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Shadow Generation in Mixed Reality: A Comprehensive Survey

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Shadow Generation in Mixed Reality: A Comprehensive Survey

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ABSTRACT

This paper provides an overview of the issues and techniques involved in shadow generation in mixed reality environments. Shadow generation techniques in virtual environments are explained briefly. The key factors characterizing the well-known techniques are described in detail and the pros and cons of each technique are discussed. The conceptual perspective, the improvements, and future techniques are also investigated, summarized, and analysed in depth. This paper aims to provide researchers with a solid background on the state-of-the-art implementation of shadows in mixed reality. Thus, this could make it easier to choose the most appropriate method to achieve the aims. It is also hoped that this analysis will help researchers find solutions to the problems facing each technique.

Keywords:
Augmented reality, Hard shadow, Mixed reality, Shadow rendering, Soft shadow.

1. INTRODUCTION

There is no doubt that augmented reality (AR) has the potential to become a fascinating widespread technology not only in computer graphics but also in many other subjects. In about two decades, AR or in general, mixed reality (MR) has turned into one of the most attractive topics in computer graphics with many researchers attempting to obtain satisfactory results [1−3]. In MR, realism can be achieved through the addition of shadows for virtual objects onto virtual and real objects.

AR is a subdivision of MR, which combines the real world with virtual objects. AR makes it possible to control virtual objects in a real environment as desired. For instance, AR allows having the interaction of a snake in a movie using a virtual snake instead of a real one.

Many researchers have recently focused on AR as most computer graphics applications require computer-generated objects to be seamlessly integrated into natural images or videos such as environmental assessments and computer games. Moreover, the appearance of virtual objects should reveal the consistency of the effect of the interaction between objects or even sky colour in outdoor rendering.

There are various shadow techniques such as drawing a dark shape similar to the occluder under the occluder on the plane. Although it is not realistic, it has been used for a period of time. The other simple method used to create real-time shadow is projection shadows, which are still employed in game engines especially in AR [4−6] and many works in Teyyare Animation Studio. This technique, initially proposed by Tessman et al. [7] is a fast rendering method whereby shadows are created. Although this method is fast, it can only project shadows on a flat surface such as walls or on the ground.

Shadow volume, proposed by Craw [8], is the famous geometrically based technique to generate shadows on arbitrary objects. The main step in this technique is silhouette detection, which is the expensive part of the algorithm.

Shadow maps [9] mark an important milestone in the evolution of shadow generation, which are image-based and, as a result, faster than shadow volumes. Shadow maps are used in many different fields of computer graphics. Various improvements are employed in shadow maps [10−14].

This paper presents a comprehensive and up-to-date review for researchers interested in AR shadow generation. The paper can be considered as a starting point for researchers to overcome the current problems of shadow generation in AR.

In general, projection shadows are easily and quickly rendered to be applied in AR but suffer from casting on other objects. On the other hand, geometrically

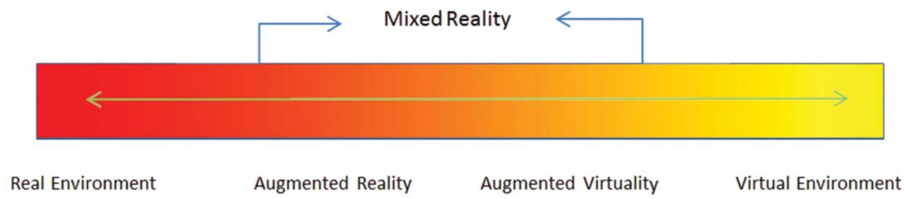


Figure 1: Taxonomy of mixed reality environments [15].

based shadows are sufficiently accurate but suffer from high rendering costs. Image-based techniques are currently considered for shadow generation in AR. It seems that the current image-based technique should be intended for generating realistic shadows in MR.

2. DEFINITION OF MIXED REALITY

MR is the integration of virtual environments (VEs) and real environments (REs). A virtual object set within an RE constitutes an (AR) system. An AR system incorporates more real objects and a few virtual objects with the real AR taking a dominant role over the virtual. On the other hand, if a real object is set within a VE, the system is called augmented virtuality (AV). In this case, most of the system is virtual. Figure 1 illustrates these concepts.

In general, MR can be characterized by the integration of virtual and real objects, real-time interaction, and 3D registration.

AR is used in many different areas, including training aid for surgery [16], maintenance and repair, annotation, robot path planning, entertainment, and military aircraft navigation and targeting [1].

In addition to the inclusion of some virtual objects within the RE, AR makes it possible to remove or hide some objects in REs, which is known as diminished reality.

3. TIME LINE OF SHADOW IN AUGMENTED REALITY

Until very recently only a few researchers focused on shadow generation in AR. Nevertheless, much research is presently being conducted in this realm to improve the knowledge base. An accurate timeline of shadow generation in AR is presented in Figure 2.

Sato et al. [17] were the first researchers who added shadows in AR systems. The real flashlight technique,

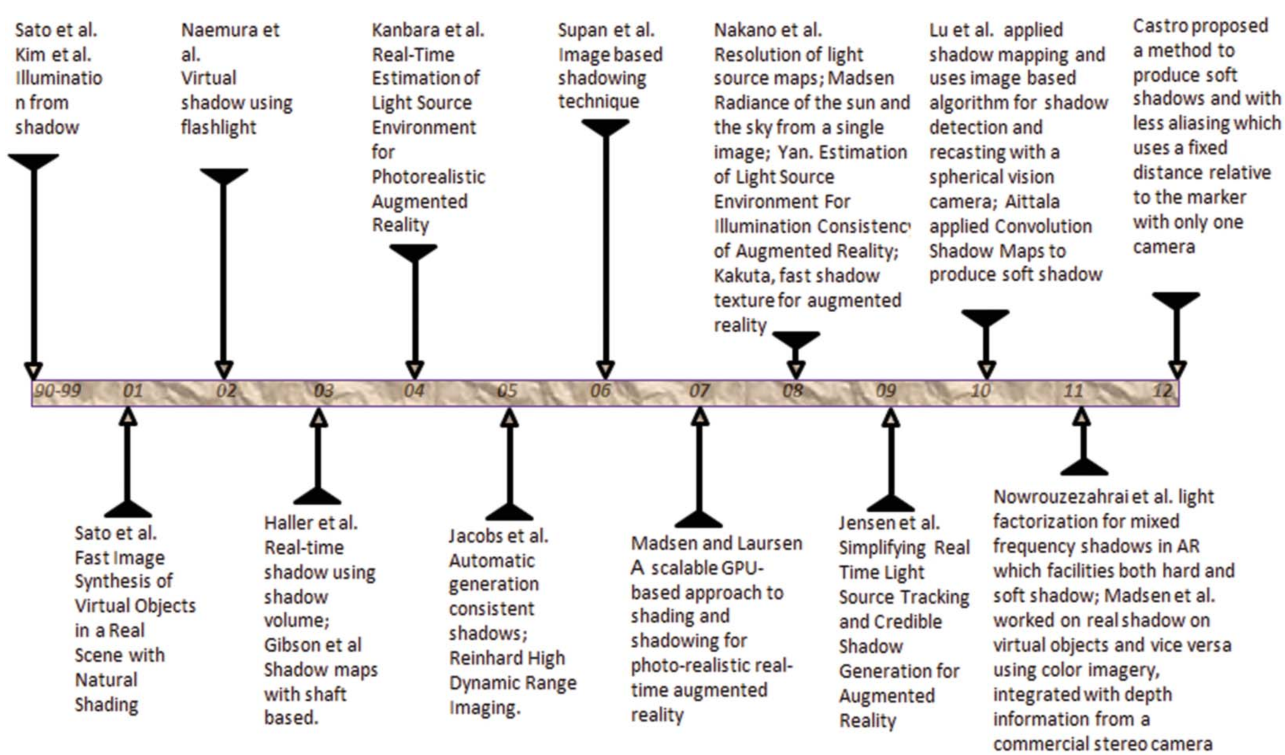


Figure 2: Timeline of shadow generation in AR.

proposed by [18], was employed to include shadows in AR. Haller et al. [19] generated hard volume shadows on other objects using the phantom technique, which will be explained in geometrically based hard shadow generation. Kanbara et al. [20] employed shadows in AR focusing on light source detection, which forms the basis of work done by [3]. Jacobs et al. [21] focused on colour-consistent virtual shadows in a real scene. Their work is image-based rendering.

Madsen et al. [22] presented graphic processing unit (GPU)-based shading to render the AR scene realistic. The physically based approach to represent real scene illumination is the distinguishable feature of the technique. Nakano et al. [23] worked on light source estimation to generate soft shadows. They increased the number of light sources and reduced the resolution of light source maps. Jensen et al. used the concept of Kanbara et al. [20] to generate soft shadows using projection shadows with respect to the real light source. Aittala et al. [24] applied image-based shadows such as convolution shadow maps to cast shadows on other objects. Nowrouzezahrai et al. [25] performed soft shadows for animated objects. In 2012, Castro et al. [26] generated soft outline shadows using projection shadows as there were no shadows cast on other objects.

4. REAL-TIME SHADOW TECHNIQUES

4.1 Projection Shadows

In this method, the entire object is simply rendered a second time from the light source position. This method is useful due to its high rendering speed. It is fast due to projecting a shape on a flat receiver. There is no need to use any buffers or create volume or detect the silhouette. Through the application of the following shadow matrix, the projection of objects will be constructed. Figure 3(a) illustrates the theory of projection shadows while Figure 3(b) shows the conventional projection shadows in AR.

In computer graphics, projection shadows are widely used especially when the focus is not on shadows, examples include mobile AR, motion animation, and tracking. Among the latest works focusing on shadows using projection shadows for generating soft shadows are [4−6,8].

4.2 Shadow Volumes

In this technique the silhouette of occluder must be recognized. This part is called silhouette detection. Silhouette detection has made shadow volumes an expensive technique in shadow generation. It requires more calculations to recognize the geometry of occluder and the scene [27,28]. The accuracy of the results from shadow volumes is the main advantage of the method which prevents this technique from being outdated. The accurate and sharp shadow edges are not so easily generated using other techniques such as shadow maps. Moreover, shadow volumes do not scale well with multiple light sources. The next step after silhouette detection with the respect to the light source is the generation of a volume between the occluder and shadow receivers. Any pixel located within the volume is in shadows and must be shaded accordingly [8]. Figure 4(a)−(c) shows the volume, the conventional shadow volumes, and volumetric shadows with shaft of light [30], respectively.

Among the many improvements made by researchers one can refer to Billeter's [29] who presented single

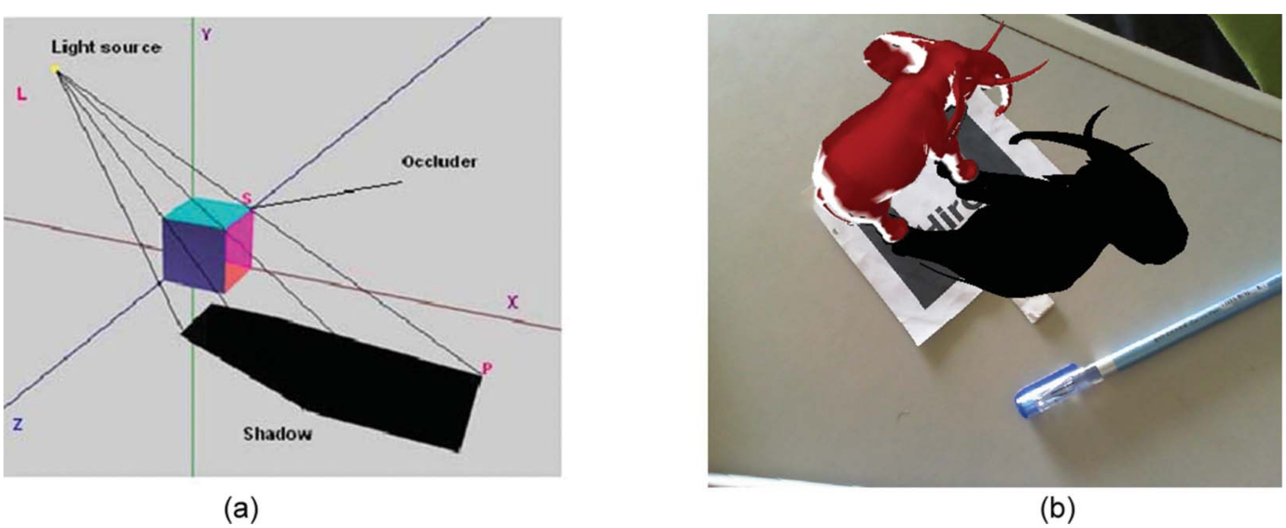


Figure 3: (a) Theory of projection shadow and (b) result of original projection shadows in AR.

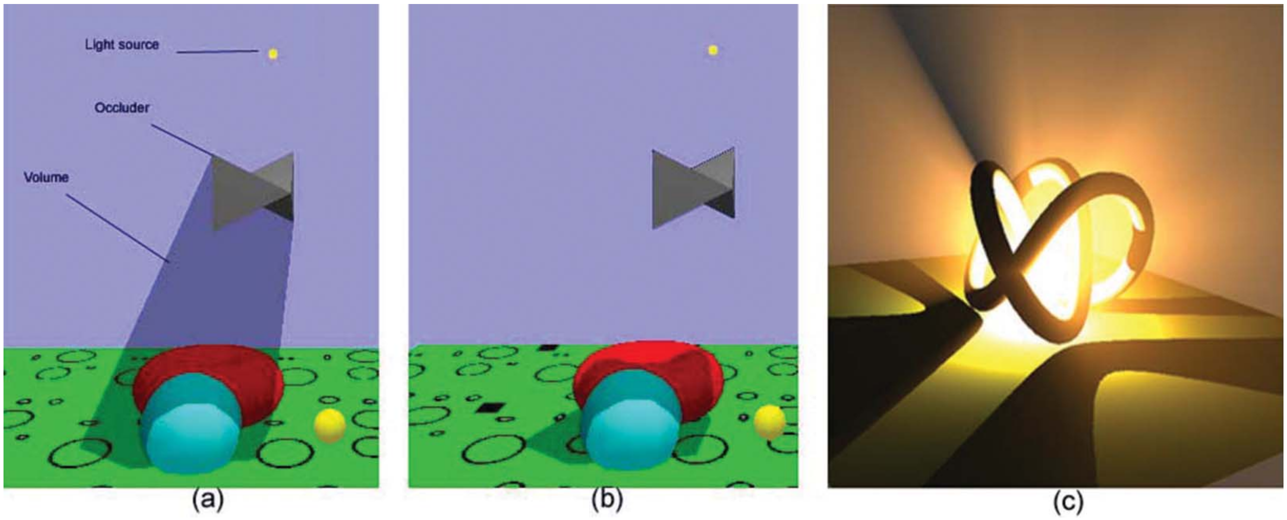


Figure 4: (a) The volume of shadow volume, (b) result of shadow volumes, and (c) volumetric shadows [29].

scattering effects in homogeneous participating (Figure 5(a)), and Baran [30] who also used shadow volumes for single scattering (Figure 5(b)), the resulting shadow volumes can be used for generating realistic shaft of light for indoor rendering. In the case of AR, Madsen et al. [31] performed shadow volumes to cast virtual shadows on real objects.

Kolivand et al. [32] prepared a survey on shadow volume improvements indicating the step-by-step progress of shadow volume algorithms. They categorized different techniques to enhance geometrically based shadow algorithms.

4.3 Shadow Maps

Shadow maps are one of the best shadow generation techniques due to fast and easy-rendering of 3D objects regardless of silhouette detection. Numerous improvements on shadow maps and the widespread use of the real-time case prove this claim. This rendering is relatively inexpensive. The two main shortcomings are z-aliasing and undersampling. Z-aliasing occurs due to inadequate shadow map resolution. During the coordinate transformation, a mismatch between the sampling rate of screen-space pixels and shadow texels is likely to occur. Aliasing can be attributed to resolution. Aliasing can be improved by creating a high-resolution shadow map. Undersampling caused aliasing artefacts, which are based on the point-sampled method. In general, it can be said that there is an uneven mapping of resolution between the scenes rendered from each viewpoint. Another problem is that it is difficult to use shadow mapping technique to cast shadows from light surrounded by objects.

Figure 6 (left) shows the result of conventional shadow mapping where aliasing can be observed easily while soft shadows on the right illustrates the ability of shadow maps.

Sato et al. [17] computed total irradiance from the radiance distribution of the real scene to generate shadows

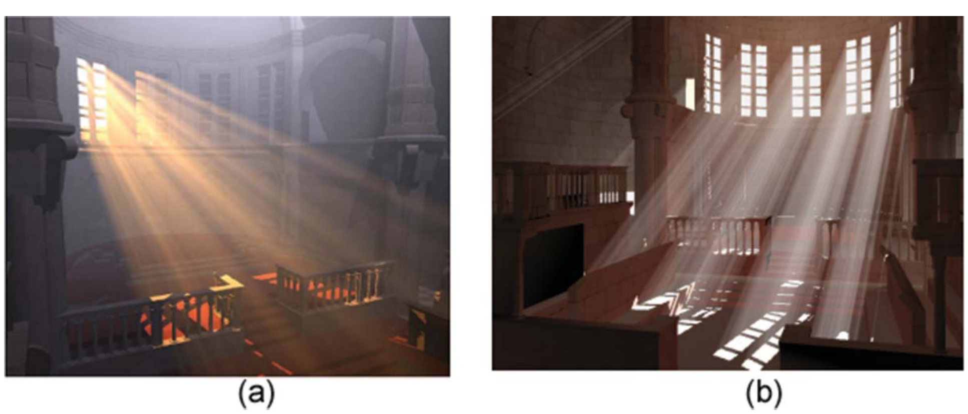


Figure 5: Volumetric shadows: (a) [29] and (b) [30].

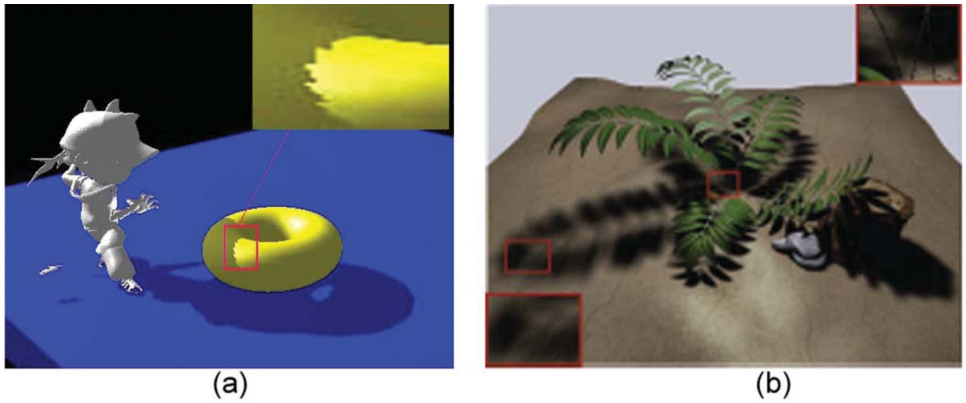


Figure 6: (a) Conventional shadow maps with aliasing and (b) an improvement on shadow maps [12].

in AR. The overlap between real and virtual shadows is avoided during the implementation. Pessoa et al. [33] produced the shades, which used the simple shadow mapping without self-shadowing.

Scherzer et al. [28] categorized and analysed various improvements on shadow mapping algorithms. They introduced many different parameters for selecting a suitable image-based algorithm.

5. SHADOW GENERATION IN AUGMENTED REALITY

There is not much difference between common shadow generation and shadow generation in AR except for casting shadows on real objects. Moreover, implementing shadows in AR is more costly as it involves management of two different data-sets, the data coming from capturing the REs and the virtual data augmented in REs.

To achieve a realistic MR, shadows play an important role and are an essential factor for 3D impression of the scene [19,21]. AR simulation of shadows for a virtual object in REs is difficult due to deeds reconstruction of the real-world scene, especially when details approximation of the real-scene geometry and the light source are known [21]. Jacobs et al. [34] prepared a classification of the illumination methods into two different groups, common illumination [2,19,21,35,36,37,38] and relighting in MR. The credibility of shadow construction with the correct estimation of light source position can be found in [3,20].

Geometry techniques are based on detecting the geometry of the scene, including occluders and shadow receivers while image-based techniques are 3D rendering techniques, which capture the environment and represent the real scene as an image. Image-based techniques are currently receiving much more attention than conventional geometrically based techniques. Silhouetted detection is an extensive part in the geometrically based rendering technique while image-based techniques use a collection of images to render new views. In the geometrically based techniques the geometry of the whole environment must be known, whereas in the image-based technique there is no such requirement. The scene will be recognized by capturing the scene into Z-buffer or depth map.

5.1 Hard Shadow in AR

Hard shadows are those with a point light source having a sharp brim and including fully shadowed regions without any soft edges. They are widely used in AR due to their shorter rendering time as compared with soft shadows, which require more calculations.

5.1.1 Geometrically Based Cases

Naemura et al. [18] introduced a technique to create the virtual shadow of real objects with respect to a virtual light source where the real objects and the virtual light source are equipped with 3D sensors. Projection shadows are used for simple objects while shadow maps are applied for more complicated objects. The technique is employed for both hard and soft shadow cases.

Jacobs et al. [21] proposed a real-time rendering method to simulate colour-consistent shadows of virtual objects in MR. Their method includes three steps. In the first step, the shadows of real objects are identified using texture information. In the second step a mask is generated to prevent further rendering in these shadow regions, which is called the protection step. The last step in virtual shadow generation is intended for virtual objects based on shadow volume. They claimed the method is implemented in both shadow volume and shadow mapping. The technique takes into account the overlapping problem of [19] and [39].

The overlap is removed between the virtual and real shadows by removing the parts of virtual shadows located in the real shadow regions. The disadvantage of the method is the need for different scale factors for different materials or different directions of light source. Only one light source is used and the overall lighting conditions are ignored.

Haller et al. [19] modified shadow volumes to generate shadows in AR. In this algorithm a virtual object such as the real one is simulated but not more accurately. These are called phantoms. The silhouette of both the virtual and the phantom objects are detected. Phantom shadows could be cast on virtual objects and virtual shadows could be cast on phantom objects.

This method requires many phantoms to cover the real scene. Silhouette detection, the expensive part of shadow volumes is the main disadvantage of this technique especially in complicated scenes. To recognize a real object and to generate the phantom is another problem with this algorithm. This approach has the advantage of producing shadows with less aliasing than the conventional shadow mapping but it is more costly and more sensitive in terms of the complexity of the geometry especially for mobile devices.

The method is improved in [40] focusing on photorealism and non-photorealism effects on virtual objects. They avoided using shadow mapping algorithm since shadow maps destroy the impression due to the use of big rasterized shadow map pixels. Merging virtual lights and real lights resulted in four types of shadows related to virtual and real objects.

5.1.2 *Image-Based*

Hu [41] investigated and proposed some rebus definitions on shadows for AR using supporting lines. The algorithm simply blends with depth maps for real objects and shadow maps for virtual objects, then combines the graphics and the input image using Z-keying (depth map). The following chart is an overview of the algorithm.

The problem with this method is self-shadowing, which is not specified. The other drawback is that like most of the other simple triangulating scheme it is sensitive to noise. In the course of determining the location of the light source some support line direction mistakes are amplified.

Nowrouzezahrai et al. [25] applied light factorization for mixed frequency shadows in AR facilitating both hard and soft shadows using shadow mapping algorithm with surrounding scene lighting. Although, they emphasize direct and indirect lighting, they could generate both hard and soft shadows for static and animated virtual objects in AR. The shadow generation is based on shadow maps.

Virtual Asuka [42] is an AR project where shadow mapping is applied and image-based algorithms for shadow detection and recasting with a spherical vision camera are employed. First, shadow regions are detected using camera sensitivity. Then, by applying the illumination invariant constraint and employing the energy minimization method [42] the shadow regions are picked up and used to recast shadow onto the virtual object with the spherical vision camera. Recasting the shadow regions on the virtual objects forms the main part of this algorithm. Since the foreground depth and height is estimated using the spherical vision camera, the shadow maps are applied on the non-flat surfaces using a simple formula.

The algorithm can be used for static objects and the camera must be fixed in the MR system. The main issue with this algorithm is the inability for dynamic cameras, which allow viewers moving in the virtual world.

5.2 Soft Shadow in AR

Soft shadows are the main requirements in the current AR systems to make the environments maximally realistic. The widely used techniques are categorized as follows.

5.2.1 *Geometrically Based*

Sato et al. [17] and Wang et al. [43] proposed different methods for shadowing and shading, respectively, considering illumination estimation but not requiring specific calibration. Wang et al. [44] combined these two methods and presented a hybrid method for multiple directional source estimation.

Geometrically based algorithms were not used for soft shadow generation until Kakuta [45] introduced Virtual Kawaradera project, which is the reconstruction of the Kawaradera temple located in Asukain village using AR. In this project a fast shadowing method is presented for virtual objects. The method creates shadows using a set of basic images rendered in advance.

The method is based on [46] technique, which uses a set of images rendered in advance. They used multiple lights, which approximate the illumination of the real

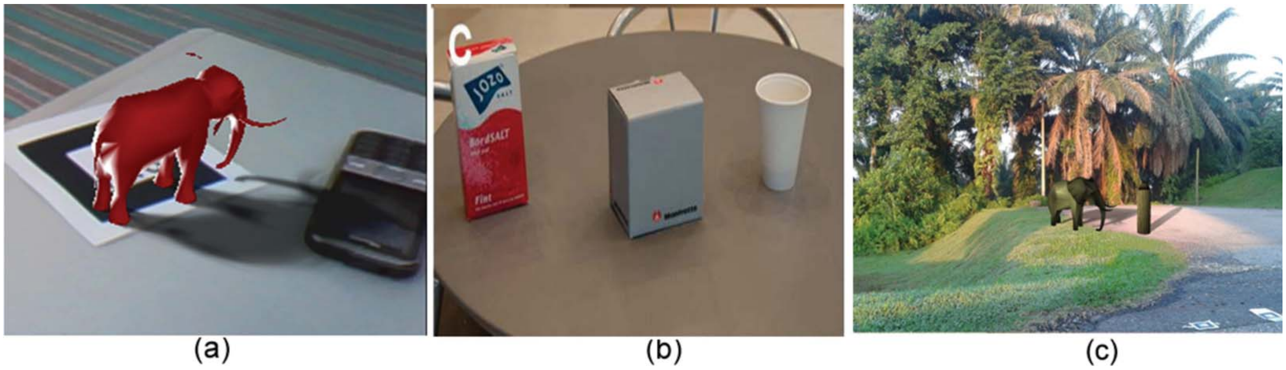


Figure 7: (a) Soft projection shadows [6], (b) soft projection shadows [3], and (c) soft projection shadows for outdoor rendering [47].

world. The next step is to synthesize these basic images to generate soft shadows. The main difference in [46] is the fact that it took samples only from the direction of vertices while [45] took samples from whole points in every polyhedron face corresponding to various outdoor scene conditions.

They have approximated the scene illumination taking into account a hemispheric surface light source as follows:

For shadow generation, they expressed the shadow with rough areas and set some shadowing planes in front of the building. The method used basic images as mask texture just for some obvious parts on-line and whole components off-line. The big problem is matching the virtual scene radiance of the real scene with synthesized images in AR systems.

Jensen et al. [3] proposed a method to generate soft shadows using a real light source (Figure 7(b)). They initially captured the environment light from a specular sphere, and then searched for the dominant light direction using the median cut algorithm. The disadvantages of this technique are its use of projection shadows and incapability to generate shadows on other objects. They generate soft shadows using a number of light sources. Therefore, far light sources could generate almost desirable results but for close light sources the results were not acceptable. Noh et al. [4] also use the same technique. Kolivand et al. [6] improved the technique employing soft shadows for virtual objects in REs (Figure 7(a) and 7(c)). The technique works successfully for far and near light sources. The technique is applied for outdoor rendering taking sky colour into account to make the scene more realistic by applying the interaction between sky colour and virtual objects in MR.

Gibson et al. [36,47] developed the Haller's method [19] for simulating soft shadows, which were suitable for photorealistic AR. In this algorithm shaft-based hierarchical data structure and a technique for soft shadow generation using multiple shadow-maps are integrated. The trade-off between realistic shadows and rendering time is highlighted in the algorithm. The prominent point of the algorithm is indoor and outdoor illumination except for direct sunlight or other directional illumination. It is worth mentioning that this algorithm is not view-dependent and it is possible to move the camera inside the AR system.

Madsen et al. [22] proposed an AR rendering system using high dynamic range of environment maps, which could represent the real illumination inside AR systems.

Recently, Madsen et al. [31] worked on real shadows on virtual objects and vice versa using colour imagery, integrated with depth information from a commercial stereo camera setup. The method is applied taking into account the estimation of the radiance of the sky and the sun for outdoor scenes. Shadow detection is highlighted in this paper as well as the radiance of the sky and the sun for outdoor environments.

5.2.2 *Image-Based Shadowing*

Much image-based lighting (IBL) research has focused on virtual light source positioning in off-line rendering [45,48]. This is where the environmental map regions should be divided in terms of equal integrated brightness. Agusanto et al. [37] used the IBL technique to improve lighting without considering shadows. Karlsson and Selegard generate soft shadows in AR using the IBL technique [49].

Supan et al. [50] proposed a soft shadow technique for AR systems, which used a dome of shadow casting

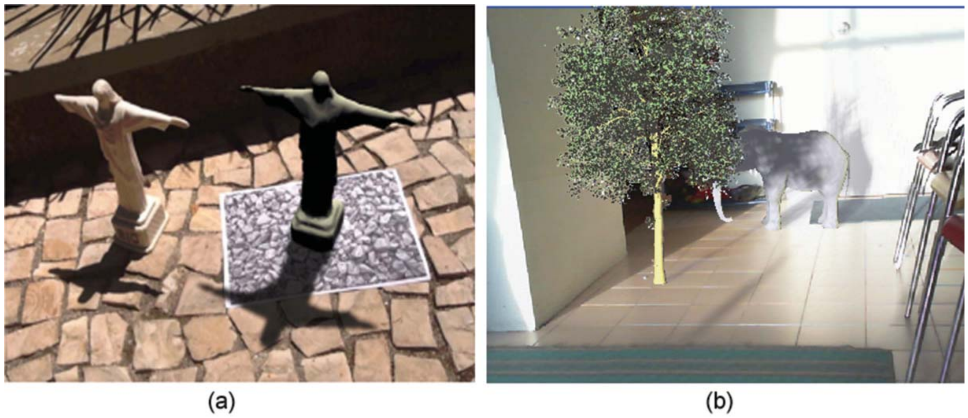


Figure 8: (a) Castro results [26] and (b) Kolivand results [56].

light source to approximate the result of environment shadowing. Seamless integration of a virtual scenario, image-based shadowing, presentation of three setups, and no pre-processed data are the main advantages of this technique.

The method is image-based but there is no evidence documented for casting shadows on the other objects.

Nakano et al. [23] proposed a technique to find the resolution of the light sources maps to create perceptually correct shadows. First, they conducted a set of systematic subjective evaluations, and then applied this information to control the resolution of the light source maps to construct the artificial shadows.

Yeoh et al. [51] proposed a technique for realistic shadows in MR using a shadow segmentation approach, which recovered geometrical information on multiple faded shadows. The paper focused on dynamic shadow detection in a dynamic scene for future requirements in MR environments. The technique is similar to shadow catcher in [52] but in dynamic scenes. By introducing a repetitive reinforcement operation, soft shadows and further enhancement of the system robustness are achieved. Among the numerous shortcomings of this method one can refer to the irradiation of the occluder to become detectable, unstable shadow detection in more brightly lit environments, and camera-dependence of the light sources.

Aittala [24] applied Convolution Shadow Maps (CoSMs) [53] to produce soft shadow in MR employing both mip-map filtering and fast summed area tables [54] to enhance blurring with variable radius.

Castro et al. [26] proposed a method to produce soft shadows with less aliasing using a fixed distance relative to the marker, but with only one camera (Figure 8 (a)). The method also performs one sphere mapping such as [20], but selects a source or sources of light most representative of the scene. This is important because of hardware limitations of mobile devices. The method supports self-shadowing as well as soft shadowing. They used filtering methods such as percentage closer filtering (PCF) [55] and variance shadow maps (VSM) [11] to generate soft shadow.

The method is applicable to both external and internal scenes. They found that the VSM is very advantageous compared to its predecessors shadow mapping and PCF. The main problems of this method are related to sampling and aliasing depths. These problems are closely connected and depend on the resolution for calculating visibility. Kolivand et al. [56] employed hybrid shadow maps (HSMs) to caste soft shadows on other virtual and real objects, which can be seen in Figure 8(b) [57].

6. DISCUSSION

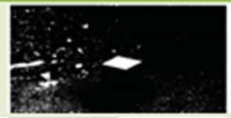
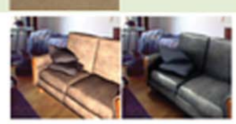
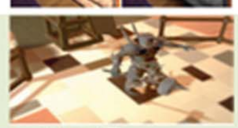
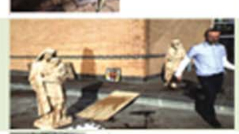
Now, we are going to give some practical hints on the choice of the appropriate technique to be used in a particular situation (See Table 1).

MR environments have attracted much attention in many areas such as computer graphics, archaeology, architecture, art, commerce, education, industrial design, medical, military, navigation, sports, and entertainment.

Shadows are the main factors rendering the virtual object more realistic in MR systems. Although soft shadows look much more realistic, high rendering time is the main reason why hard shadows are still usable.

Although, both shadow volumes and shadow maps can be implemented in the current generation of

Table 1: Comparison between applied shadows in mixed reality

Year	Researcher	Technique	Light focusing	Quality	Result
1999	Sato et al.	lighting	Yes	Low	
2000	Naemura et al.	H-G	Yes	Low	
2003	Haller	H-G	No	Medium	
2004	Kanbara et al.	H-G	Yes	Medium	
2005	Jacobs et al.	H-P	Yes	Low	
2006	Supan et al	S-I	Yes	High	
2007	Madsen et al.	H-I	Yes	Medium	
2008	Nakano et al.	S-I	Yes	Low	
2009	Jensen et al.	S-G	Yes	Low	
2010	Aittala et al	S-I	No	High	
2011	Nowrouzezahrai et al.	S-I	No	High	
2012	Castro et al.	S-I	No	High	
2013	Medsen et al.	H-G	No	Medium	
	Kolivand	S-I	Yes	High	

Note: H is hard shadow supporting, S is soft shadow supporting, I represents the image-based technique, G is supporting by geometrically based technique, and P is projection shadow techniques. Algorithms taking illumination into account are marked Yes.

graphics cards such as ATI Radeon and NVIDIA GeForce. Hardware-accelerated shadow maps usually make use of one texture unit whose number is considered too few in current graphics cards especially for NVIDIA GeForce more than three [58].

Although shadow volumes generate sufficiently accurate shadows, they are not suited for a scene with many small objects such as trees. Shadow volumes cannot cover the shadows of hair, fur, and smoke. They are limited by using stencil buffer.

Shadow mapping requires an extension to be implemented in current graphics hardware. It uses GL_ARB_SHADOW to compare depth values.

Aliasing is the biggest problem of shadow maps, especially when the light source is situated far away from the occluder, which produces a small shadow. Aliasing occurs due to synchronization of the two depth maps. The scene must be rendered separately for each light source. This will take longer for an omnidirectional light point. It requires a 180° shadow frustum that must be handled by buffering. A problem occurs when a light source is located inside the scene as this situation requires six buffers to handle all shadow cases.

Shadow volume is the most accurate technique used to create shadows on other objects. A sharp outline of shadow volume would make it more precise. The geometrical base of shadow volume makes it quite different from aliasing. Shadow volume has some advantages as well as critical limitations.

In general, geometrically based techniques are expensive due to silhouette detection. Anti-aliasing is the prominent advantage of the geometrically based technique, which makes them suitable for hard shadow generation. When the light source is near to the occluder geometrically based techniques are appropriate.

Image-based techniques are fast enough, especially for hard shadow generation and they are convenient for soft shadows as compared with geometrically based techniques. Nevertheless, they still suffer from aliasing. Most previous MR techniques applied simple shadow maps with the exception of some recent research. CoSMs, PCFs and VSMs are the latest algorithms employed to avoid aliasing. In these cases variance shadow mapping is very advantageous compared to its predecessors shadow mapping and percentage closer filtering.

Projection shadows are suitable when the focus is not on shadows. Examples include animations, gestures, and mobile AR. Soft projection shadows are appropriate when shadow receivers are flat and fast shadows are required. To cast shadows on other virtual objects shadow maps and their extensions, e.g. CoSMs, FCF, VSMs, and HSMs, are convenient techniques.

Considering the fact that all processing relevant to soft shadow generation is performed in the graphics cart, a high-quality graphics card is needed. For instance, to use CSMs and HSMs for the generation of semi-soft shadows, NVIDIA GeForce above 8800 is necessary while shadow volumes can be implemented using any hardware.

Various techniques can be used for light source detection. For instance, Aittala et al. [24] take the real-light information into account using a white ping pong ball. Nowrouzezahrai [25] considers the real-light information using a reflective sphere. Madsen also takes real-light information (sun direction) into account.

Illumination is the state of the art to enhance the realism of mixed reality environments. Ray-tracing and radiosity techniques are convenient to reveal the illumination not only in VE but also in MR.

7. CONCLUSION

This paper has surveyed shadow generation algorithms, the state of the art for each technique, their applications and limitations in MR. Diversity types of shadow generation in MR environments are categorized through hard shadows and soft shadows, which are the highlighted categories in shadow generation. For each part, geometrically based and image-based techniques are classified. After categorizing and summarizing the widely used techniques, the paper identifies the main limitation of each.

Projection shadows are still used in AR due to low rendering time. The big problem with this category is limitation of flat surfaces. Shadow volumes are used in AR but not more, due to extensive calculations in silhouette detection. The accurate outline are the only reason why these kinds of shadows are still used. Image-based shadows are the last type of shadows, which are mostly appreciated due to having shadows on other objects and low enough rendering time compared to geometrically based shadows without worry about silhouette detection.

To date, PCF, VSM, and CoSMs are the only state-of-the-art shadow generation, which have been employed in MR. More recently, HSMs are performed in MR to generate soft shadows in outdoor MR rendering. Some other algorithms such as deep shadow maps [59], adaptive shadow maps [60], perspective shadow maps [61], layered variance shadow maps [62,63] could be effective in the case of soft shadows or even semi-soft shadows.

Appling illumination using ray-tracing and radiosity in MR environments is one of the state of the art to make the virtual objects indistinguishable from the real ones.

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