UDC 004

A REVIEW OF GRAPH-ENHANCED AUGMENTED AND MIXED REALITY

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Abstract

Augmented Reality (AR) and Mixed Reality (MR) are the leading technologies that provide us with new ways to interface between the digital world and real spaces. This paper presents a literature review on the evolving intersection between graph theory and AR/MR, and how graph-based approaches advance these technologies. We present an analysis of the literature on this topic published between the years 2019 and 2024. This time frame captures articles discussing a variety of applications including, but not limited to, cultural heritage tourism, navigation, gaming, education, and collaborative work. The review also describes the functionalities of graphs within the AR/MR environments, including visualization, spatial understanding, scene rendering, network cutting and user engagement. We assess the opportunities and challenges of using graph-based approaches, summarize some of the research areas currently on the agenda, and suggest some possibilities for future work in this area.

Keywords: augmented reality; mixed reality; graph theory

Introduction

The development of new technologies has led to the design of applications to solve the problems of everyday life. In fact, when designing such applications, it is crucial to design using suitable visualization criteria. People's interaction with the world around them, as well as their ability to understand and process information about this world, is evolving significantly. The integration of augmented reality (AR) and mixed reality (MR) and graph technology could change how we engage with the world around us. In many fields, there is growing interest in exploring approaches that utilize mixed reality (MR) and augmented reality (AR) technologies [1]. Mixed and augmented reality have become embedded in our daily activities. Major developments in areas such as navigation [2], social networking [3], entertainment [4], remote sensing, and engineering [5] demonstrate the promising potential of AR and MR technologies.

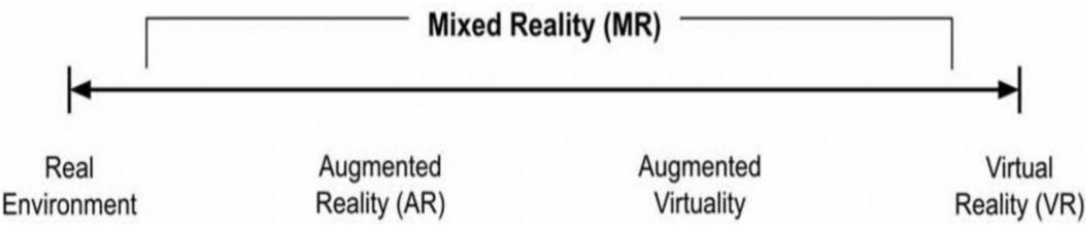


Figure 1 – The Reality-Virtuality Continuum, as proposed by Milgram in 1994 [6].

A widely accepted definition of AR is provided by Azuma, who defines it as a technology that integrates real and virtual objects that interact in real time and are embedded in the real world [7]. AR implies boosting, i.e. the putting into use of visible spectrum images, video, and 3D models into real-world environments and surroundings of the environment perceived by the user. This technology helps to erase the boundaries of the virtual and the real by enabling people to use digital content in the actual world [8].

MR, on the other hand, takes it a step further and combines digital information with the physical environment, allowing for more interactive experiences [9]. MR is able to merge the classical notion about physical and virtual worlds being two opposites into a single strong sense [10]. Together with other sensing capabilities, objects may be placed anywhere along the reality-virtuality continuum to not differentiate them clearly. This fusion, based on a single design of a real object and a virtual object, seamlessly integrates the real and virtual perceptions in MR. For this reason, the user's understanding of the MR reality is layered and complex since the divisions between physical things and pictorial representations are blurred.

Euler’s work on the Seven Bridges of Königsberg is considered the beginning of graphs [11]. He stated that graphs are mathematical structures that represent relationships between entities by using nodes (or vertices) to represent entities and edges to represent the connections between them. Recent work has improved Euler's work, showing how graphs can be leveraged in augmented and mixed reality systems to enhance real-time data visualization and improve user interactions in immersive environments [12]. The role of graphs in augmented and mixed reality systems is to organize and contextualize digital components by representing relationships and structures visually and interactively.

This paper is structured as follows: In Section 1, an overview of the research problem and aims of this study is given and describes the framework for the analysis carried out thereafter. In Section 2, the works relevant to the topic are discussed. Section 3 describes the research methodology including the techniques, and the conclusion is presented in Section 5.

Related Works

After a brief introduction to AR, MR and Graphs, this paper presents an in-depth review of the existing literature and analyses related applications and papers.

Augmented Reality Applications with Graphs

Augmented Reality (AR) is becoming a game changing technology in which the digital information is integrated with the real world in such a way as to enhance the experiences of users. An enormous development in the capacity of AR applications to present and handle complex data was especially brought about by the combination of graph theory and graph algorithms.

Qassimi and Abdelwahed [13] focus on information overload which is an aspect of concern in Cultural Heritage Tourism, and it is made worse by the many platforms that allow users to post content. Their paper, presents an innovative method for suggesting appropriate sites of the cultural heritage to a sightseerer. Noting the drawbacks of folksonomy with uncontrolled vocabulary and the resulting ambiguity of meaning, the authors offer a solution based on semantic graph. Their system is designed to provide an advanced semantic/meta description graph for each site, and the graphs are then used to map semantic relations between tags of similar sites and between the sites themselves. As a result, recommendations are expected to give preferences in suggestions that are more relevant rather than that the artificial intelligence using folksonomy concepts. The authors indeed found some promising results from their experimental evaluations, showing the efficiency of such semantic graph-based recommender systems in the context of cultural heritage tourism.

Büschel et al. [14] investigates the effectiveness of visualizing graphical link attributes in mobile augmented reality (MAR) environments. The study focuses on how different visual coding techniques for connectivity attributes such as color, thickness, and animation affect user comprehension and task performance in MAR graph visualizations. The research will focus on the interaction between these graph visualization principles and what MAR uniquely offers, by spatial mapping and real-world context, to identify the optimal strategy for representing intricate relationships within augmented overlays. The research contributes to knowledge on how graph-based information can be conveyed effectively in MAR, leading toward the creation of more intuitive and insightful graph-based AR applications.

Li and Wang [15]'s interactive AR graph demonstrates the effectiveness of graph theory in depicting the complex interactions between Chinese painters. In this case, the 3D space can be defined as an AR space in which these networks can be visualized. Users can immerse themselves in the environment and comprehend how painters interacted and the numerous trends that shaped art history. In the same vein, Schwajda et al [16] propose an orthogonal visuals approach where 2D graph data is transformed into 3D AR space for better interactivity and visual understanding.

This study aims to investigate how different types of graphical representations, including directed graphs and weighted graphs, affect the understanding of complex datasets and the various AR tools they utilize in their respective cases. They also highlight the potentially powerful capabilities of AR when it comes to accurately depicting the data behind complex datasets. In addition, they provide quantitative evidence of the effectiveness of the proposed AR visualization, considering the effects on user performance and satisfaction in terms of metrics.

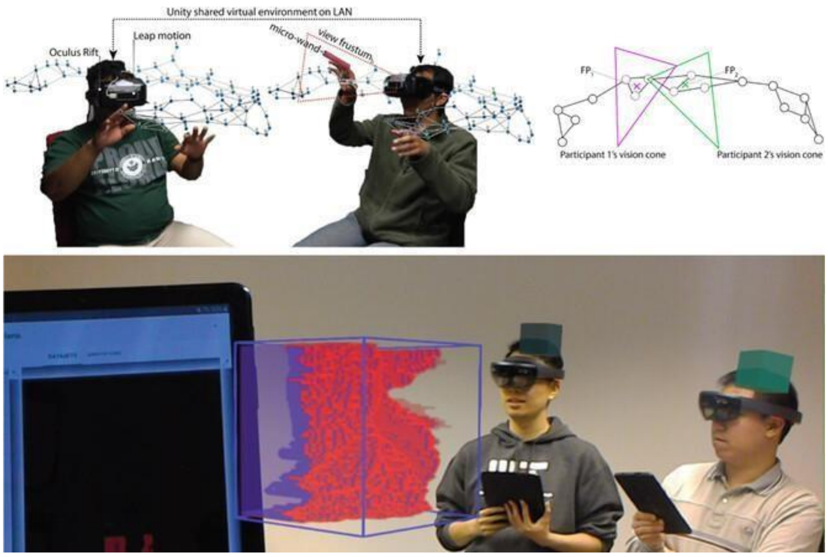


Figure 2 – Examples of XVA systems with cross-device and collaborative features are starting from above, Cordeil et al's analysis evaluation of immersive collaborative networks‘ evaluation (top, © 2016 IEEE. Reprinted, with permission, from Cordeil et al.[CDK*17]); follow up figure caption This is an illustration of a volumetric data visualization and analysis prototype described by Sereno et al. (bottom, © M. Sereno, L. Besançon and T. Isenberg, reprinted, with permission, from Sereno et al.[SBI19]).

Lampropoulous et al. [9] provide a gathering where in-depth review of ar functionality improvement with the use of learnt deep, networks, semantic web and knowledge graphs. Knowledge graphs represent relationships between objects and concepts and are introduced as a contextual background to AR applications so as to make them meaningful. With a focus on different application areas such as museum guidance, education, and healthcare. The study sheds light on how these technologies can bewenchical to Augmented Reality Experiences. The merger if knowledge graphws especially enables the users to know more about real-life objects and the concepts behind them making one more immersed into the AR applications. AR applications especially multi-users and collaboration’s have great expectations for the network performance. Pereira et al [17] implemented Arena, an AR edge networking architecture open out to enhancing network performance, and enlarges networks of AR edge applications. Arena uses graph based means in network resource optimization to cut latency. The research describes and Animates the design and Aggregation of Arena with evidence through simulation of performance enhancement. Contributing to this field, Jeon and Woo [18] eCAR architecture addresses the limits of edge performance in optimizing collaborative AR experiences. eCAR uses graph-based methods to improve efficiency and scalability. eCAR addresses the problems of helping a large number of participants experience a common AR fidelity using remote forces. Since several networks carry an AR device and global edge servers that use graphs as data movement devices, a graph will likely identify connections. Alternatively, it is possible that nodes represent users and the virtual objects they interact with in the shared space of the AR that honors a graph. Since directed graphs will show how edges correspond to interaction, the paper seems to cover the main ideas and principles laid out in directed edge computing systems based on graphs.

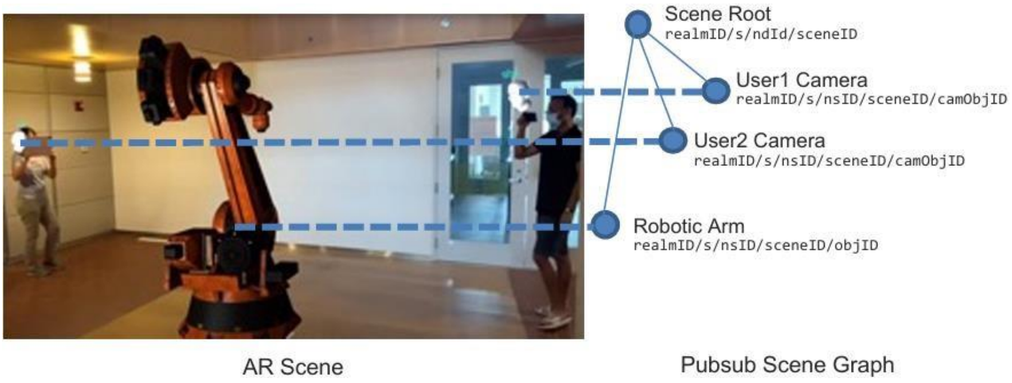


Figure 3 – ARENA Scene The objects in an ARENA Scene are indirectly networked via a PubSub bus where each object is controlled by a topic endpoint. The topic hierarchy is partitioned by Realm (RealmID), owner namespace (nsID), Scenes (sceneID) and objects within the Scene (camObjID or objID)[17].

Liu et al. [19] present an approach for the generation of AR gaming sceneries, which combines the ideas of spatial design and reality. Their approach implements a graph-based scene representation which assists in the development of more adaptive and interactive gaming environments, enabling the use of sophisticated graphical tools for the purpose of creating animated structures based on AR for the entertainment industry. The experimentation proved the viability of the proposed adaptive method for game development using AR, demonstrating a prototype of implementation. Qiu et al. [20] describe NavMarkAR, an augmented reality navigation system that uses landmarks to assist users from elderly populations who wish to improve their spatial cognition. In their work, they used graphs to represent the landmark relations that form the AR-enhanced mental maps, helping the them use augmented reality. One of the participants' evaluations conducted in the study showed that NavMarkAR helped elderly subjects to enhance spatial cognition and orientation abilities. Graph-based AR will evolve in the future by looking at more efficient graph algorithms and data structures and new interaction modes. Of great importance is still performance optimization, without which the use of mobile devices remains a great challenge. Graph based augmented reality applications are very mobile and so user interface and user experience design are also very important. Additionally, bearing in mind Artificial Intelligence and Deep Learning as well as Computer Vision makes it possible to make AR systems smarter and more context-aware. In conclusion, Graph-based techniques stand out in enhancing the efficiency and flexibility of the developed AR applications because the research in this area would be further developed to revolutionize the user interactions with either real or virtual worlds.

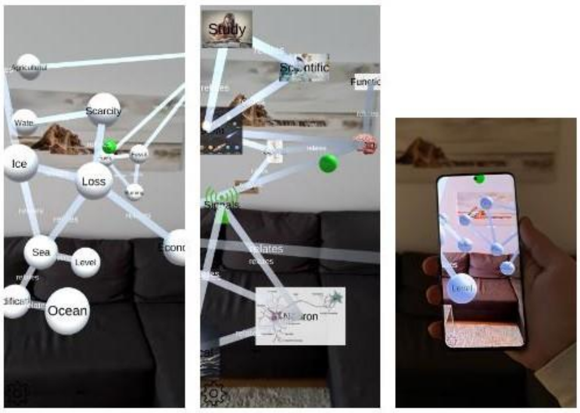
According to Belcher et al. [21], there is an improvement in the use of Augmented Reality (AR) in the visualization of complex graphs in three dimension. These systems allow users to use AR to visualize graph structures overlaid on the real environment and to interact with the graphs themselves. Such systems employ a tracked handheld display which renders the graph such that the user can view the graph and even move the graph nodes and edges in the 3D space. The authors of this paper argue that this approach overcomes some of the limitations inherent in viewing the graph in a 2D space, most notably providing spatial cues and enabling comprehending the complex relationships of the graph apace in a natural manner. The paper describes a prototype implementation demonstrating the proof of concept for the idea and usability aspects of augmented reality in graph visualization, especially for software visualization and social network analysis.

In their work, Tahara et al. [22] elaborated the concept of Retargetable AR which makes use of a 3D scene graph to enhance augmented reality addressable to indoor spaces. They put forward the idea of directed acyclic graphs (DAGs) as a means of establishing the interconnection and organizational structure between objects in a scene, thus rendering the effective and appropriate visualization and interaction of the virtual options within the context in which they are placed. The retrieval of a scene graph where locations of virtual objects are placed with consideration of their spatial semantics attributes are not random since the system provides high-level attributes related to the virtual and its orientation. This means that objects for the tangible world are virtually projected onto the real world in perfect compatibility that, for instance, virtual furniture can be projected on a real table, and virtual decorations can be put or painted on the walls. In addition, the retarget ability feature allows transferring the AR for other indoor spaces just by using another scene graph, therefore increasing the applicability and universality of the system. Their findings highlight the relative effectiveness of the Graphics representation in AR as they are able to create meaning coherent sites using the AR interface.

Mixed Reality Applications with Graphs

Graph-based techniques are relatively new in Mixed Reality (MR), and they are contributing to the enhancement of user experience and resolving some of the technical aspects related to MR. Several key studies highlight the diverse ways in which graph structures and algorithms can enhance MR experiences.

Hensen et al. [23] conducted a study which aimed at creating interactive visualizing learning structures with the help of knowledge graphs in MR. They made knowledge graph nodes and edges as 3D objects and relationships in the MR environment, so that users were able to touch abstract ideas. Such interaction allows users to get a better comprehension of difficult topics in comparison to ordinary visualization. This study confirmed the effectiveness of knowledge graph implementation into MR in designing the environments that deinstitutionalize learners and make them more engaged in the learning process.



(a) Sphere representation. (b) Image representation. (c) App on a smartphone.

Figure 4 – Two KG representations and a student using the app on a smartphone[23].

Localization is one of the most important elements when considering MR interfaces due the fact that MR has to be accessed from different devices. Addressing the issue of cross-device localisation, Osipov, Ostanin and Klimchik [24] attempted to compare different point cloud registration algorithms with some graph-based methods, such as FIGRA.Their objectives in the research were to find out reliable algorithms which could facilitate effective global localization in MR.

Hernández et al. [25] explored the development of thermodynamics-informed neural networks for realizing physical realism in MR simulations. As dealing with graph neural networks (GNNs) in their particular application raises more questions than it answers, their research demonstrates the promise of embedding physical constraints in the learning of neural networks. This method is intended to produce more reliable and realistic simulations of MR, in areas such as engineering and design, whereby realistic physical interactions need to be modeled in great detail.

Mu et al. [26] designed a spatial location and tracking model for MR using the concepts of SLAM algorithms. This model incorporates a visual slam where visual images are collected and used for creating a three-dimensional perspective of the surroundings and the position of the MR device in it. Although the specificity of the scope remains a prominent concern, particularly in assessing the accuracies and real-time aspects of these algorithms without comparing them against other SLAM algorithms, these are still promising findings. Future studies should aim to improve algorithms and test their effectiveness in many scenarios so that they can be used as scalable in higher-order MR environments.

Regardless, the paper remains a valuable document for researchers wanting to study this emerging interdisciplinary area and as noted in Table 1's analysis of various applications, aptly highlights future research opportunities.

Table 1 – Related works

Reference	Study Topic	Technology	Chart Type
Qassimi & Abdelwahed [13]	Cultural Heritage Tourism	AR	Semantic Graph
Büschel [14]	Link Visualization in Mobile AR	AR	Visual Encoding
Li & Wang [15]	AR-Based Artist Network	AR	3D Graph
Schwajda et al. [16]	2D to 3D AR Conversion	AR	Directed Graph
Lampropoulos et al. [9]	Information Graphs in AR	AR	Knowledge Graph
Pereira et al. [17]	Arena: Edge Computing AR	AR	Graph Optimization
Jeon & Woo [18]	eCAR: Edge Computing Optimization	AR	Graph-Based System
Liu et al. [19]	AR Gaming Environment	AR	Graph-Based Scene
Qiu et al. [20]	NavMarkAR: AR Navigation	AR	Graph-Based Routing
Belcher et al. [21]	3D AR Graph Visualization	AR	3D Graph
Tahara et al. [22]	Retargetable AR	AR	DAG (Directed Acyclic Graph)
Hensen, Rechtmann & Neumann [23]	Information Graphs in MR	MR	Knowledge Graph
Osipov, Ostanin & Klimchik [24]	Positioning in MR	MR	Point Cloud
Hernández et al. [25]	Physical Simulation in MR	MR	GNN (Graph Neural Network)
Mu et al. [26]	SLAM Tracking in MR	MR	Visual SLAM

Discussion

This literature review is helpful in understanding the confluence of graph theory and augmented/mixed reality (AR/MR) technologies focusing on research published between 2019 and 2024. The authors are successful in demonstrating the cross-domain applications of graph approaches, such as in cultural heritage, navigation, gaming, and collaborative work. The review describes the main functionalities graphs provide in AR/MR environments: Visualization and understanding of space, rendering of scenes, optimization of networks, and participation level of users. Nonetheless, some challenges regarding performance optimization for mobile devices, interface design, and the application of AI and computer vision are also pointed out. It is clear that the variety of applications is a notable strength; however, the lack of a comprehensive comparative analysis of different graph-based approaches and their performances across applications is a missed opportunity for critical appraisal. Despite these shortcomings, the paper works well as a starting point for researchers wanting to delve into the interdisciplinary domain while outlining the optimum research strategies, such as the formulation of efficient graph algorithms, the design of interaction models, and customizing AR/MR content.

Conclusion

This paper has demonstrated both the almost ubiquitous nature and the use of graph theoretic structures in the context of LBSN research. Although no of the papers under review set out primarily to study the topology of any graph, it is important to realize that the use of different graph algorithms and structural designs greatly enhance the quality of such research. Researchers across different fields of study often employ various forms of graph structures in solving particular problems and developing their contributions in LBSN. In order to grasp the scope of research activity in this field better, the classification of the articles based on the types of graph structures used is especially helpful. Concepts and structures of graphs and their applications in this case include heterogeneous graphs made up of nodes and edges representing various components and relationships, implicit spatial networks that depict the geographical context of location-based services, graphs representing information flow and how such information flows within a social network, and graphs evolved out of specific requirements in LBSN areas. This classification not only enables one to see how graph structures are employed and used in LBSN studies, but also emphasizes the range of approaches that scholars take. Each category corresponds to a particular view as to how graph theory could further clarification of social relatedness with regard to space – and only space – indicating the complex use of graph in this extremely active area of thinking.

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