Controllable Image-based Lighting with Environmental Importance Sampling

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Abstract

We present an efficient image-based lighting (IBL) [1] technique where a spheric panorama is potted onto a sphere as an environment mapping to illuminate the point-based object inside it. Previous IBL techniques generally have some special demands, such as integrating with high dynamic range images (HDRI) and requiring sophisticated computation for 3D geometry of the object. To avoid these limitations, we design an improved algorithm. Generally, Our method involves adopting a fast image importance sampling method based on error diffusion and measurement of the discrete reflectance properties from image sequences with interpolation. Besides, we perform smart optimization of the calculation to enhance rendering efficient.

Compared to the previous works, we aims to take ordinary photographs for texture mapping with merely hundreds of images for BRDF computation, and produces controllable realistic lighting effects on objects at arbitrary view point. Our experimental results have shown great visual realities, accurate light distribution on the object, and finer visual modulation through the added object-scene interaction.

Keywords--- **Importance sampling, BRDF, Reflectance Field Image, Panorama**

1 INTRODUCTION

Image-based lighting is the simulation of illuminating real or synthetic objects with the captured images of environment light from the world. One of the key goals of IBL is to achieve a seamless visual integration between objects and the real environment. This simply means that we should make objects blend harmoniously into the real scene and allow dynamic objects to be lit accurately according to the light distribution of environment, preferably using a global processing technique (i.e. everything in the surrounding scene can affect the given object inside it), while still keeping the rendering process fast.

The general framework for IBL can be described as 3 steps:

1. modeling the real-world illumination from photographs.
2. transforming the illumination into some kind of environment mapping.
3. putting the object to be lit inside the environment and implementing useful strategy for lighting simulation.

Acquisition of the surrounding illumination for objects is the first necessary step if realistic rendering is to be achieved. It not only guarantees consistent looks between the object and the environment but also influences the accuracy of further rendering computation. Optical devices are used to capture environment illumination form the real world, which is characterized in the form of irradiance images. These images usually have two special traits:

1). they're omnidirectional, which means that there's always exactly one pixel in the image corresponding to every incidence light direction from the real world.

2). the relationship between pixel values should reflect the distribution of environment light as precisely as possible. Thus, different instruments and methods for light collection bring on distinct levels of realistic light recurrence.

Once the real-world illumination is captured, it will be mapped onto a representation of the environment surrounding the object. The first representation of environment mapping was developed by Jim Blinn and Newell[2] . In this case, the environment is projected onto a large sphere using a latitude-longitude mapping indexed by the reflected ray. Greene et al. [3] proposed another mapping technique in which the environment is projected onto the six sides of the cube. This method is very simple and allows for observation from all directions. Later, Williams[4] put forward the first environment mapping supported by the commercial graphic card—sphere mapping, where the irradiance image is equivalent to what could be seen in a perfectly reflective hemisphere when viewed with an orthographic projection. Each representation has its applicable scope and should be carefully selected.

Since the realistic environment for illumination has been built, any object can be then placed inside it. Though no limit should be put on the relative position between them, the object is naturally deemed to be positioned at the center of the mapped environment for perfect all-sided viewing. To exhibit realistic rendering effect, the object must look not only real itself but also visually consistent and coherent with respect to the real environment, which implies that the inherence of light distribution on the objects should be analyzed. BRDF (Bi-directional Reflection Distribution Function) [5] is widely used to capture the reflectance properties of non-transparent objects. It is defined as a function which returns the ratio of incoming and outgoing light energy according to any position of the object surface. By correctly obtaining or estimating BRDFs of objects, many controls such as changing a view point, relighting in new illumination environments, removing or

*The work was supported by the NSF grants of Beijing (No. 4072013)

adding highlight spots on the object can be manipulated more easily. With the measurement for the BRDFs of objects, it's possible to simulate how light from the environment illuminates the inner object with several optional scene rendering schemes.

Generally, there are two important factors to the IBL process: the modeling of the real-world light and the measurement of BRDFs. With this in mind, we focus on newly optimized operations to enhance the perceptively visual reality of the rendered scene. To model the illumination environment, we construct a refined spherical panorama and perform sphere mapping on it. And we can effectively recover the entire BRDFs of objects by linear interpolation with a fully new application of importance sampling. The remainder of this paper is structured as follows: Section 2 reviews the related works. Section 3 to 4 presents the steps of our approach in detail. The experimental results are analyzed in section 5, and the conclusions are in section 6.

2 Related Works

2.1 Modeling for Illumination Environment

Many useful methods have been put forward for modeling environment irradiance. Debevec et al.[6] first introduced a very simple light collecting method. They used a camera to take two photographs of an omnidirectionally reflectional mirrored ball placed in the scene and synthesized them into a whole irradiance image. Panorama stitching [7] is a good means of attaining higher resolution environment irradiance. Firstly, many photos of the same scene in widely viewing directions are taken using a common or panoramic camera. Then, pictures are joined up to form an intact panoramic image.

One limitation of the above methods is that they both produce regular digital images. It is known that pixel values of most digital images are of low dynamic range and also nonlinearly compressed, which means that some pixel values are not strictly proportional to the quantities of their corresponding light energy in the world. In contrast to regular images, high dynamic range images (HDRI) [8] can store large brightness variation of the environment light. Commonly, Pixels of HDRIs are represented by single-precision floating point numbers for each color channel, leading to a marvously huge light intensity variation from thousands to billions. There are mainly two steps for creating HDRI as decribed below:

(1). taking a number of images of the real-world environment with multiple exposure levels to solve for the response curve of imaging system.

(2). composing a linear-response picture of the shot environment.

Due to a mass of mixed image processing, this technique requires intricate controls as well as advanced devices to complete. Besides, it's time consuming for accurate calculation.

2.2 Measure of Reflectance Properties

Acquisition for the reflectance properties of objects is a complex problem in computer graphics and computer vision all along. Ward et al. [9] invented a gonioreflectometer which consists of a light source and a detector for directly measuring BRDFs of materials. Though this device works well, it's really time consuming when used to model the complicated objects due to vast reflectance sampling. Thereafter, researchers [10,11] also developed other devices to improve the efficiency and accuracy of BRDF measure(see Fig.1). However, their methods required highly strict experimental procedures.

Fig.1. An impactful advanced system for BRDF measure [10].

Since it's very inconvenient to measure the full BRDFs of materials, some researches began to focus on making approximation for them. Currently, image-based BRDF acquisition becomes more and more popular, which can be categorized into two sorts: one is to create different physically inspired analytic models, and the other is to deal with dense image gathering.

The first methods attends to describe BRDFs in the form of parameterization. For instance, BRDF can be decomposed into diffuse reflection and specular reflection according to the empirical Phong illumination model. In the light of this model, Yu et al. [12] solved the parametric reflectance equation by image-based calculation. Similar extended methods can also be adopted to add virtual objects into a real scene [13]. However, this simple parametric model failed to provide good perception of visual realism for complex objects. Afterwards, some refined models are brought out. Sato et al. [14] used the Torrance-Sparrow reflection model and tried to analyze images of the same scene taken in varying lighting conditions to calculate parametric values of this model.

Due to the limitation of parameterization, these models are incapable to capture the BRDFs of sophisticated objects accurately. Accordingly, there are some researches on acquiring dense samples of BRDFs and utilizing them directly in the rendering process. This sort of approaches preserves those subtleties of the measured data which are lost in the parameterization based methods. Marschner et al. [15] built image databases for BRDF samples and could directly measured objects with known shapes. Debevec et al. [16] collected more than 4 thousand images to model illumination-controllable human face rendering. Observing that plenty of the BRDF samples can be computed from one single image, Matusik et al. [17] acquired dense BRDF samples from spherical objects for a large representative set of materials. With an effective estimation scheme for BRDF reconstruction, they managed to realize continuous transitions of lighting effects for various materials.

2.3 Discussions

In conclusion, the parameterization methods are obviously not adaptive for measuring objects with intricate texture or structure, and the image-based BRDF sampling methods inherently result in great data abundance, along with the unwieldy storage problem. Therefore, it makes sense to perform some significant mathematic analyses on the sampled BRDFs, leading to the following interesting questions: can we gather quantitatively fewer sampling images for BRDF measure to simplify the computation? How about the practical feasibility of solving for the complete set of BRDFs with merely a linear combination of discrete sampled data? If the decomposition approach still works well with this limitation, it seems that the linear combination of sampled BRDFs is at least visually valid for modeling physically involuted reflection models. Therefore, one of our motivations is to explore and testify the essence of this hypothesis.

3 Data Acquisition

3.1 Scene Modeling

To build up the scene, we first need to create the object model and the environment mapping separately and then combine them with methodical spatial arrangement to form the circumstance of lighting simulation. Since the modeling quality for each of them can directly influence the perceptively visual reality greatly at the first sight of the scene, we carefully choose effective and efficient modeling methods to guarantee it.

Point-based modeling defines 3D models as a set of dense sampled points on a solid object's surface. It decreases the difficulty of realistic modeling, and improves the rendering performance. Considering the complex geometric and dynamic lighting traits of objects, we prefer to create them in the representation of point cloud. We then apply a hardware accelerated splatting method [18] for point-based object modeling. Compared with most point-based modeling approaches, it not only generates amore uniformly distributed point set, but can also avoid the commonly seen cloud holes and aliasing effects.

It is known that spherical panorama is the most ideal reflection model among all kinds of panoramas. Though HDRI is a more accurate representation, we don't select it because it requires special advanced devices and an extremely time consuming process. Instead, we adopt spherical panorama as the representation for environment mapping. In fact, it comes that spherical panorama is enough to provide realistic light information in our approach. Explicitly speaking, we adopt a useful approach [19] to automatically synthesize a spherical panorama from image sequences. This method does not require any particular equipment to capture images, and all the involved manual operation is quite simple. Based on the image dividing and warping algorithms, this optimized method can avoid the accumulation of registration errors which often frustrates congeneric methods, and hence works well in capturing real-world illumination.

3.2 Images Acquisition

To relight the acquired object in a new environment, we must acquire an additional set of images which are used to construct the surface reflectance field. It takes only two steps to complete this process. First, we uniformly select a series of light positions and camera positions around the object and mark them as the sampled positions. Second, for each pair of a light position and a camera position, we place a light source and a camera respectively and take a image of the object with a common digital camera as shown in Fig.2. We call this set of all images the reflectance field images. These images together provide necessary information for further BRDF measure and are used to recover the full surface reflectance field as described in Section 6.

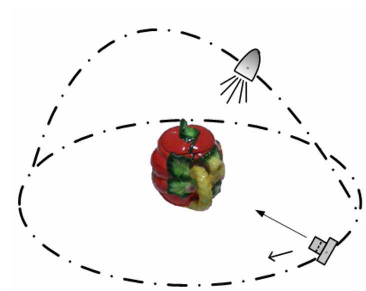


Fig.2. The imaging system. The directional light source and the camera are located in a series of positions, and each two adjacent positions have the fixed intervals of azimuth and inclination.

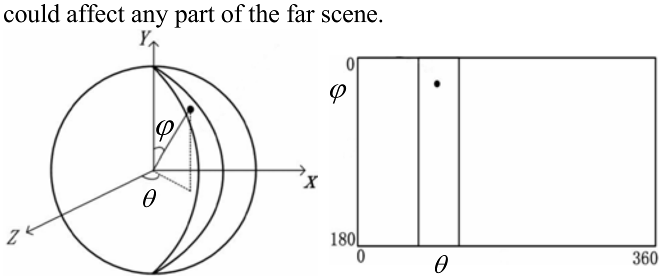
3.3 Image Importance Sampling of Panorama

A key idea of our work is the compact integration of image importance sampling and lighting computation. It facilitates the high visual reality of scene rendering and also provides a flexible means to control the light intensity distribution on objects. While there are some other applications [20, 21] also making use of importance sampling, they simply sample from the energy distribution of the environment and just use the sampled points as light sources to illuminate the objects inside it. These methods aim to reduce the amount of calculation and apparently cause an inaccurate reflection on the real-world illumination due to the discard of most important light information. To guarantee realistic lighting effect, we still take all the acquired real-world light into consideration. Generally, we discover some new crucial characteristics of the sampling results, and make very different use of them compared to those methods as described above. Through necessary steps for optimization, we also manage to cut down the cost of computation greatly.

One of the most efficient methods to generate sampled points on our panorama is afforded by an improved halftone technique based on error diffusion [22]. Integrated with threshold modulation, it can remove visual anomalies more effectively and generate sampled points faster, which is key to our rendering scheme. In our algorithm, the amount of sampled points to be used is relatively small but should be accurate enough to compensate for the loss of light details within normal photographs and provide correct information for further computation. Again, this method meets our demand very well.

4 ILLUMINATION COMPUTATION

Based upon the above works, an image based lighting system has been developed to generate synthetic lighting scene using sampled BRDFs. The scene to be rendered is deemed to be composed of the point-based model and the spherical environment mapping as created in the scene modeling. Accordingly, we can divide the scene into two parts: the near scene and the far scene. Firstly, the spherical panorama is potted onto a sphere with adjustable radius as the far scene. We represent it in the form of spherical coordinate. For any point on the sphere, θ is used for its azimuthal angle and φ is used for the zenith angle. The spatial position correspondence between the original panorama and its mapped result can be deduced easily as shown in Fig.3. As a result, we can treat each pixel in the original panorama as a directional incidence light source. For some pixel t of the original panorama, the latitude and longtitude of its corresponding position on the spherical surface can be denoted as θ_t and φ_t, and its gray value $I(\theta_t, \varphi_t)$ is used as the intensity of the light source. Next, the object is positioned at the center of the sphere to allow uniformly all-around viewing, which also means that the object is considered as the near scene. According to their position relationship, we make a hypothesis that only light from the far scene illuminates the near scene , and no reflected light from the object surface could affect any part of the far scene.



(a) (b)

Fig.3. the spatial position correspondence between the spherical environment mapping and the original spherical panorama.(a).The environment mapping. (b).The original panorama.

Once the scene is built up, we can simulate the light intensity distribution of the distant incidence light on the computer-generated object. There are some important problems to be solved for the correctness and robustness of rendering effects: how can the overall structure of BRDFs be reconstructed properly? To boost the calculation efficiency, can any measure such as speculative precomputation or mathematical transformation be taken? Combined with importance sampling, what kind of optimized strategy should be performed to enhance realistic scene lighting? We'll discuss them in the following paragraphs.

4.1 INTEPOLATION SCHEME FOR BRDF MEASURE

To achieve realistic scene rendering, we must employ strong strategy to recover the full reflectance properties of the object as accurately as possible. Currently, the most difficulty is that we only have a limited number of scattered BRDF data. Fortunately, scattered data interpolation techniques have been proven very useful for data retrieval in many areas, such as chemistry, physics, and engineering. Therefore, we determine to make use of it effectively. By performing linear interpolation from a set of nondensely-sampled BRDFs, it is able to recover the complete BRDFs of objects.

In our algorithm, the unknown BRDFs can be estimated through coefficient interpolation of the gathered reflectance field images. For arbitrary incidence direction *i*, we first compute all the spatial angles between each marked lighting direction and *i*, and then choose the *m* nearest marked lighting positions which have the *m* smallest values. Similarly, we can get the *n* nearest marked camera positions about any reflection direction *e*. Besides, the cosine values of these spatial angles are also computed as weights in further calculation. Finally, we can perform the weighted sum of the $m \times n$ reflectance fields to compute the BRDF of some point p with respect to incidence direction i and reflection direction e — $f_{\vec{p}}(\theta_i, \varphi_i, \theta_e, \varphi_e)$ as shown in (1).

$$f_{\vec{p}} = \sum_{s} \omega(\theta_{(e,s)}, \varphi_{(e,s)}) \sum_{t} \omega(\theta_{(i,t)}, \varphi_{(i,t)})\, f_{\vec{p}}(\theta_t, \varphi_t, \theta_s, \varphi_s) \quad (1)$$

4.2 ORIGINAL RENDERING EQUATION

Given arbitrary fixed view point, We can directly work out the environment light distribution $L_{\vec{p}}$ on each point $\vec{p}$ of the object surface according to the discrete form of the accumulation principle based on global illumination as (2) describes.

$$L_{\vec{p}} = L_{diff} + \sum_{i} f_{\vec{p}}(\theta_i, \varphi_i, \theta_e, \varphi_e) \bullet I(\theta_i, \varphi_i) \quad (2)$$

where $f_{\vec{p}}(\theta_i, \varphi_i, \theta_e, \varphi_e)$ figures the BRDF of $\vec{P}$ according to incidence direction i and reflection direction e and $I(\theta_i, \varphi_i)$ is the light intensity of the corresponding panoramic pixel. Assume the object is non-emanative, L_{diff} can be set zero. Thus, we can solve the rendering equation by constructing a hemisphere around the surface normal associated with $\vec{P}$, and then accumulating the results of multiplying the intensity of any incidence light covered by the hemisphere with the corresponding reflectance function.

While this scheme shows great simplification, there are two drawbacks with it. On one hand, the rendering effects lack of perceptively visual reality due to the accumulated errors of interpolations within the inadequate reflectance field images. On the other hand, it requires a completely new calculation to find a different set of BRDFs as long as the view point changes, often leading to an unbearable wait for the new rendering effect.

4.3 IMPROVED VARIATION OF RENDERING EQUATIONS

To improve calculation efficiency, we perform a series of innovative transformations on (1) to eliminate any unnecessary repetitive calculation. Integrated with the comprehensive use of sampling results to promote the visual reality, we finally have a step-by-step rendering scheme as described below.

$$L_{\vec{p}} = \sum_{s} \omega(\theta_{(e,s)}, \varphi_{(e,s)}) \sum_{t'} I'_{t'} f_{\vec{p}}(\theta_{t'}, \varphi_{t'}, \theta_s, \varphi_s) \quad (3)$$

$$I'_{t'} = \sum_{i'} I(\theta_{i'}, \varphi_{i'}) \quad (4)$$

Explicitly, we implement the new scheme by taking the following steps. First, We make a Voronoi decomposition on the panorama based on the sampled points. It is known that Voronoi diagrams are suitable for representing classified geometric information in a compact form but are often difficult to generate fast. To advance the computation efficiency, we make use of a high-performance method to complete the participation [23]. For each sampled point, we then find its corresponding Voronoi polygon and all the intensity value of pixels inside this region are accumulated to it as (4) indicates (also see Fig. 4). It can be seen as the redistribution of all the incidence lights, also called the "light disassembling". Second, we choose sampled points as the new marked light positions and preserve the old marked camera positions. Then new reflectance field images are generated from the old ones with a numeric interpolation similar to the previous BRDF measure. Finally, the environment irradiance focused onto the object can be worked out with (3).

With dual optimization performed, we don't need to compute the full set of BRDFs for each point on the object continually, which really saves a lot of time. Besides, the previous two steps can be treated as precomputation, hence the calculation amount decreases greatly indeed while the storage for preprocessed data is quite small.

(a)

(b)

Fig .4. Light disassembling for spherical panorama. (a). The sampled environment mapping (18 sampled points colored with pink) (b). The disassembling result. The brightness of each eclipse centered at the corresponding sampled point indicates the value of accumulated intensity for it.

5 Experimental Results

Our method has been tested on both the virtual and real objects. All the renderings are performed on the computer with 2.8GHz Pentium4 CPU and 512MB RAM using OPENGL. As for any point-based object, we place it in different illumination environments and simulate the dynamic scene lighting with the improved rendering equations as shown in Fig.5,6,7.

For the real object in Fig.5., we set 20 camera positions and 20 light directions, leading to 400 reflectance field images. And for the virtual object in Fig.6., we select 30 camera positions and 30 light directions, so there're 900 reflectance field images in all. Comparing to Debevec et al.[16] and Matusik et al.[17] , the amount of the images we use is several hundred other than thousands or more. From the rendering effects of one scene with distinct samplings, we can see fewer sampled points leads to higher level of real light contrast on the object, which is physically and perceptively rational. Any rendering frame rate is between 0.2fps~0.4fps with different scenes and sampling points in the results. (also see Fig.5,6,7 for more details).

6 Future Work And Discusions

In this paper, we have introduced a new approach for realistic scene lighting with the full-scale usage of importance sampling. Integrated with a fast sampling scheme, our method can provide flexible illumination-controllable levels of visual reality and a perceptually meaningful avenue to diversely relight the object inside the environment mapping. From the experimental results, we can observe how different rendering effects of the same scene can be achieved while good harmony between the computer-generated object and the real environment is still kept primely.

Unlike general image-based lighting techniques, we don't use any HDRI for environment mapping and merely take common photographs for computation. Yet it's enough to generate the present rendering effects as seen. Besides, the rendering effects can be altered simply by modulating the distribution and amount of sampled points, which also shows the potential for intuitively specifying and exploring particular lighting effects. To correctly recover the anisotropic BRDFs, we use image-based, non-parametric representations for object reflectance and evaluate them through an interpolation scheme. It turns out that the linear decomposition can provide physically correct BRDFs, also implying further application for modeling objects with more plausible reflection properties. And we believe that it is better to use measured data other than a parametric model to preserve tiny reflectance details of the object.

Due to the geodesic error of camera calibration and exposure, there are still a few flaws in the results. In the future, we would like to seek better measuring methods to solve these problems. Since the incorporation of importance sampling is effective in the improvement of the rendering effect, the extensional use of it will be explored too. Another challenge is to measure BRDF data from rarely complex objects such as a strange-shaped object with multiple materials. Moreover, we will consider how to achieve real-time rendering by hardware acceleration.

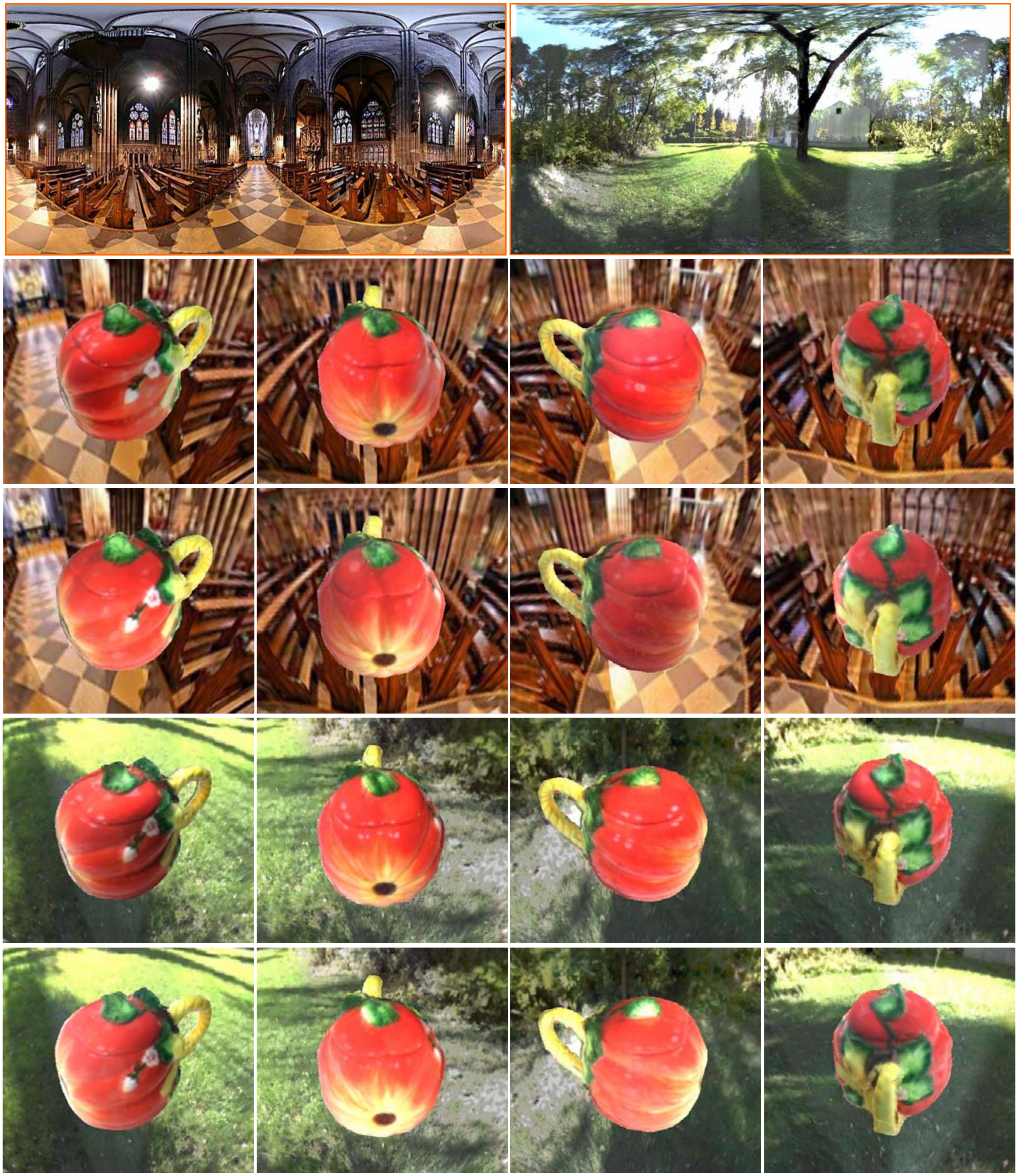


Fig.5. Rendering a real object in different illumination environments. Row 1 shows the two spherical panoramas available. Row 2 and row 3 give some of the rendered frames with distinct samplings on the first panorama.(15 sampled points for row 2 and 52 for row 3). Row 4 and row 5 also give part of the rendered frames with distinct samplings on the second panorama.(12 sampled points for row 4 and 64 for row 5). The amount of sampled points is 254,176 for creating this point-based object. The rendering frame rates from row 2 to row 5 are 0.337 fps, 0.241 fps, 0.352 fps and 0.226 fps separately.

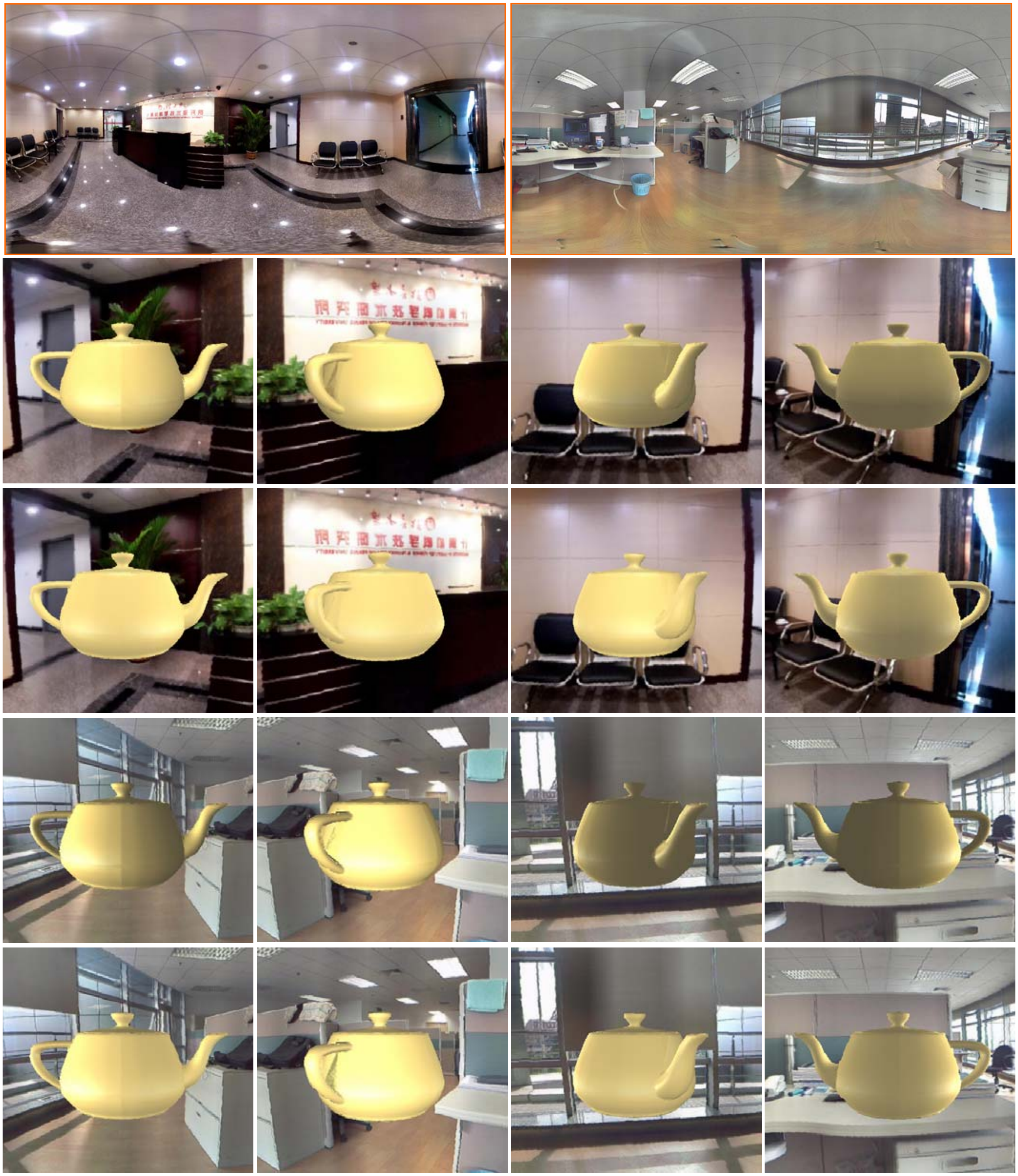


Fig.6. Rendering a virtual object in different illumination environments. Row 1 shows the two spherical panoramas available. Row 2 and row 3 give some of the rendered frames with distinct samplings on the first panorama.(11 sampled points for row 2 and 82 for row 3). Row 4 and row 5 also give part of the rendered frames with distinct samplings on the second panorama.(18 sampled points for row 4 and 70 for row 5). The amount of sampled points is 260,895 for creating this point-based object. The rendering frame rates from row 2 to row 5 are 0.354 fps, 0.201 fps, 0. 326 fps and 0.213 fps separately.

Fig.7. Rendering objects with more complex textures and structures . Row 1 gives some of the rendered frames for the illuminated virtual man(36 sampled points on the panorama). Row 2 gives some of the rendered frames for the relighted real teapot (28 sampled points on the panorama). The amount of sampled points are 175,612 for creating the man and 241,467 for the teapot. The rendering frame rates from row 1 to row 2 are 0.328 fps and 0.319 fps separately.

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