Diminished Reality in Architectural and Environmental Design: Literature Review of Techniques, Applications, and Challenges

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Abstract –

The development of new visualization technologies, such as Mixed Reality (MR) and Augmented Reality (AR), has enabled many applications to improve our daily life. For example, AR has been used in landscape assessment by overlaying virtual objects on a real-world scene to enhance the user's experience. For many advanced visualization scenarios, the virtual removal of objects is done to prevent their intermingling with the existing objects, which could lead to inaccurate visualizations. Diminished Reality (DR) is the technique of virtually removing and seeing through undesired objects in an environment in real-time. The main objective of this paper is to review recent studies to provide an overview of the main procedures, techniques, and applications of DR. In this regard, this paper investigates definitions of DR, its enabling technologies, and its potential applications. It also discusses the current challenges of using DR systems in the Architecture, Engineering, and Construction (AEC) industry.

Keywords –

Diminished reality, Augmented reality, Construction Visualization, See-through vision, AEC industry, interior design, landscape simulation.

1 Introduction

Many new computer devices and software products have been introduced to the consumer market with the development of extended reality (XR) in recent years. XR refers to the environment that is generated by computer graphics and wearables to blur the line between a virtual environment and the real-world using human-machine interactions [1]. It consists of all the different forms of computer-altered reality, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR).

VR can be defined as a 3D computer generated environment, with which a user can connect and interact through various input and output devices in real time [2]. VR systems require the use of a Head-Mounted Display (HMD) device, such as Oculus [3], HTC Vive [4], and Google Cardboard [5] or an immersive combination of projection screens such as CAVE (Cave Automatic Virtual Environment [6]) to generate realistic sensations, such as images and sounds. AR generally refers to a technology that can display virtual objects onto the physical world in the form of an overlay to provide an enhanced experience[7]. AR adds more depth of relationship with the real environment, which VR systems lack, by adding computer-generated content to the real world. However, the fact that in AR scenarios the real and virtual worlds are separated decreases the level of user immersion. MR overcomes this challenge by merging the real and virtual worlds. In MR, the user can execute practical scenarios and experience interactions between virtual and real objects [8]. There are many practical applications of XR, and it has been implemented in various fields, namely Architecture, Engineering, and Construction (AEC) [9], retail industry [10], manufacturing training [1], marketing [11], entertainment [12], and medical science [13].

DR is a technique to visually diminish or see-through an object by recovering the background images of the area that is occupied by the object [14]. To date, various studies have explored the development of DR technology and its potential applications. The motivation for this research came from the lack of attention paid to DR applications and challenges. The main contribution of this paper is to provide a review of DR technology and the extent to which it has already influenced various applications, and the existing challenges to be addressed in the AEC industry.

2 Review Methodology

This research is the initial stage of a comprehensive research project to develop a framework to implement a DR technology in the AEC industry.

A "mixed methods systematic review" was implemented as the strategy to discover the knowledge gaps in this domain by summarizing and evaluating the evidence [15].

The overall process of review consists of four stages i.e., identification, screening, eligibility, and inclusion. In this research snowballing technique is used in combination with the systematic literature review method to ensure all key articles were covered. By using the mixed methods of review strategy, 65 key articles were filtered for the review of the DR techniques, in different applications. As shown in Figure **1**, 11% of studies are conducted for the application of AEC industry. This paper will review the DR technique, challenges, and opportunities in the AEC industry.

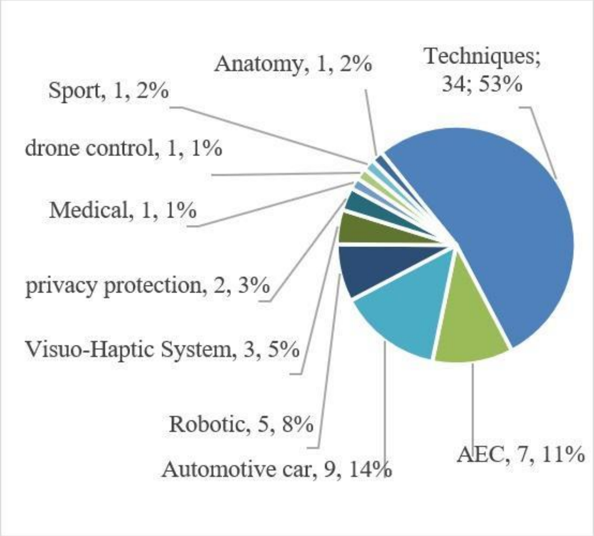

Figure 1. Number and percentage of the DR applications in 65 papers.

3 An Overview of Diminished Reality Techniques

To eliminate an object from a scene, the background information must be acquired from the scene using sensors such as cameras. Diminished reality techniques are classified according to the background recovery techniques used to fill in the space, namely inpainting-based diminished reality (IB-DR) and observation-based diminished reality (OB-DR). The inpainting-based diminished reality (IB-DR) technique fills the Region of Interest (ROI) with a plausible texture estimated from pixels surrounding the region or image patches around the ROI [16]. IB-DR approaches are basically based on computer vision and image processing techniques for object removal and reconstruction [17].

In observation-based diminished reality (OB-DR), the concealed view is recovered using the background observation results. Existing OB-DR approaches use multi-view-based procedures to get information about the occluded background. These methods give more convincing results than IB-DR methods, since they use the real scene behind the occluded objects. OB-DR can be classified into two categories depending on the background observation methods used: pre-observation-based diminished reality (POB-DR), real-time observation-based diminished reality (ROB-DR).

In POB-DR methods, the background is observed beforehand that is without the presence of the objects to be diminished. For example, Kido et al. [18] used a 3D model of the hidden background, which was generated in the pre-processing step to rebuild the DR background.

In this category, the model of the environment is reconstructed before the real-time procedure. Therefore, a high-quality DR result is expected. However, the time interval between the pre-observation stage and the DR processing stages may cause photometric and geometric differences between the physical and virtual scene [19].

In the case of ROB-DR, the background is observed in real-time using additional cameras. For example, Kameda et al. [20] used several surveillance cameras in the scene for seeing through the walls in real-time. This paper will review OB-DR methods including ROB-DR and POB-DR methods.

This paper will review OB-DR methods including ROB-DR and POB-DR methods. According to Mori et al. [14], the general approach for implementing a DR system is divided into four steps: scene tracking, object detection, background generation, and composition. (See Figure **2**).

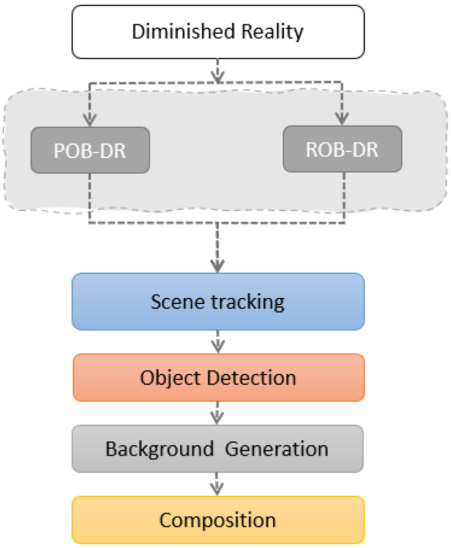

Figure 2. Overview of the general process of the DR system.

3.1 Scene tracking

In each DR system, to achieve the 3D recovery of a scene, the geometry of all the cameras is required, including the main camera and the background observer camera. Scene tracking can be classified into a fixed viewpoint and free viewpoint, depending on the camera movement. Six degrees of freedom (6 DoF) camera pose estimation including three elements for the position and three elements for the orientation of the camera relative to the object is performed. Scene-tracking methods can be classified into marker-based tracking and marker-less tracking approaches.

Marker-based tracking relies on explicit image patterns placed in the scene to estimate the camera pose. While these methods are fast, robust, and low-cost, they suffer from limitations, such as requiring uniform lighting conditions and recognizable markers that contrast strongly with the environment [21].

To avoid using such markers, several studies have focused on developing efficient marker-less tracking methods. Marker-less methods can be divided into sensor-based and vision-based methods. In sensor-based methods, positioning methods and sensors are employed to estimate the camera pose [22]. As for vision-based approaches, computer vision and image-processing techniques are used for camera pose estimation and tracking. While vision-based methods are more accurate and reliable than sensor-based methods, they are currently more complicated to implement and require a 3D model of the environment.

3.2 Object detection

The detection of the object to be diminished have become challenging procedures in DR [23]. Some studies used the manual detection of objects. In these methods, the ROI is determined by users to find their desired object. Manual detection of ROIs can be applied in the static environments where the target objects and cameras are not moving [14]. Some other studies tried to use automatic or semi-automatic methods for the object or ROI detection. In these methods, various features have been used for object detection, such as Haar-like features [24], histograms of oriented gradients [25], and CNN-based (Convolutional Neural Network) object detection algorithms [26]. Deep learning-based object detection is capable of detecting ROIs in dynamic scenes. For example, Kido et al. [18] utilized deep learning methods such as MobileNetSSD to determine ROIs of moving objects. There is also another category in DR studies that recovers the background without determining the ROI in the image. In this category, background images are overlaid on the user's perspective view. Even though this method decreases the computing cost of determining ROIs, it may result in unexpected artefacts surrounding the objects to be diminished [14].

3.3 Background generation

The background information must be registered to the user's viewpoint in a 3D scene. The information for the background generation can be sourced from surveillance cameras [28,29], a panorama image [29], depth camera on the HMD [30], handheld RGB cameras [18], RGB cameras mounted on a drone [31], and 3D laser scanners [32].

There are two approaches for background generation including: (1) 3D modelling and rendering, and (2) Image-based rendering (IBR). The former approach is a traditional way for the real scene simulation. In this approach, the geometric and illumination information of the scene is recovered in the modelling section using common methods such as Structure from Motion (SfM) and texture mapping. Then, the new viewpoint image is generated using the reconstructed scene from the modelling process. While the 3D modelling and rendering method is capable of completely displaying the scene's geometric information, it is extremely complicated, and requires high processing time and computational cost. Otherwise, 3D modelling and rendering methods result in non-photorealistic outputs with low computational cost.

On the other hand, IBR methods can directly generate the scene using acquired images. In these methods, new views are generated from a set of input images by transferring pixel values of the input images to their positions in the new views [33]. Rendering results in IBR methods are photorealistic because they are produced directly through input images. However, despite the traditional 3D modelling and rendering methods that enabled the users to see the background scene from any random viewpoint, IBR methods cannot continuously achieve random viewpoints because of the limitation in the input image viewpoints. Most common techniques in the IBR methods are light field rendering [34], unstructured lumigraph rendering (ULR [35]), and view-dependent texture mapping (VDTM [36]).

3.4 Composition

Composition is a post-processing step that is required to improve the DR result and decrease inaccuracies that may occur between the projected ROI in the current frame and the recovered background model. This process is also called seamless cloning in some studies [37]. In this procedure, the local differences are corrected in the boundary of the ROI and interpolated inside the ROI. The result is then added to the recovered background model to compute the corrected values. Composition process improves the DR results by reducing the visible seams in the stitched frames and adjusting the light mismatches. In this regard, alpha-blending processing [38] is more commonly used in DR studies. It produces new blended pixels by combining weighted background and foreground pixels. The results in DR studies indicate that alpha blending is computationally inexpensive and produces efficient solutions in dynamic scenes [39].

4 DR and Displaying Devices

Devices in DR studies can be used to display the main view, in which a user can see the results of the DR system, and the background view that observes the hidden background view. For the main view, research on diminished reality uses different display devices, such as head-mounted display (HMD) devices, hand-held display devices, and web cameras.

In several studies, HMD devices were used to implement and display DR effects. DR systems involved with Video See-Through-HMDs (VST-HMDs) devices provide users with immersive displays. On the other hand, Optical See-Through HMDs (OST-HMDs) are physically not applicable in a diminished reality system since pixels cover the real world in a semi-transparent manner [40]. Although this feature of OST-HMD devices was beneficial in the applications that aim at removing undesired objects semi-transparently (e.g. in [30]).

HMDs are not the only devices that are used in DR applications. Kameda et al. [20] proposed a new visualization method with a handheld mixed reality (MR) device that is a camera attached to a handy subnotebook PC (HPC). Handheld MR devices are more useful for realizing see-through vision in outdoor environments.

For background observation in DR studies, imaging sensors, namely fixed or moving RGB cameras and RGB-D cameras are more commonly used. However, the use of a 3D laser scanner to measure point cloud data of the background scene has also been emphasised [32].

5 DR Applications in AEC

DR is applied to simulations of various scales ranging from small-scale interior design applications to large-scale landscape assessments.

5.1 Interior Design Simulation

DR can improve the communication efficiency of design participants during the design process. DR function is used to display indoor renovation plans in a single-user MR system by Zhu et al. [41]. They later used a collaborative design system that allows multiple people to participate in the same MR environment simultaneously during the early design stage [30]. This study used a combination of the point clouds as a large-scale mesh of environment and BIM data as a 3D modelling of the complex objects for the background reconstruction. The BIM model production and modification for the DR background creation is time consuming and requires more resources than other methods such as point cloud. However, it is suitable for complex physical objects.

5.2 Landscape Simulation

DR momentum is also observed in urban design in the case of building, removing, or replacing a new construction. In an attempt to retain a good landscape, stakeholders must use simulation to plan potential landscapes with the innovative designs. By overlaying a 3D design model onto the physical world, AR can be applied to evaluate the potential landscape on a vast scale. DR, on the other hand, can be used to visually remove the structures during development. Inoue et al. [42] used DR for building and vegetation designs simulation. Kido et al. [18] presented a DR system to remove moving objects and immobile exterior structures in real-time for onsite landscape simulation. Yabuki et al. [32] developed a point cloud-based DR system to remove the outdoor buildings in real-time and facilitate landscape simulation. Fukuda et al. [43] developed an AR/DR system, in which the green view index is measured simultaneously with the DR simulation in an urban and planting design application.

6 DR Challenges in AEC

Determining efficient approaches at each stage of the DR processing, such as scene tracking and background recovery, is important due to the diversity of applications in this domain.

6.1 Registration and Alignment Issue

An accurate registration and alignment of the camera's position and orientation is an important challenge in implementing AR and DR techniques in outdoor environments. In many studies, special equipment or artificial indicators are utilized to estimate the camera pose. For example, Yabuki et al. [32] used feature points on video images and known points in point cloud data measured by a 3D laser scanner to get an accurate registration for DR simulation in urban areas. Calibration markers are also useful in camera pose estimation. Kameda et al. [20] used distinguishable structures of buildings, so called landmarks, as calibration markers. Texture of these markers is required to be updated to deal with the illumination changes in the outdoor environment. Surveillance cameras embedded in the environment are useful to update these texture changes in the landmarks.

Stable tracking is difficult in an outdoor environment due to the illumination inconsistencies in the image and the existence of various sources of noise. Therefore, maintaining stable tracking over an extensive period can be a critical problem to improve the user experience of outdoor AR/DR systems [42].

An efficient method of background reconstruction is very important for diminished reality in the AEC industry applications. Discontinuity will appear at the boundaries of the reconstructed background and the rest of the reference view without a proper reconstruction. Multi-camera approaches are advantageous by allowing real-time updates of the background. However, they require additional cameras, are less flexible than single-camera techniques, and require a more elaborate setup [44]. In addition, existing multi-view geometry-based DR techniques used depth searching in overlapping areas of each image, making it impossible to see the image from different angles. These methods are computationally expensive because of using several cameras.

6.2 Illumination Consistency

Illumination consistency between the run-time processing and 3D virtual model of the background environment is another challenge in DR systems. To solve this issue, Fukuda et al. [45] used deep learning algorithms during the DR simulation to achieve this illumination consistency. Liu et al. [46] solved the problem of illumination consistency in AR and MR using surrounding light estimation in the real environment. Most POB-DR systems managed only static scenes under consistent illumination conditions since they assumed that the object elimination is done instantly after background observation or is performed in indoor environments. IBR methods can help solve these practical problems in POB-DR [39].

Inconstant illumination and noises are also affecting the stable object tracking in the outdoor environment. Inoue et al.[42] used perspective n-points (PnP) problems to estimate camera motion in an outdoor environment. PnP is a problem of estimating the camera pose from n 3D-to-2D point correspondences. In this method, the n 3D points are in advance defined as tracking reference points and their corresponding 2D points are traced by estimating the optical flow. Liu and Chen [40] applied a fast colour correction at high frame rates to compensate for the lighting changes that may occur between scanning and run-time.

6.3 Heavy Data

In outdoor environmental applications, utilizing effective strategies to overcome the challenges of treating vast amounts of data and considering a wide field of view is essential. For instance, in architectural and urban applications, loading a 3D city model is heavy and time-consuming on mobile devices and tablet computers, which makes these devices less applicable than a laptop PC in DR simulations for architectural and urban design applications. Therefore, a distributed computing system available over the internet, such as cloud computing would be a good option for these applications [18].

To summarize, existing DR approaches generally rely on one or more of the following assumptions: multiple viewpoints, planar surfaces, limited camera movement, markers for pose estimation, simple backgrounds, or existence of a pre-scanned models without objects to be removed. However, several studies attempted to solve the aforementioned challenges.

7 Conclusion

This study reviewed previously published articles found in the literature to propose a three-part overview of the various DR applications. The first part focused on the definition and influences of DR, the second categorized the enabling technologies in DR, and the final part introduced applications of DR in the AEC industry and existing challenges. This study has found that there are numerous applications for DR, for instance, AEC industry, autonomous cars, entertainment, and visuo-haptic systems. DR presents many challenges, such as difficulties of processing a large amount of data for large-scale environments, registration and alignment problems, and illumination consistency. Nevertheless, several studies attempt to solve these challenges. In general, this research extends our knowledge on the relevance of DR in various applications and presents a general workflow for implementing a DR solution.

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