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Short Paper

Using Spatial Augmented Reality to Increase Perceived Translucency of Real 3D Objects

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Abstract

Translucency is an important optical and perceptual attribute that has a significant impact on the appearance of objects and materials. Expensive and time-consuming manufacturing process is required to produce a translucent replica of an opaque real object. The human visual system has a poor ability to understand optics, and it relies on intensity distribution in the image to distinguish translucent and opaque materials. In this work we demonstrate a novel method of using spatial augmented reality to increase perceived translucency of more optically opaque real 3D objects by projecting energy patterns onto them that mimic the energy distribution of optically translucent materials. We conducted a user study to verify that the result looks convincing, and it is impossible to tell the transmitted and projected light apart. This opens promising directions for effective alteration of material appearance using projection systems, which can be used to enhance understanding and appreciation of historical artifacts.

CCS Concepts

• ***Computing methodologies*** $\rightarrow$ ***Mixed / augmented reality;***

1. Introduction and Background

We interact with translucent materials daily, such as human skin, foodstuffs, wax, jade, and alabaster. Translucency is an optical and perceptual property that significantly affects object's appearance. Optics of translucency, i.e. how light penetrates, propagates inside, and re-emerges from an object is relatively well understood and described by the Radiative Transfer Equation [Cha60]. On the other hand, it is still poorly understood how the human visual system (HVS) perceives translucency and tells translucent and opaque objects apart. The research indicates that the HVS does not measure or estimate the optical quantities to reconstruct the optical process, but it instead relies on regularities in spatial intensity distribution in the image, such as the brightness near the edges [FB05], the contrast between different parts [Mot10], and the lack of shadows where they would normally appear in opaque objects [GTHP21] (these are thought to be the cues to translucency). A comprehensive review on translucency perception can be found in [GTHP21].

In order produce a translucent-looking object, an expensive manufacturing process is needed. Despite emergence of advanced 3D printing technologies, little is known on how material's optical properties relate to perception, and hence, the user has to go through a complex trial-and-error process to produce physical object with desired visual properties [UTB*19]. One way to change appearance of objects is Spatial Augmented Reality (SAR), where the real-world structured illumination is superimposed on a real world object [BWZ14, RWF99]. It is a cost-effective, fast, and minimally invasive method, which makes it attractive for cultural heritage applications [ALY08, YHS03]. Amano [Ama19] has used SAR to manipulate translucency. The algorithm relies on Motoyoshi's [Mot10] notion that perceived translucency depends on contrast between specular highlights and diffuse areas – and therefore, is inherently limited with the shortcomings of that notion. Gigilashvili and Trumpy [GT20] took graphical renderings of optically translucent and opaque objects of the identical shape, subtracted the latter from the former, and found the spatial distribution of the pixel intensities that is present in the translucent object but is missing from the opaque one. Afterward, they demonstrated that if we project this difference on top of a digital projection of an opaque object, the original translucent look can be reconstructed. This work is inspired by [GT20], but we want to extend it to real physical objects.

Considering that the HVS relies on statistical regularities instead of assessing optical properties, we hypothesize that if we project light onto the part of an object where transmitted light would emerge from if it were more translucent, the HVS will not be able to tell the actually transmitted (re-emerged) light and the projected (and subsequently reflected) light apart, and hence, the opaque object (or the one with little translucency) will appear more translucent. To the best of our knowledge, this is the first attempt to test this hypothesis in practice.

If this method is successful, it will have practical implications for cultural heritage applications. For instance, the method can be used

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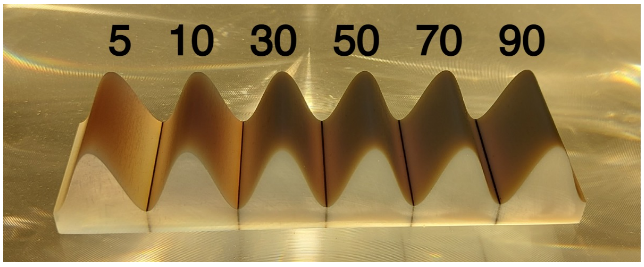

Figure 1: *The 3D printed object that was used in the experiment. It has six different levels of translucency. The number above each segment corresponds to the percentage of the white material (the rest was clear transparent material).*

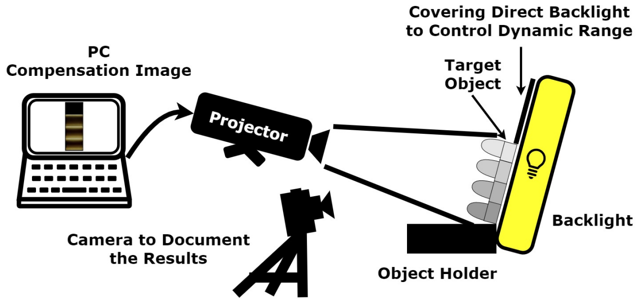

Figure 2: *Our experimental setup (not to scale). The object with spatially varying translucency is placed on a light box. The rest of the light box is covered to avoid saturation of the camera. We project a pre-calculated compensation image to introduce energy in the opaque parts and match their appearance with the parts that transmit light from behind.*

for virtual restoration when the actual restoration material does not match in terms of translucency. This will restore the harmony of the artwork by rendering translucency on the restored parts that are not as translucent as the original material, e.g. when plaster or cement is used for restoration of a marble object. Another example is displaying a full replica made of a cheaper opaque material, or displaying the object in multiple simulated materials.

The method will enhance the learning experience in the interactive museum settings. It will help the museumgoers understand the optics by simple and immediate means and appreciate the different aspects of materials used in the artworks, e.g. how important is a proper choice of materials to render specific visual effects. This develops interest in optics, material appearance, and aesthetics among young museumgoers and helps the communication of art with public.

2. Methodology

To test the result of manipulating the translucency appearance, we used a 3D printed object with spatially varying translucency (see Figure 1) that was lit from behind. We captured a photograph of the object and calculated pixel-wise differences between its most translucent part and other parts, respectively. These pixel-wise differences were used to calculate a compensation image that was projected onto the object. The schematic representation of the setup is shown in Figure 2. The process is explained in detail below.

2.1. Sample Preparation

We used Stratasys J55 3D printer and two materials white and clear transparent to 3D print the object. The degree of translucency was manipulated by the mixing ratios of the two materials. The proportion of the white materials was 5%, 10%, 30%, 50%, 70%, and 90%, in each of the six segments, respectively (Figure 1). To minimize the mutual impact among the segments, they were separated by a 0.5 mm wide strip of black ink. Each segment had a rectangular 3.5×2.3 cm base, which was 1 cm thick. To vary the thickness and generate broad range of translucency cues, a sinusoidal bell-shaped part was added on top of the base for each segment, which was 2 cm tall at its peak. Thus, the object was minimum 1 cm and maximum 3 cm thick in the vertical direction. Translucency difference was noticeable only among the first four segments; those with 90%, 70%, and 50% of white material did not differ visually, so only the latter was included in the study along with 30%, 10%, and 5% segments (the one with 5% of white was the most translucent and least opaque). This was previously noticed by Vu *et al.* [VUTN16], who found that the correlation between material mixing ratios and perceived translucency is highly non-linear and adding non-clear material above certain threshold does not yield a noticeable difference.

2.2. Image Acquisition

To manifest object's translucent properties at their fullest, the object was placed on a Macbeth PLT 1620 light box. Multiple previous works showed that objects look more translucent when they are lit from behind [XWG*14, FB05, GTHP21]. We used Nikon D610 DSLR camera to acquire a photograph of the back-lit object. To avoid dynamic range limitations, first, there was a dim ambient light in the room (this produced shadows, i.e. more translucency cues); and second, parts of the light box that were not occluded by the object were covered to avoid saturating the sensor by directly staring at the light source. The camera parameters were as follows: ISO-50; F-stop of f/22; and exposure time equal to 1/4 sec.

2.3. Calculation of a compensation image

We set the goal to equalize the translucency appearance, so all sections of the sample described in Sec. 2.1 and depicted in Figure 1 have the perceived translucency level of the 5%-section. For this, we had to identify the intensity and spatial distribution of the energy that was present in the most translucent part and was missing from other segments of the object, and then project the difference of the pixel values of raw linear images onto less translucent parts (we call this difference a *compensation image*). As the size of the segments is identical, we can calculate the pixel-wise difference. The object onto which we are projecting is not a flat screen and hence, the classic color management for digital projection cannot work. Since object's surface normals deviate from the projection axis, different parts of the object will reflect different portion of light, with the orientation orthogonal to the projection reflecting the most. Therefore, we had to manually process the compensation image to obtain the right colors. Wherever simple linear difference does not render satisfactory results, the compensation image need to be white balanced and gamma corrected (see Eq. 1, where *WB* is a white balance operator, *T* and *O* are translucent and opaque parts, respectively, and *C* is a compensation image).

$$C = WB(MAX(0, T - O))^{\frac{1}{\gamma}} \tag{1}$$

2.4. Projection

We used Sony VPL-AW15 projector to project the compensation image onto the back-lit object. We manually registered the compensation image with the 3D object and evaluated the result by visual inspection. Initially, the color of the real translucent part and opaque parts with simulated translucency differed. Therefore, we had to go through a trial-and-error color management process to produce the minimal difference between the target and achieved appearance. The primary novelty and objective of this work is to demonstrate that the augmentation is feasible and convincing in terms of translucency. After this proof of concept in context of translucency, automatizing the accurate reproduction of color appearance will be explored in future works. We are aware that color management and reproduction in 3D scanning of cultural heritage objects is an open problem with multiple solutions proposed [SMKG11, VPF*06]. In the future, we will consider working in spectral domain and implement color management methods into our algorithm.

2.5. User Study

We conducted an online user study using the images to evaluate the performance. We showed the original and augmented images of the object from different perspectives, and for each image, we asked the participants to answer an yes-no question whether all four parts of the object appeared translucent. Finally, we showed a video explanation of the method and asked them whether the results of the method were overall convincing.

3. Results and Discussion

The results were first evaluated visually by the authors and were considered convincing. Afterward, they were documented with Nikon D610 DSLR camera. They are illustrated in Figures 3 and 4. The video demonstrations of the effect can be found at the following link: `https://github.com/davitgigilashvili/ARTranslucencyGCH`. As it is shown in the figures, it is hard to distinguish transmitted and reflected light, and translucency of more opaque segments is enhanced considerably. We want to highlight that the results were convincing to a naked eye both when observed from a static position, as well as when the observer moved to different angles.

11 observers participated in the user study. The results (Figure 5) show that our method clearly evokes perception of translucency as the parts that are not initially considered translucent become translucent after projecting the compensation image. Besides, the

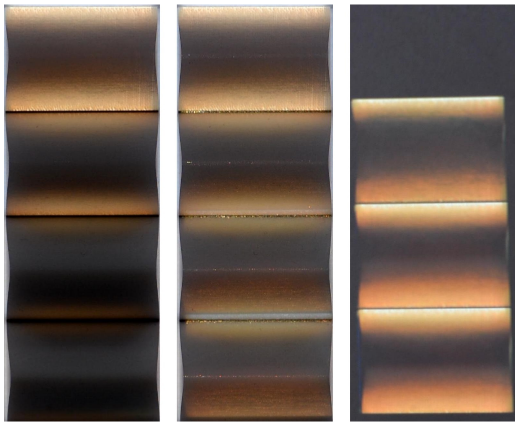

Figure 3: *Left: The back-lit object before projection. While the top part of the object looks highly translucent, it gradually becomes more opaque in the bottom segments. Transmitted light is noticeable at the thinnest parts, while the peaks of the sinusoids that are 3 times thicker than the base remain relatively opaque for all patches. Middle: The back-lit object with the AR projection. Translucency is simulated in a convincing manner in the parts that were substantially more opaque before projection. It is not possible to tell real transmitted and projected light apart. Right: Compensation image projected on a blank screen, which is used to produce the image in the middle.*

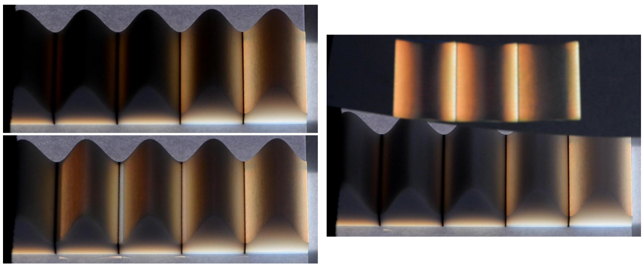

Figure 4: *The result is convincing from a side angle too. The top left image illustrates the original appearance. In the bottom left, translucency is simulated by projection. In the right one, the object and the compensation image are shown (the compensation image does not reach the object as it is occluded by a sheet of paper).*

approach and the simulation overall were found convincing by 9 out of 11 observers.

This work demonstrates that the concept of compensating energy by projection systems introduced by Gigilashvili and Trumpy [GT20] on the example of digital images can be extended to real 3D objects. This opens up a promising avenue for SAR as a fast and affordable way to simulate translucent appearance in real world scenes. If color management pipeline is refined and automatized, this solution can be readily applied to static scenes, such as museum artifacts. Although the solution is robust to observer's motion, both the object as well as the light source remain static throughout our experiment. Future work should address how changes in natural illumination affect the results. In this scenario,

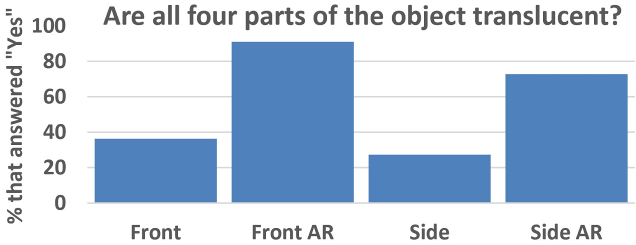

Figure 5: *The results of the user study for the object shown from front (Fig. 3) and side (Fig. 4). "AR" means that the compensation image is projected.*

real-time calculation of a compensation image and automatic registration will be needed. Another limitation that merits future attention is the dynamic range of the scene, limited by the specifications of current acquisition and projection devices that will be used for compensation image calculation and projection, respectively.

4. Conclusions

To produce a translucent-looking version of a real 3D object, an expensive manufacturing process is needed for creating its optically translucent replica. Human perception research has, however, revealed that the human visual system does not measure and invert optical properties and rather relies on statistical regularities in the image (such as edge brightness or contrast between specular and non-specular parts). We demonstrated in this work that it is possible to increase perceived translucency on optically more opaque objects if light projected to and reflected from their surface mimics these statistical regularities. This enables us to manipulate translucency appearance in a fast and affordable way. Future work should address shape-aware color management pipeline for the projected image that uses 3D model information to automatically compute desired compensation image. Also, more work is needed to investigate whether this method can work real-time for dynamic scenes – e.g., to ensure that changes in natural illumination throughout the day are accounted for.

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