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Doctoral Dissertation
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Digital Transformation Technologies for Virtual Experiences

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Summary

Over the past two decades, digital transformation has gained increasing attention, driven by the convergence of multiple Digital Transformation Technologies (DTTs) across several sectors. Among them, Virtual Reality (VR) has emerged as a key technology for creating immersive and interactive Virtual eXperiences (VXs), often enhanced through integration with other DTTs, such as laser scanning, descriptive CAD tools, and large language models. Despite their potential, the creation of VXs still faces significant challenges. Current VX design practices often lack principles for specific target users in various domains, while technical complexity and interoperability issues frequently hinder the creation of virtual environments. Although the integration of other DTTs could possibly address these challenges, several of them remain underexplored in the context of VXs.

This doctoral thesis investigates current challenges in relation to VXs and their combination with other DTTs, aiming at analyzing their strengths, limitations, and applicability across various domains. The presented investigations, conducted over the years of the Ph.D. program, address a wide range of topics, including virtual design for user accessibility, automated reconstruction of virtual environments for VX creation, and the use of generative AI-based technologies to develop conversational agents. In this context, the research explores the convergence of VR with several DTTs, such as 3D photogrammetry, Building Information Modeling (BIM), and Large Language Models (LLMs).

This thesis is divided into five chapters. Chapter 1 serves as an introduction to the context in which the thesis is placed, providing an overview of DTTs and their combination within VXs. The three following chapters regard the activities carried out during the years of author's Ph.D. research. Each chapter is divided in sections representing one or multiple investigations.

In particular, Chapter 2 includes an investigation set in the context of VX design employing immersive VR. Specifically, it considers a category of users often overlooked within certain domains, namely those with Autism Spectrum Disorder (ASD). Since these types of users usually experience discomfort in relation to social presence (e.g., crowds) and sensory overload (e.g., bright lights, sudden noises), the research explores the creation of inclusive VXs that leverage immersive VR technologies. By defining a methodology based on user-centered design principles, a

specific emphasis is put on VXs within the Cultural Heritage (CH) domain. Since most research on ASD in this context remains theoretical, the methodology was applied to a real-world use case, developing an immersive virtual visit in a museum specifically tailored to users with ASD. The workflow for creating the Virtual Environment (VE) of the application involved manual creation and the adoption of Environment Reconstruction (ER) technology, specifically 3D photogrammetry, to digitally reproduce a hall of a real-world museum. Experiments with ASD users were also conducted, obtaining results that confirmed the efficiency of the developed methodology. Additionally, although the adoption of ER technology was not directly the main focus of the investigation, it highlighted the high effort and time-consuming process required for reconstructing the environment and creating the experience.

The above considerations have led research activities to focus on workflow automation for reconstructing VEs in VXs. Chapter 3 addresses this challenge by describing an investigation involving alternative ER technologies for creating VEs. More specifically, it investigates the usage of BIM, usually adopted for the planning and maintenance of buildings, in the scenario of VXs for CH sites. Since most of the current solutions rely on proprietary tools, the investigation proposed a semi-automated BIM-to-VR workflow that adopts an open-source file format to reconstruct the VE and create the experience. The innovative potential of the workflow is showcased in a real-world use case, leveraging a VR platform that automatically reconstruct the VE of a museum and build a virtual tour starting from an enriched BIM file.

Subsequently, Chapter 4 presents two investigations exploring the use of DTTs based on generative AI for the creation of Embodied Conversational Agents (ECAs). The first is placed in the context of User eXperience (UX) within the CH domain. In order to achieve an optimal design for a unified UX across multiple VXs, the research takes into account two elements: VE and ECA. For the latter element in particular, the investigation proposed an ECA architecture that leverages LLMs and prompt engineering guidelines for building efficient agents. From this preliminary investigation, the research shifted towards the enhancements of specific capabilities of ECAs, namely their perception of the environment. Thus, the second investigation in this chapter regards the creation of environment-aware ECAs. Since this capability is often a core feature for improving interaction and conversation quality between ECAs and users, a possible solution relying on Vision Language Models (VLMs) is proposed. Therefore, the investigation introduces an approach to integrate a VLM-based module into traditional ECAs to enable environmental awareness. The approach was validated within an existing VR application derived from the state-of-the-art, i.e., a videogame. Additionally, an exploratory testing phase with users was conducted to evaluate the efficiency of the devised approach and the potential of VLMs in this context.

Finally, Chapter 5 presents a comprehensive summary of the conducted investigations and the overall conclusions of the thesis. The main contributions that emerged from the conducted investigations can be summarized as follows:

1. In VR applications, adopting a user-centered design based on key principles can be crucial for allowing the creation of effective VXs for specific target users (e.g., ASD individuals) and purposes. However, employing VR as a standalone DTT to craft such experiences may result in both conceptual and technical difficulties during the phases of design and development. A solution to these challenges can rely on converging other DTTs with VR, also when they are not usually adopted in the considered context.

2. The technical development of VEs can be supported by alternative ER technologies (e.g., BIM) for automating the workflows and easing the VX design process. Although a manual intervention is still currently required to fully enable this convergence of DTTs, the adoption of ER technologies in VR applications represents a first step towards optimizing workflows for creating VXs.

3. The aspects related to UX, Human Computer Interaction (HCI), and user guidance in VXs can possibly be sustained by using generative AI-based DTTs for creating ECAs. This objective can be achieved by carefully designing the prompt engineering modalities and architectures of the involved ECAs. However, the use cases in which such ECAs are placed should be cautiously selected to allow a fair evaluation of their potential benefits within VXs. Additionally, ECAs can be empowered with specific capabilities that can enhance their architecture and improve users' perception. Although based on preliminary results, the latter aspect proved to be truthful for certain perceptual dimensions (e.g., perceived knowledge), while others remained unaffected (e.g., human likeness). Thus, future research should aim to explore in a deeper way the unaffected dimensions to further enhance ECAs in VXs.

Overall, the investigations carried out during the three years of the Ph.D. studies highlighted valuable insights regarding VR and other DTTs. With a deeper exploration of VXs nature and the adoption of other DTTs, future applications of these technologies could be beneficial across various domains. Furthermore, the evolution of digital transformation is still ongoing, continuously introducing new DTTs. It is hoped that the convergence of such technologies with VR will bring further value within VXs, expanding their potential and opening new research opportunities.

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