Constructing Panorama with Light Probe and HDR Fusion

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Abstract

Panorama is a wide-angle view of a physical space. In many scenarios, a panorama photograph can efficiently express the information about a space and help create sense of immersive when constructing virtual environment. However, capturing panorama photograph can be costly, requiring 360-degree camera with a series of lenses and sensors to synthesize the result. In this project we are going to exploit an efficient way to capture and construct a panorama photograph, with the help of a spherical probe.

1. Introduction

Traditional methods to capture a panorama photograph are always costly. In this project, we want to explore another efficient method with little loss in the quality of the result photograph.

The basic idea of this method is to extract the contents reflected by the spherical light probe, and then applying transformation to the extracted image to make the result into images with expected format. However, there are two major difficulties through this procedure:

1.1. Detail of the Materials

The panorama constructed in this method is with less quality than that constructed by 360-degree camera or other method based on multiple image synthesis. This is because the corresponded field of view of the light probe is smaller than the included scenario, which leads to the less sample density. This loss of information is hard to recover.

Another major source of loss of detail lies in the intensity of the image. Since the environment of lighting may be varied dramatically within a space, we need additional operation on the captured photos of the light probe. To reduce the loss of detail, we are going to apply techniques in High Dynamic Range Imaging. In this project, we are going to use LDR merging algorithm.

1.2. Transformation Algorithm

The most accurate way to reconstruct a panorama image based on the configuration of the light probe is following the propaganda direction of the lights and proceed like ray-tracing algorithm. However, this algorithm lacks efficiency and includes a large portion of unnecessary numerical calculation. With a good symmetry property of the light probe, we can simplify the transformation algorithm with better performance and similar quality of the result. The transformation algorithm will be introduced in detail in the following sections.

2. Related Work

There are existing equipment or software using to capture panorama photograph, below are several examples:

2.1. Spherical / 360-degree Camera

Figure 1. An example of 360-degree camera.

This type of camera is designated to capture panorama photos. In most of the cases, they are made up of multiple lenses and sensors with different directions, covering all possible perspective by at lease one set of cameras. This type of camera can synthesize the taken image by different smaller camera and result in high quality panorama photo. However, the cost of this type of camera is high and if the users are not trying to pursue a very high resolution, there are easier choices.

2.2. Rotating Line Camera

This type of camera is more simplified and economy. Originally, it represents reformed digital cameras with stabilizers and rotational structures. In recent years, such functionality is infused with other types of camera, like the cameras on mobile phones and other photograph applications.

The limitation of this type of camera is that the captured panorama cannot cover all/most of the perspectives from the camera. If the user takes a photo along one certain direction, for example, from left to right, then the contents at the top of the camera and at the bottom of the camera are missing.

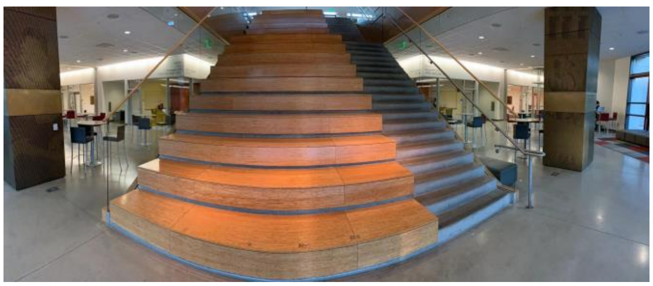


Figure 2. Panorama photo taken by iPhone XR with its panorama function.

3. Method

The construction of panorama photograph can be separated into several stages [1][3]:

3.1. Collecting LDR Photos of the Light Probe

The first step of the construction is to collect plentiful photographs of the light probe at an expected perspective.

Settled the light probe on a tripod or other kind of stable platform. The settled position should be the same as the expected view position of the final result image.

Settled a digital camera at a stabilizer or other type of stable platform. The settled position should be at least 10 times of the diameter of the probe. Make the camera focused on the surface of the light probe. Adjust the field of view so that the sphere covers as much field of view as possible.

Adjust all parameters so that the captured image is sharp and clear and keep the settings the same throughout this step, except for the aperture speed or exposure time. Capture a photo.

Adjust the aperture speed to 4 times faster than the original setting, capture the second photo. Adjust the aperture speed to 4 times slower than the original setting, capture the third photo.

The collected photos can vary from case to case, but we have to record the corresponded exposure time and keep other parameters the same from others.

After this step, we should have multiple LDR photos with exactly the same perspective and captured contents. Clip the photos so that only the part of the light probe remains, the resulting images should have the same dimensions.

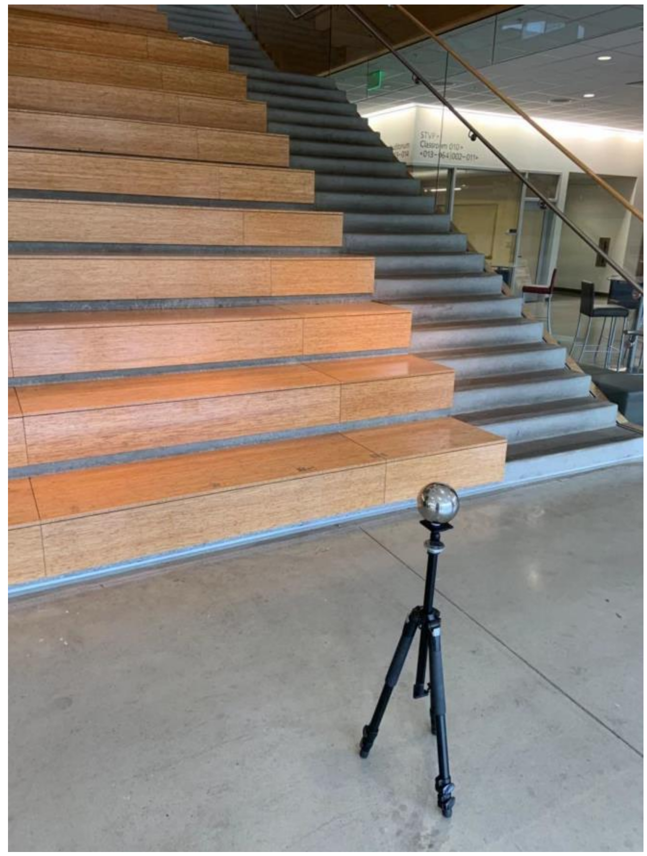


Figure 3. The configuration of the equipments.

3.2. HDR Fusion through LDR Merging

Apply HDR fusion based on the captured LDR photos in the previous step.

Compute a weight demonstrating whether a pixel is well-exposed or not. The closer to the center of dynamic range the pixel is, the higher the weight should be. Here we can use the semantics [2]:

$$w_{ij} = \exp(-10 * \left(I_{lin_{ij}} - 0.5\right)^2)$$

Now we get the weight values for all pixels in all different LDR photos, we will use it as part of the next step. Calculate the corresponded value of the pixel after merging all LDR values at the same position:

$$x_{ij} = \exp\left(\frac{\sum_k w_{ij_k} * (\log\left(I_{lin_{ijk}}\right) - \log(t_k))}{\sum_k w_{ij_k}}\right)$$

The values of x represent the relative radiance of the merged photo. Scale the result with a scalar and apply an additional correction with an exponential to get a better image result.

At this time, we should have a fused image of the light probe which retains most of the details in the image. This image will be used to reconstruct the panorama photo through transformations in next step.

3.3. Reflective Model

The last step of this procedure is to transform the contents on the light probe into the space of the panorama image. For this project we expect the result to be in equirectangular semantic.

For the simplicity of this step, we make an approximation that the view vectors (vector from the camera to the target point) are the same on the whole light probe. This approximation will not lead to a large error because of the configuration of the camera and the probe, that the distance between them is dominant as compared to the diameter of the probe, making the difference in view vector ignorable from point to point.

The clipped photo of the light probe can be considered as the projection of the sphere to the plane perpendicular to the view vectors. Let the view vector be z axis, let the center of the sphere be the origin, normalize the x-y coordinate so that the left-down corner has x-y coordinate (-1, -1), and the top-right corner of the pixel has the coordinate (1, 1), then we can figure out that the pixel with coordinate (x, y) have the normal vector:

$$\mathrm{N}(\mathrm{x,y}) = \left\langle x, y, \sqrt{1 - x^2 - y^2} \right\rangle$$

Assuming the pixel at position (x, y) is the result of reflection, with the view vector and the normal vector confirmed, we can figure out that the reflective vector by:

$$\mathbf{R} = \mathbf{V} - 2 * (\mathbf{V} \cdot \mathbf{N}) * \mathbf{N}$$

3.4. Spherical Transformation

Now we have the reflective vectors represented by all pixels. Transform the coordinate system into spherical coordinate for `scatteredInterpolant` function.

Knowing that a vector (x, y, z) in Cartesian coordinate can be represented as a vector (r, θ, φ) in Spherical coordinate with the transformation (Slightly different because in this case y is the up vector but not z):

$$\mathrm{r} = \sqrt{x^2 + y^2 + z^2}$$
$$\theta = \mathrm{arc}\ \cos(\mathrm{y})$$
$$\phi = \mathrm{arc}\ \tan\left(\frac{\mathrm{x}}{\mathrm{z}}\right)$$

With the reflective vectors in spherical coordinate, we can use scatteredInterpolant function to interpolate to the equirectangular panorama image values.

4. Result

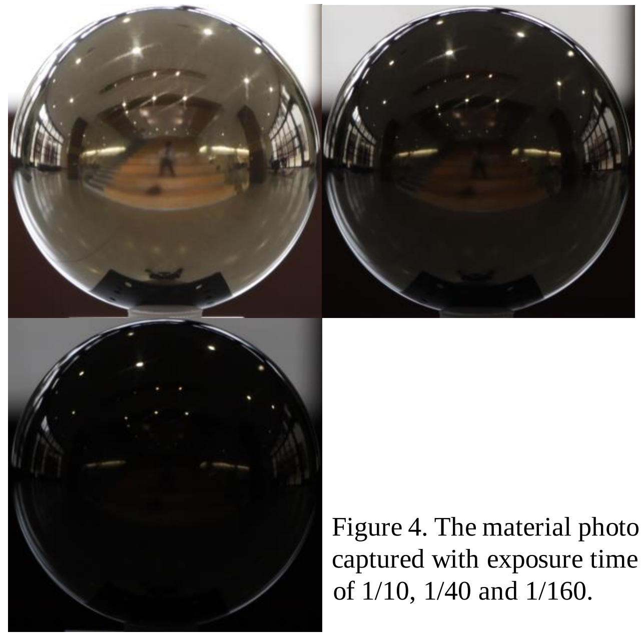


Figure 4. The material photo captured with exposure time of 1/10, 1/40 and 1/160.

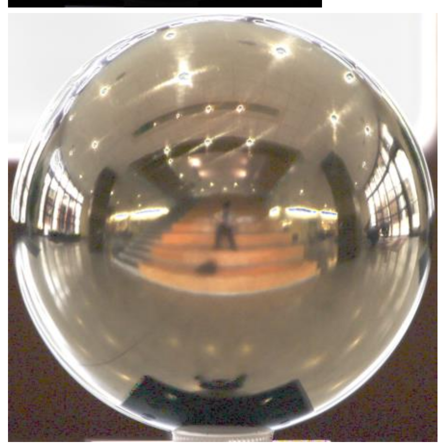


Figure 5. The HDR got from LDR merging.

Figure 6. the resulting equirectangular panorama.

5. Analysis and Evaluation

5.1. Quality of the Panorama

Comparing Figure 2 and Figure 5, we can discover that using light probe can cover contents that would be missed by rotating line camera. However, since rotating line camera can sample at different perspective for multiple times, the resolution of Figure 2 is far higher than the resolution of Figure 6. Similarly, compared to other panorama photograph taken by 360-degree camera, the quality of our result is lower. The advantage lies in the cost of this method. We just use one digital camera and a spherical mirror as light probe to capture the panorama.

5.2. Comparing the Geometry

As compared to the common picture taken, panorama renders object in a twisted way. This is because of the reflective model of the spherical mirror. Also, though small enough to be ignored in the approximation, the radius of the sphere probe increases the extent of being twisted for originally straight objects in the space.

Figure 7. Scene with vertical and horizontal structure. (Observe the frame of the window).

Figure 8. The twisted frame shown on the light probe.

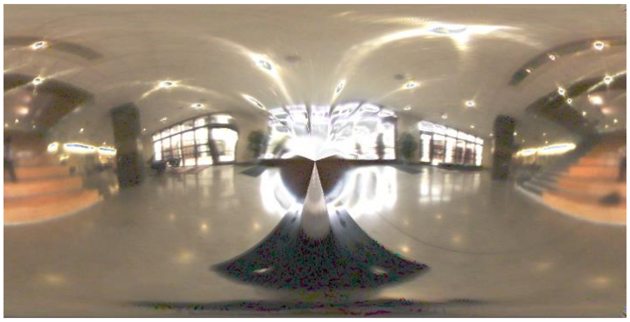
Sense of being twisted makes the panorama picture hard to view on a plane. It makes more sense if we can map this as a texture to another geometry, which will be discussed in next section.

6. Discussion, Limitation and Future Work

6.1. Uncovered Region

Though the spherical transformation gives us values for all pairs of (θ, φ), the region right behind the light probe is never shown on any part of the light probe and thus leads to missing contents.

To effectively collect the information behind the light probe, we need to first change the way we map the pixel with the angle and the assumption of same view vector at all positions. We can construct a virtual inner-sphere representing the background of the environment and see the projected pixel on the inner-sphere. This way of mapping clarifies the region where uncovered contents should be located. Second, we need to sample the environment at different perspective. For example, first take the picture in front of the sphere and then take one from the back. With the supplemented sample and more accurate way of mapping, we can reconstruct the space with no uncovered contents. Discontinuity at the center of shifted image below proves the uncovered region. In the image below I offset the angle so that the contents at the edge of the sphere is rendered in the center of the panorama photo.



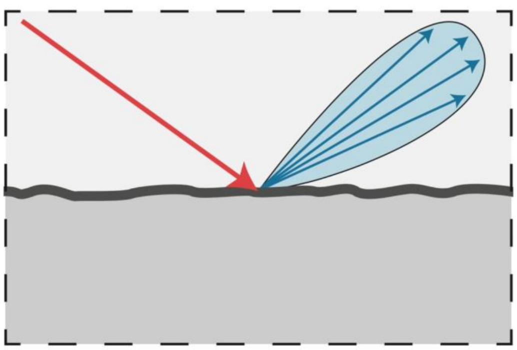
6.2. Blurry Pattern

Due to the limitation of material, the light probe we used in this project is not perfectly spherical and metallic. We have seen a clear relation between the type of loss of the probe and the pattern in the result.

The first type of blurry is distributive, diminishing the sense of edges and scattering the point light sources at all direction. This is caused by the scattered loss that randomly change the surface geometry of the probe, making the reflective model not completely metallic.

Figure 9. Projection of light on the ground

From the figure above we can see, the light from the outside of the room should lead to a hard edge at the ground, but in the panorama image we got, the edge is not clear as it should be. The figure below demonstrates the imperfect surface reflective model.



The second type of blurry is no longer extending to all direction with same effect. The best demonstration lies in the crossing appearance of the lights.

Figure 10. Crossing appearance of light.

This crossing specular highlight shown above satisfies the antistrophic specular highlight mentioned by Ward[4], in which the quality of being metallic is different along different directions on the surface. In this model, the specular component is based on the closeness of the reflected vector with two designated direction:

$$k_{\text{specular}} \frac{1}{\sqrt{(\mathbf{L}\cdot\mathbf{N})(\mathbf{V}\cdot\mathbf{N})}} \exp\left(-2\frac{((\mathbf{H}\cdot\mathbf{T})/\alpha_x)^2 + ((\mathbf{H}\cdot\mathbf{B})/\alpha_y)^2}{1+\mathbf{H}\cdot\mathbf{N}}\right)$$

The corresponded type of loss causing this pattern should be the brushing of the sphere at a certain direction. Differ from the random loss mentioned before, the change of shape in this type of loss is not independent and following a certain direction in general.

Figure 11. the difference in reflectivity on different direction for brushed metals.

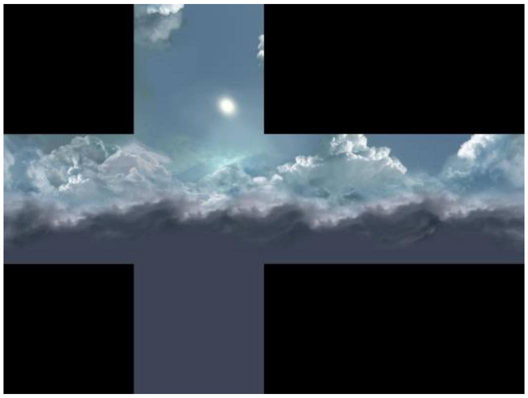
6.3. Improving HDRI Algorithm

The HDRI algorithm I used in this project is LDR merging with weight. This leads to a result showing the relative radiance, which needs additional adjustment on parameters. Also, the performance when a pixel cannot be expressed by a proper value by all LDR images is bad. This leads to the dark pixels at the center of the lights shown in the image because the weight of this part in all three LDR images are about zero. I believe there are better choices than LDR merging to generate an HDR image in this scenario.

6.4. Other Representation of the Panorama

In this project we transform the panorama photo into equirectangular image (the row and column represent equally distributed φ angles and θ angles). We can further map this image to other geometry to make the photo more visually appealing to the viewer, like the texture of an inner-sphere geometry.

On the other hand, we can also try to transform the image into other formats. For example, based on the coordinates of the pixels, we can transform the sphere region into a skybox which is consist of six square subgraphs. Below is an example of the skybox texture.



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[2] Mann, Picard "On Being 'Undigital' with Digital Cameras: Extending Dynamic Range by Combining Differently Exposed Pictures", IS&T 1995.

[3] DEBEVEC, P. E., AND MALIK, J. Recovering high dynamic range radiance maps from photographs. In SIGGRAPH '97 (August 1997), pp. 369–378.

[4] Greg Ward, Measuring and Modeling Anisotropic Reflection, Computer Graphics (SIGGRAPH '92 Proceedings), pp. 265–272, July 1992..