate synchronous collaborative sensemaking activities in Visual Analytics [26]. Recently, Donalek et al. [25] published a progress report of the exploration of VR as a collaborative platform for information visualisation. They provided a description of iVIZ, a web-distributed collaborative VR visualisation system that supports the Oculus Rift. Their studies are still at an exploratory level and thus the authors did not provide evidence of how effective this system is for collaborative visualisation of big and complex data. Telearch [12], a virtual reality system for collaborative archaeology, and Shvil [27], an augmented reality system for collaborative land navigation, both support distributed collaboration. However, both systems are designed for specific use cases. A further prominent use of augmented reality in is industrial applications, e.g. to support asynchronous collaboration [28].

To conclude, VREs featuring 3D stereoscopic vision, high resolution and head tracking provide considerable benefits for collaborative visual analytics. The current technologies each have their own advantages and disadvantages. For example, the CAVE2 supports collaborative work of a considerable group of people in a large room (diameter 8m), with a 3D stereoscopic display. Yet the CAVE2 provides head tracking for only a single user. Conversely, HMDs such as the Oculus Rift provide 3D stereoscopic vision with head tracking for every user, but prevent users from moving freely in space since their HMD is tethered to a desktop machine. Despite these limitations, the current technologies are now adequate to allow us to explore a design space for immersive data exploration. The following section explores several use-cases from researchers at Monash University that exploit these emerging display technologies—but also other media and modalities—to allow people to experience their data "immersively".

III. IMMERSIVE ANALYTICS

In this section we introduce what we mean by immersive analytics using a number of examples.

The most obvious developments in technology that allow immersive analytics are the new low-cost virtual reality HMDs such as Oculus Rift, augmented reality HMDs such as Google Glass or (soon) Microsoft HoloLens as well as augmented reality through mobile phones or tablets. These support immersive 3D data visualisation as well as allowing data visualisation to be physically embedded in the real world. In addition, there is great potential to support distributed collaboration. A serious issue is interaction: motion and gesture tracking devices like the Kinect and Leap Motion provide one possible approach. Figure 1 gives a potential use case for such devices that can be explored by immersive analytics.

An obvious and already popular use for 'immersive' display technology is in constructing virtual environments that allow walk-through and 'fly-over' of (for example) engineering or architectural designs. This technology is being put to novel use by the Monash Immersive Analytics lab in reconstructing ancient artefacts for archaeological analysis[16]. Figure 3 shows a virtual reconstruction of the ancient Angkor site. However, our visualisation is not just about reconstructing a view of the site, but rather reconstructing activity in and around the site using multi-agent technology. We explore data gathered from this simulation using visual analytic techniques such as overlaid heatmaps of activity, e.g. Figure 3(b). Besides supporting the evaluation of hypotheses, e.g. on the settlement density, detailed 3D interactive animations like the Angkor virtual reconstruction can also be used to disseminate knowledge, e.g. for educational purposes [29].

The term 'immersive' suggests 3D virtual reality style displays. However, this is only one possible direction for research. We see touchscreens that allow direct interaction with data as being more natural and therefore more 'immersive' than mouse and desktop display. There has been exciting research, for example, about the natural collaborative experiences supported by tabletop interfaces [9]. Large displays utilising projectors or tiled displays have been in use for many years. Particular applications have been as command and control centres or for immersive scientific visualisation and for immersive display of engineering and architectural designs. Next-generation CAVEs provide higher resolution and contrast than their predecessors. The rapidly decreasing cost of video projectors and of 3D and Ultra-High-Definition (4K) monitors that can be combined in tiled displays mean that CAVEs and 'mini-CAVEs' are now affordable for wide spread use in research groups and industry. Combining large displays with touch or spatial tracking can support multiple users in a way that allows them to collaborate in a seamless way that 'immerses' them in their data. Figure 2 explores a use-case exploiting such devices. Another driver for immersive analytics is that scientists, engineers, architects and analysts are increasingly trying to understand heterogeneous data. Some components are physical and have a natural 3D representation while other components are more abstract and are better visualised in 2D. The development of cheap 3D display technology means that it is now possible to provide

[16]http://www.infotech.monash.edu.au/research/groups/3dg/projects/visualising-angkor.html

(a)

(b)

Fig. 3. (a) A virtual reconstruction of the ancient Cambodian town and temple of Angkor. Our visualisation is not just about reconstructing a view of the site, but rather reconstructing activity in and around the site using multi-agent technology. (b) We explore data gathered from this simulation using visual analytic techniques such as overlaid heatmaps of activity.

hybrid 2D/3D visualisations, for example, by combining 3D tracked monitors such as ZSpace[17] with 2D displays.

Immersive analytics is not only about visualisation. While vision is our most important sense for quickly exploring our environment, sound and touch are also powerful ways of understanding the world. Their use in data analytics has largely been overlooked. A particularly important application is for presenting data to people who are blind or have severe vision impairment. One of the most disabling consequences of vision impairment is lack of access to information: the development of audio and haptic presentation devices for such users is a potential application area of immersive analytics with huge social benefit. Figure 4 shows the GraVVITAS system[18] [30] developed at Monash University to enable blind people to interact with information graphics through touchscreen devices with sonic and haptic feedback.

Despite much progress with technologies for creating immersive virtual and augmented reality experiences, until we have perfect brain-computer interfaces a gap will remain between the tangibility of real physical objects and virtual objects rendered in immersive environments. However, it is already possible to experiment with "physicalisations" of data in order to study the benefits of "perfect" immersion. Indeed, people have been constructing physical representations of data for some time. An early and famous data physicalisation was a tangible matrix display by Bertin [31]. Bertin was an advocate of reordering tabular data displays to better show high-level structure (such as clustering). His physicalisations featured crude interactivity allowing people to physically reorder matrix

[17]http://zspace.com

[18]http://gravvitas.infotech.monash.edu

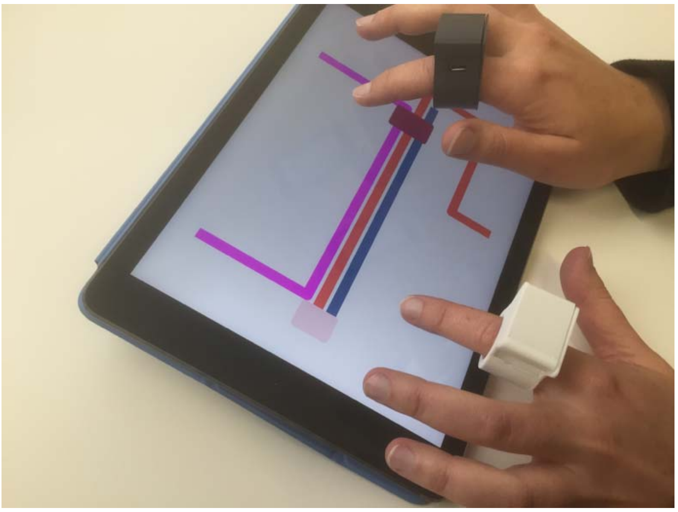


Fig. 4. Immersion is not just visual. Sound and haptic feedback can make information graphics and data analytics applications accessible to people with severe vision impairment.

rows of dots mounted on skewers.

Another data physicalisation is shown in Figure 5(a). This physicalisation of inflation vs. unemployment data for OECD countries over ten years was an early experiment by a current member of the Monash Immersive Analytics team in avoiding the limitations of digital display and haptic technology while testing the cognitive effectiveness of 3D data spatialisation [32]. In 2003 construction of this physicalisation was a time-consuming process, constrained by the materials and tools available. In 2015 digital fabrication is emerging as a technology with huge potential to allow people to engage with data in new ways [33]. Machines such as 3D-printers, laser cutters and CNC-routers have all fallen massively in price in recent years making it easier than ever for people to create physical representations of their data automatically. Figure 5(b) shows a data physicalisation recently produced in our lab very quickly using laser-cutter and vinyl-printer/cutter devices. Furthermore, with such automatic fabrication techniques we can produce physicalisations of large data-sets with ease.

Immersive analytics shares many goals with visual analytics, in particular: how to derive insight from complex, big data sets. However, we can see from these various scenarios and case-studies that in contrast to visual analytics, immersive analytics focuses on the investigation of the use of new immersive technologies and considers multi-sensory interaction, not only visualisation. In short:

> *Immersive Analytics investigates how new interaction and display technologies can be used to support analytical reasoning and decision making. The aim is to provide multi-sensory interfaces for analytics approaches that support collaboration and allow users to immerse themselves in their data. Immersive Analytics builds on technologies such as large touch surfaces, immersive virtual and augmented reality environments, haptic and audio displays and modern fabrication techniques.*

IV. Research Questions

The overarching goal of immersive analytics research is to understand how (and whether) new interface and display technologies can be used to create a more immersive kind of data analysis and exploration. The kinds of devices and environments include augmented and virtual reality displays, large high-resolution 2- and 3-D displays, haptic and audio feedback and gesture and touch controlled interaction. These potentially require very different interaction and visualisation models and techniques to those used in standard visual analytics. Some of the main research questions are:

1) Much research has been devoted to computer-assisted collaboration both synchronous and asynchronous and local and remote. The new devices and environments potentially support new models for collaboration as shown in Figures 1 and 2. What paradigms are potentially enabled by these new interaction modalities? How do we evaluate them?
2) Traditionally 3D visualisation has been used in the physical sciences, engineering and design; while 2D visualisations have been used to display statistical and abstract data in information visualisations. Increasingly there is a need to combine both sorts of visualisation in holistic visualisations. For instance, in the life sciences different aspects of a cell are displayed using 2D images and 3D volumes, 2D network data and the various -omics data. Can these new technologies support more holistic visualisations of such data incorporating 3D spatial information as well as abstract data?
3) What questions do technologies like augmented reality raise significantly for data and visual analytics? For instance, traditional information visualisation supports open-ended exploration based on Shneiderman's information mantra: overview first, zoom and filter, then details on demand. In our view a different model is required for analytical applications grounded in the physical world. In this case objects in the physical environment provide the immediate and primary focus and so the natural model is to provide detailed information about these objects and only provide contextual information on demand.
4) What are the interface 'tricks' and affordances such as high-resolution displays, sound, touch and responsive interaction that change the user perception from an allocentric view of the data to a more egocentric and immersive view of the data?
5) What are the lessons that can be learnt from previous research into the use of 3D visualisation for information visualisation? Do the new technologies invalidate the current wisdom that it is better to use 2D visualisation for abstract data since the designer of the visualisation has complete freedom to map data to an occlusion free 2D display?
6) What are the most fertile application areas for immersive analytics? For example, these could be in life sciences, disaster and emergency management, business (immersive) intelligence and many more. What are domain-specific requirements, what are general requirements? What are typical workflows

(a)

(b)

Fig. 5. Data physicalisations: (a) A physicalisation of inflation vs. unemployment data for OECD countries over ten years. The physical instantiation of this dataset was an early experiment [32] in avoiding the limitations of digital display and haptic technology while testing the effectiveness of 3D data spatialisation. This model, constructed in the 2000s, was time-consuming and tedious to build with conventional tooling. (b) A physicalisation of a grouped graph. The group hierarchy is represented by stacked levels. Using modern fabrication techniques such as 3D printing, laser-cutters, vinyl cutter/printers, etc. we can prototype such physicalisations very quickly and easily.

for data analysis in the different domains, are they domain-specific or are they generic across the different domains?

7) How do we develop generic platforms that support immersive analytics? Currently there is a wide range of different development platforms and existing cross-platform tools, however, they do not quite have a broad enough focus for immersive analytics. For example, Unity[19] is designed for gaming applications rather than analytics while the Visualization Toolkit (VTK)[20] is targeted at scientific visualisation applications.

V. Conclusion

Research and development for approaches related to immersive analytics are scattered across several research communities and domains. In addition, a large part of the development for emerging technologies is done in companies and start-ups. With our Immersive Analytics initiative we would like to bring together these efforts and establish a community of researchers, developers, educators and users from both academia and industry in this area. There are no dedicated events for Immersive Analytics such as a conference or workshop yet for discussion and dissemination of immersive analytics research, therefore we would like to foster community building by two dedicated Immersive Analytics seminars in Dagstuhl and Shonan in 2016.

[19]www.unity3d.org
[20]www.vtk.org

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