A Framework for Perceptual Studies in Photorealistic Augmented Reality

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ABSTRACT

In photorealistic augmented reality virtual objects are integrated in the real world in a seamless visual manner. To obtain a perfect visual augmentation these objects must be rendered indistinguishable from real objects and should be perceived as such. In this paper we propose a research test bed framework to study the different unresolved perceptual issues in photorealistic augmented reality and its application to different disciplines. The framework computes a global illumination approximation in real-time and therefore leverages a new class of experimental research topics.

KEYWORDS: Human perception, photorealistic augmented reality, real-time global illumination

INDEX TERMS: H.1.2 [Models and Principles]: User/Machine Systems—Human factors; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology

1 INTRODUCTION

Augmented Reality (AR) technology offers a way to represent visually virtual content related to the real world. Its applications have been proposed to advertise products, in architectural visualization, edutainment systems or for enhancing cultural heritage sites.

As much progress has been made considering the spatial registration of real and virtual content (geometric), there are still a large number of issues with respect to the visual integration (photometric). These issues can be divided into two main areas: problems that are of technical nature, like the narrow field of view of Head Mounted Displays (HMDs) and problems that are of perceptual nature. For example depth perception differs for virtual objects compared to real objects. Although there are many studies in this area, there are still open questions and we are not absolutely certain which parameters influence perception.

To address these issues, we propose a software research framework offering new possibilities to investigate these perceptual issues. With the proposed framework we are able to study perceptual issues with shadows, dynamic environmental illumination and indirect illumination as shown in Figure 1 – all at real-time frame rates. Kruijff et al. [1] wrote a taxonomy of the main perceptual issues in AR. They classified these based on the so called perceptual pipeline which consists of five stages: *Environment*, *Capturing*, *Augmentation*, *Display Device* and finally the *User*. The work in progress we present here fits into the *capturing* and *augmentation* stages of the perceptual pipeline.

Our main contributions are:

- A framework for studying photorealistic rendering techniques in AR to investigate perceptual issues and visual cues
- An advanced rendering system that enables different rendering modes and styles
- A preliminary user-study to test our framework

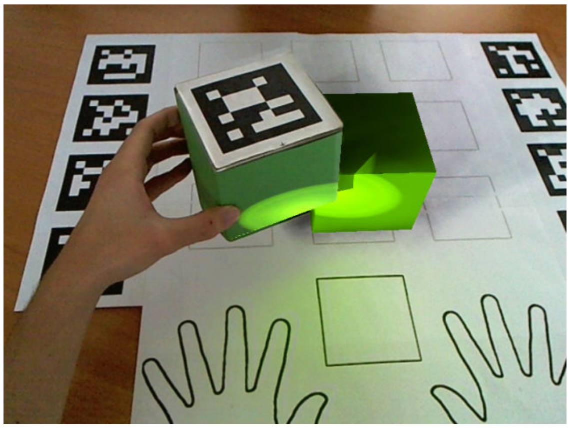

Figure 1. This figure shows the augmented scene of our experiment including shadows and color bleeding.

2 RELATED WORK

We divided the related work section into three main parts. First, we discuss a selection of work on perception of shadows and indirect illumination in AR and Virtual Reality (VR). Then we present two studies about the perception of environmental illumination and finally work that is directly related to our preliminary user-study and the proposed framework.

A lot of research studies the influence of shadows and indirect illumination in AR and VR applications. Hubona et al. [2] experimented with positioning and resizing tasks under varying conditions. They found significant differences for all independent variables. Sugano et al. [3] studied how shadows influence the presence of virtual objects in an augmented scene. The experiments showed that the shadows increased the presence of the virtual objects. Madison et al. [4] generated several different images of a plane and a cube. With different visual cues enabled and disabled the participants had to tell whether the cube was touching the plane or not. Similar to that work, Hu et al. [5] generated several different images of a plane and a large box using a Monte-Carlo path tracer. Their results showed that stereo vision is a very strong cue followed by shadows and indirect illumination. Furthermore shadows combined with indirect illumination are similarly as strong as stereo vision.

In all of these studies, indirect illumination was either not included as an independent variable or the studies used static images to overcome the computational costs caused by indirect illumination. However, our proposed research framework enables setting up interactive experiments including studies with indirect illumination effects.

Some studies investigate thresholds in environmental illumination. Nakano et al. [6] studied how much the resolution of an environment map could be decreased until the increasing error is noticeable. Lopez-Moreno et al. [7] studied how much the illumination direction of an object could differ until human observers noticed the error. The results showed that the error threshold was even larger in real scenes than in synthetic ones. However, only static environments were used for these experiments and it would be interesting how the thresholds work in dynamic setups.

Our research framework is an extension of the method proposed by Knecht et al. [8]. It basically uses a variation of the instant radiosity algorithm by Keller [9] combined with differential rendering from Debevec [10] to compute global illumination suitable for augmented reality applications.

Similar to our study Thompson et al. [11] tried to find out if improved rendering methods also improve distance judgment. The experimental setup and distances to estimate are different to our user-study. However, their results are similar to ours (see Section 6.3).

3 PHOTOREALISM IN MIXED REALITY

As argued in Section 1 it is plausible that virtual objects should look photorealistic in an augmented reality setup. In the ideal case virtual objects are indistinguishable from real ones. However, what does it take to make virtual objects look photorealistic and even better, make them indistinguishable from real objects? We start with the work from Ferwerda [12]. He introduced three different varieties of realism and pointed out that an image is just a representation of a scene. This representation describes selected properties and we should not confuse this with the real scene. The three varieties are:

Physical realism, where the visual stimulus of a scene is the same as the scene itself would provide. Physical realism is hard to achieve due to the lack of appropriate display devices that can recreate the exact frequency spectrum.

Photo-realism, where the visual response is the same as invoked by a photograph of the scene. This kind of realism should be targeted in photorealistic AR systems based on video-see-through output devices. If the virtual objects are represented using the same kind of photorealistic mapping function, they would be indistinguishable from real objects.

Functional realism, provides the same visual information as the real scene. That means, that the image itself can be rather abstract but the information retrieved from it is the same. A construction manual of a cupboard will contain abstract drawings but usually no photographs for example.

3.1 Studies on photorealism

Having Ferwerda's [12] three varieties of realism helps to focus on what kind of realism we want to achieve in photorealistic AR. However, it is still not fully understood what photo-realism actually means in a perceptual context. Therefore Hattenberger et al. [13] conducted experiments to find out which rendering algorithm creates the most photorealistic images. They used a real scene and added a virtual cow in the middle of it. Several different rendering algorithms were used to calculate the final results. Observers had to choose between two images compared to a photograph of the scene and decide which one looks more real. Results showed that observers preferred light simulations that took indirect illumination into account and furthermore, that noisier images were preferred to more smooth ones (with some exceptions). Although the authors state, that the results cannot be generalized because they belong to this particular scene, the results indicate, that there are also other important factors in photorealistic AR that influence the perception of the scene.

Elhelw et al. [14] tried a different approach. They used an eye-tracking system to find the gaze points in images. From that they derived which image features were important for the participants to decide if the image looks real or not. They found light reflections/specular highlights, 3D surface details and depth visibilities to be very important image features. For their user-study they used different sets of images from clinical bronchoscopy. These images look quite abstract in shape and texture. However, it would be very interesting to test this method on other images that are related to AR applications.

These are two examples of user-studies that tried to find answers on what makes an image photorealistic, without altering specific image features. We propose to divide the known image features in an AR setup into two main categories: The *visual cues* described in Section 3.2 and the *augmentation style* described in Section 3.3. While visual cues have a local nature augmentation style can be seen as global feature in an image.

3.2 Visual Cues

Visual cues are very important for the human visual system (HVS) as they help to organize and perceive the surrounding environment. Visual cues can deliver depth information and let us recognize inter-object relationships.

In AR visual cues can be exploited to embed virtual objects into the real scene. We split visual cues into *inter-object spatial cues* and *depth cues*.

Inter-object spatial cues

Shadows belong to the strongest spatial cues available. They define a spatial relationship between the shadow caster and the shadow receiver. The influence of shadows was studied in several experiments (see Section 2). Rademacher et al. [15] furthermore found, that the characteristics of soft-shadows changed the perceived realism in images.

Like shadows *indirect illumination* between objects defines a spatial relationship. Although inter-reflections are not a strong cue as shadows are, their influence is still significant [4].

Depth cues

Beside spatial cues such as shadows or indirect illumination, cues that serve as a source for depth information are of particular interest as these allow reconstructing our surrounding environment. Drascic and Milgram [16] as well as Cutting[17] presented a list of depth cues that can be divided into four main groups: Pictorial depth cues, kinetic depth cues, physiological depth cues and binocular disparity cues.

Pictorial depth cues are features that give information about the objects position in a still image. Such cues can be occlusion, linear perspective, relative size, texture perspective or aerial atmospheric perspective.

Kinetic depth cues provide information through change of the viewpoint or moving objects. Relative motion parallax and motion perspective (falling raindrops – near vs. far) are two examples. Another cue is the so-called kinetic depth effect. Imagine a point cloud that rotates around its upper axis. The structure of the point cloud is easily recognized. However, if the cloud stops rotating every point falls back into the screen plane and the structure is not visible anymore.

Physiological depth cues deliver information to the HVS about the convergence and accommodation of the eyes.

Binocular Disparity is another depth cue that is similar to the motion parallax depth cue. The HVS automatically transforms the disparity seen due to our two eyes into depth perception. Obviously this cue only exists when a stereo rendering setup is used in experiments.

3.3 Augmentation Style

Beside visual cues that should be provided by the rendering system it is also important that the augmentation style of virtual objects is similar to the visual response of the scene. Kruijff [1] mentioned several areas where perceptual issues may arise.

Illumination

Virtual objects that are rendered into the captured image of the real world must be illuminated correctly. This is often done by using a chrome sphere to capture the incident illumination at the point where the objects will be placed. This method belongs to the outside-in approaches. Debevec [10] introduced a way to use several images with different exposure times to create a high dynamic range (HDR) environment map. However, this process is time consuming and only leads to a static environment map. Inside-out methods instead use a camera with a fish-eye lens to capture the surrounding hemisphere. These methods allow for dynamic environments. Unfortunately there are only a few HDR cameras on the market. So the source for the incident illumination is only of low dynamic range. Once the environment map is acquired, image based lighting methods can be used to illuminate the virtual objects.

Color and Contrast

Currently most cameras offer only a limited color gamut and contrast. These limitations lead to wrong color and contrast representations. A special problem due to this tone-mapping arises, when two different cameras are used; one for video-see through and one to capture the surrounding illumination. Both map the high dynamic range illumination into a low dynamic range, *but* with different tone-mapping functions resulting in wrong colors in the final composed image.

Tone-mapping

The ideal setup for a photorealistic augmented reality system would consist of two equal HDR cameras for video-see-through and environment capturing. Using these two cameras with the same configuration would make the virtual objects look correctly illuminated and there would be fewer errors from the capturing stage. Then the whole rendering process could be performed in HDR and ideally the resulting images would be presented on a HDR display. As we do not have a HDR display our framework uses a tone-mapping operator developed by Reinhard et al. [18], which can be implemented directly on the graphics hardware.

Camera Artifacts

Computer generated images normally look absolutely clean/perfect and do not suffer from artifacts like noise or blurred edges. However, since we embed the virtual objects into a captured video frame, we need to add these artifacts to the virtual objects; otherwise they will be immediately recognized as not being real. Klein and Murray [19] developed a method that imitates a couple of artifacts such as Bayer pattern approximation, motion blur or chromatic aberration. Fischer et al. [20] could improve visual fidelity by removing aliasing artifacts and adding synthetic noise to the rendered objects. These artifacts greatly increase the appearance of the virtual objects.

4 A RESEARCH FRAMEWORK FOR PHOTOREALISTIC AR

With this background mentioned information and with the goal of performing experiments, an ideal research framework for photorealistic augmented reality has the following primary requirements:

- It must be very flexible to configure scene rendering parameters
- It must produce photorealistic results including augmentation artifacts, so that virtual objects are indistinguishable from real objects.

The framework should allow to easily hook in different modules into the rendering pipeline and it should be fast to setup experiments. The API should be designed in a way that new hardware devices can easily incorporate into the existing framework. Furthermore utility functions for data logging, tracking and calibration should be provided.

Such a framework could be used to study how the HVS processes images and how different visual cues alter perception. Especially in medical AR training simulators it is important that the spatial perception correlates with the real world. Otherwise the students are able to perform the surgery in a simulator, but would have problems in a real world environment.

With these goals in mind we developed a research framework based on the method introduced by Knecht et al. [8]. This method is able to simulate the mutual light interaction between real and virtual objects in real-time. The proposed research framework is developed in C# and runs on Windows 7 64-Bit. The graphical output is done via SlimDX and DirectX 10 APIs. It should therefore be very easy and fast to develop new experiments, as C# offers many tools and functions.

The central object of the framework is a so called *scene* object that is in its main function a hash table to store all the necessary objects for the rendering and serves as a communication platform to pass data from one task to the next. Tasks are pieces in the rendering pipeline that will be executed once every frame. The current framework has several tasks like video capturing, tracking, and rendering. As an example, the video capture task captures a new frame from a camera and passes it to the scene object. When the tracker task is executed it takes the frame, stored in the scene's hash table and uses it for estimating a camera pose. If a new experiment is designed the main procedures of the experiment are methods of an object that implements the specific task interface.

To allow for a very flexible framework the rendering pipeline can be defined in a XML configuration file that can be loaded over the GUI. This way it is easily possible to exchange a tracking system or change a camera without the need to alter the whole experiment.

As a lot of studies are about rendering visual features, shader development should be very efficient. In our framework they can be manipulated in an external editor during run-time. As soon as the shader is saved it will be reloaded automatically. This way instant visual feedback is provided.

The current renderer supports two types of shadows. For spotlight sources we use standard shadow mapping and for indirect illumination we use by default ISMs for every virtual point light. However, standard shadow mapping can also be used for the virtual point lights. Furthermore shadowing and indirect illumination can be switched on and off separately during run-time. In this way the influence of local illumination versus global illumination in an AR setup can be investigated in interactive experiments.

The fish-eye camera currently in use is only able to capture low dynamic range images. However, the rendering framework uses the method from Landis [21] to extrapolate a high dynamic range image from it. This is a very rough approximation and the best solution would be to have a HDR camera.

Dynamic spotlights are also supported. They can either be real pocket lamps that are tracked or virtual. They will illuminate the real and virtual objects accordingly.

The framework can handle multiple camera streams on the fly and the captured frames are available as textures in the video memory or directly in the main memory. This way they can easily be changed if necessary in a post-capture step.

The tracking interface currently supports three different types of trackers. The first one is the Studierstube Tracking framework. The second one is based on the PTAM tracking method from Klein and Murray [22] and the third one supports the VRPN protocol.

5 TECHNICAL ISSUES

As this is work in progress there are still several limitations and technical issues that are unsolved. One of the main issues for further perceptual studies is that the framework in the current stage does not support stereo rendering. This is definitely a goal for future work.

Calibration is crucial when it comes to accurate rendering. As Kruijff [1] mentions there are several points in the perceptual pipeline where errors decrease the quality of the final results and this is also true for this framework. If the tracking is not accurate wrong edges are far more visible due to artificial indirect illumination overlays. Methods like the one from Klein and Drummond [23] should be used to accurately move rendered edges to where they are shown in the video stream.

The fish-eye lens camera does not deliver any distance information of the environment. So it is not possible to take near light-sources accurately into account, except they are tracked.

The method used to compose the final images, limits the framework to video see-through HMDs. Furthermore the real-time global illumination computation needs a powerful graphics card and thus mobile augmented reality is not supported yet.

Several different tone-mapping operators exist and each camera has an individual way to map the incident HDR illumination into low dynamic range. This introduces many problems when compositing the final images and needs manual fine tuning to get satisfying results.

6 PRELIMINARY USER-STUDY

To test our system we have conducted a preliminary user-study on the influence of shadows and indirect illumination for five different tasks.

6.1 Experiment setup

The experiment was conducted at the HIT Lab NZ. The study setup as shown in Figure 2 consisted of a table plate with several BCH markers, two standard USB webcams, a HMD, and two targets (small green cubes with tracking markers). To track hand-movement for task four and five we attached three different markers on the participant hand: One at the index finger, one at the thumb and one at the wrist (see Figure 3)[1].

Figure 2. Participant performing the experiment.

One webcam was attached to the HMD to capture the participants view. The other one was placed above the table. Using this setup we could achieve correct tracking even in situations when the cube marker was not visible to the head mounted camera.

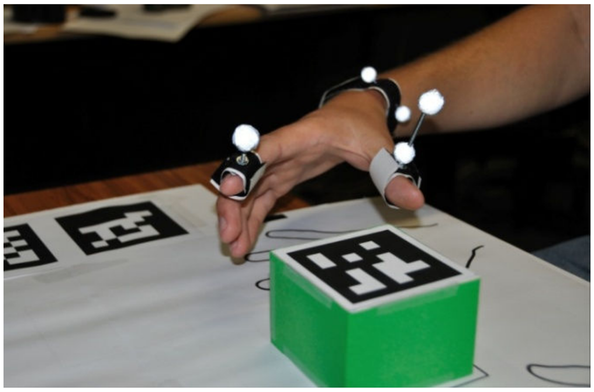

Figure 3. The green box and the markers for tracking the hand movement.

6.2 Task description

The first task showed a virtual cube at a random position, while the real cube was fixed in the middle of the table. The participants had to estimate the distance between the real and the virtual cube in centimeters.

In the second task the virtual cube was randomly placed in front of the participants. They had to grab the real cube, located on a fixed starting point, and move it to the virtual cube's position. The participants were instructed to perform tasks two to five as fast and as accurate as possible.

The third task was similar to task two but this time, the virtual and the real cube were swapped. The real cube was placed at random positions on the table by the experimenter and the virtual cube had to be moved to the same position using the cursor keys on a computer keyboard.

In task four the real cube (without any virtual augmentation) was placed at a random position on the table and the participant had to grab and lift it up as fast as possible. Before the task started

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[1] Hand movement analysis was not included in this paper.

and the scene was seen through the HMD the participants were asked to place their hands at a fixed starting position.

Task five was similar to task four except that the cube was overlaid with a virtual cube. This way the visual input was virtual, but the tactile input when grabbing and lifting was real.

Rendering modes

For all tasks, we had three conditions (see Figure 4). The first rendered the scene without any cast shadow or indirect illumination. The second included shadowing between real and virtual objects but no indirect illumination. The third rendering mode included inter-object shadowing and indirect illumination, causing color bleeding. The study followed a within subject design and the conditions were administered according to a latin square to minimize the risk of carry-over effects. After the participants had finished all five tasks they were interviewed.

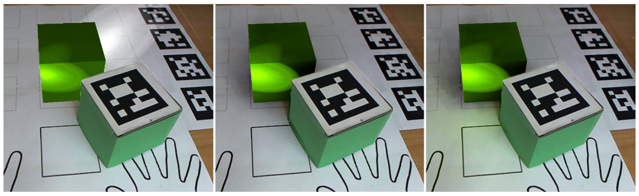

Figure 4. The three different rendering modes (left to right): no shadows/no indirect illumination, shadows/no indirect illumination and shadows/indirect illumination

6.3 Results & Discussion

Twenty-one people participated in the study, fifteen male and six female participants between the age of 19 to 59. All participants but one, who had to be excluded because of color blindness, had normal or corrected to normal eyesight.

It took between 30 and 60 minutes for each participant to finish all five tasks and the interview. Because not all data did meet the requirements for a repeated measures ANOVA (normality, shericity) we analyzed the data using non-parametric Friedman tests.

Our analysis did not show any evidence that the different rendering modes had an effect on task performance. This goes in line with the experiments performed by Thompson et al. [11]. However we have to be cautious in comparing these two experiments because in our user-study, the participants had to judge distances less than one meter, whereas Thompson's experiment was based on locomotion and the distances ranged from 5 to 15 meters. Furthermore they used an immersive VR system whereas we used an AR environment.

When we designed the tasks we were first planning to disable occlusion, so that it could not be used as a depth cue. With no occlusion the virtual cube would always be rendered on top of any real-world object – even in situations in which it should be occluded by a real cube. However, for a more realistic study setup, we decided to allow occlusion. As expected, our study shows that most of the participants used the occlusion cue to place the cubes at the right spot, regardless whether the virtual or the real cubes where manipulated (task 2 & 3). Seven participants recognized the shadows but only one recognized indirect illumination.

In task one the virtual cube was randomly positioned along the main axes and six participants mentioned that it was much easier to estimate the distance on the x and y axis rather than in depth direction. Although we could not find a significant effect to corroborate this, the distance estimation error was slightly less for the x and y axis. Furthermore the time used for distance estimation is slightly smaller when no shadows and no indirect illumination are shown. This could indicate that the cognitive load is larger with shadows and indirect illumination due to more visual cues. However, both effects are not significant and rather small.

In task two the real cube was moved to match the position of the virtual cube. Interestingly, seven participants found task three, manipulating the virtual cube to match the real cube using a computer keyboard, more intuitive and easier. The difference between the two tasks was that the target cube position in task 2 varied along three axes (x, y and z) whereas in task 3 it varied only in two axes (x and z) but not in height (y axis). Furthermore, in task 3 the participants did not have to change the cube's orientation since it was already aligned correctly.

In task 4 and 5 some participants complained that the cube was too large to grab and that the marker for hand tracking disturbed the grabbing process.

We could observe that the participants completed the tasks in very different ways. Some of the participants focused on speed, others more on accuracy. Some participants excessively moved their head to get different viewing angles, while others nearly did not move at all. These different strategies probably influenced the final results and therefore should be controlled in future experiments.

7 FUTURE WORK

We envision implementing several other features into the presented research framework. One of these features is stereo rendering. Since the rendering method already pushes the limits of the graphics hardware, rendering a complete second frame is not possible yet while maintaining useable frame-rates. However, many parts in the image pairs are the same and maybe a more sophisticated method can keep the additional rendering overhead quite small.

It is important that the fish-eye lens camera captures an HDR environment map. Our system currently uses scaled LDR environment maps since we do not have the appropriate hardware yet. The calibration process is crucial when using an optical tracking system in an augmented scene and it would be very convenient to have utility functions available that perform the necessary steps automatically and make calibration easier.

Finally, we want to perform further experiments with different tasks or similar tasks without occlusion cues. Alternatively tasks could have participants place a cube on top of another cube instead of placing it at the same position. In this way the influence of the occlusion cue could be reduced. In future study setups we will reduce the size of the cubes and use a chin rest to restrict or limit head-movement.

8 CONCLUSION

We started this paper by describing photorealistic augmented reality and where it can be used. We discussed the current issues that need to be solved and, based on this, proposed a new research framework to perform perceptual experiments. To our knowledge this is the first research framework that can take real-time global illumination and dynamic surrounding illumination effects into account. To test the research framework a pilot user-study was performed to investigate the influence of different rendering modes on user performance in five different tasks. The results indicated that there were no significant effects of these rendering conditions on task performance. However, we plan to conduct further experiments to confirm these results with altered tasks as described in the future work section.

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