RENDERING SYNTHETIC OBJECTS INTO FULL PANORAMIC SCENES USING LIGHT-DEPTH MAPS

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Abstract: We are proposing a rendering approach to address the problem of combine captured panoramas and computer generated elements. This rendering pipeline supports productions specially aiming at spherical displays (e.g., fulldomes). Full panoramas have been used in computer graphics for years, yet their common usage lays on environment lighting and reflection maps for conventional displays. With a keen eye in what may be the next trend in the filmmaking industry, we address the particularities of those productions, proposing a new representation of the space by storing the depth together with the light maps, in a full panoramic light-depth map. The main novelty in our rendering pipeline is the one-pass solution to solve the blending of real and synthetic objects simultaneously without need post processing effects. Other important contribution is the introduction of the light-depth maps that allows us to obtain more accurate computations for shadows and reflections.

1 INTRODUCTION

The realm of digital photography opens the doors for the artist work with (pre/post)filters and other artifices where long gone are the days constrained by the physical nature of the film - ISO, the natural lighting, and so on. As a creative artist we can't stand to merely capture the environment that surround us. We urge the interfere with our digital carving toolset. There comes the computer, guided by the artist eyes to lead this revolution. The photo-video production starts and often ends in its digital form. Ultimately those are pixels we are producing. And as such, a RGB value is just as good whether it comes from a film sensor or a computer render. But in order to merge the synthetic and the captures elements, we need to have them in the same space. Since we can't place our rendered objects in the real world, we teleport the environment inside the virtual space of the computer. Thus the first part of our project is focused on better techniques for environment capturing, and reconstruction.

We also wants to work with what we believe is a future for cinema innovation. Panorama movies and experiments are almost as old as the cinema industry. Yet, this medium hasn't been explored extensively by film makers. One of the reasons been the lack of rooms to bring in the audience for their shows. Another is the time it took for the technology to catch up with the needs of the panorama market. Panorama films are designed to be enjoyed in screens with large field of views (usually 180°). And for years, around the world, there were only a few places designed to receive those projections (e.g. La Gode, in Paris, France). In the past years a lot of old planetariums are upgrading their old star-projectors to full digital projection systems. Additionally new panorama capture devices are becoming more accessible everyday (e.g., Lady Bug, a camera that captures a full panorama in motion). And what to say of new consumer devices and applications such as Google Street View, gyroscopic based mobile panorama viewing apps?

All this is producing a boom in the demand for panorama productions. And with these, the opportunity to address new problems by the computer graphic industry.

Our project started motivated by these new airs. We wanted to validate a workflow to work from panorama capturing, work the insertion of digital elements to build a narrative, and bring it back to the panorama space. There is no tool in the market right now ready to account for the complete framework.

The first problem we faced was that full panoramas are a directional map. They are commonly used in the computer graphics industry for environment lighting and limited reflection maps. And they work fine if you are to use them without having to account for a full coherent space. However if a full panorama is the output format, we need more than the previous works can provide.

We propose a solution for panoramic photorealistic rendering of synthetic objects inserted in a real environment using a single-pass path tracing algorithm. We generate an aproximation of the relevant environment geometries to get a complete simulation of shadows and reflections of the environment and the synthetic elements. The environment geometry is used to generate a *light-depth environment map*, a special environment light with a depth channel used to compute the position of light samples in real world. We will discuss this idea in section 4.

We developed a modified version of the open source software *Luxrender*, *ARLuxrender* (Zang and Velho, 2011b) and (Zang and Velho, 2011a), which allows for physic based lighting rendering of virtual scenes. Additionally an addon for the 3D open source software *Blender* is available for the scene modeling and production steps, better explained at (Felinto et al., 2012). Additional information about this rendering algorithm and the production framework can be found in the *ARLuxrender* project web site (Zang and Velho, 2011a).

2 RELATED WORK

Today we can choice what technique use to capture light from the real world and use it to create lighting scenes generated by computer, but it was not so in the 80ies. If we consider a particular point in a scene, the light at this point can be described as the set of all colors and light intensities reaching the point from all directions. A relatively simple way to capture this function to a location point of the real world, is getting an image of a mirror ball that reflects light from the entire environment toward the camera. There are also other techniques for capturing omnidirectional images that include the use of a fisheye lens, a mosaic of views, and panoramic cameras.

The simplest example of image based illumination, dates from the beginning of 80ies. The tecnique is known as environment mapping or reflection mapping. In this technique, is taken a photograph of a mirror ball and directly transfered to the synthetic object as a texture. The application of the technique using photographs of a real scene was independently tested by Gene Miller (Miller and Hoffmanm, 1984) and Mike Chou (Williams, 1983). Right after, the technique started to get adopted by the movie industry with the work of Randal Kleiser in the movie *Flight of the Navigator* in 1986, and the robot *T1000* from the movie *Terminator 2* directed by James Cameron in 1991.

Debevec and Malik developed a technique of recovering high dynamic range radiance maps from photography taken with conventional camera, (Debevec and Malik, 1997). Many shots are taken with a variance of the exposure camera settings between them. After the camera response is calculated, the low dynamic range images are stacked into a single high dynamic range image (or HDRI) that represents the real radiance of the scene. We use this technique to assemble our environment map.

In 1998, Debevec presented a method to iluminate synthetic objects with lighting captured from the real world, (Debevec, 1998). This technique became known as *IBL* - Image Based Lighting. The core idea behind *IBL* is to use the global illumination from the captured image to simulate the lighting of synthetic objects seamlessly merged within the photography.

Zang expanded Debevec's work in synthetic object rendering developing an one-pass rendering framework, dispensing the needs of post-processing composition, (Zang and Velho, 2011b). In the same year (2011), Karsch presented a relevant work on rendering of synthetize objects in legacy photographies, using a different method for recovering the light sources of the scene, (K. Karsch and Hoiem, 2011).

As for panoramic content creation important work was developed in the past for realtime content in domes by Paul Bourke (Bourke and Felinto, 2010). Part of our work is inspired on his multiple ideas on full dome creation, and the work of Felinto in 2009, implementing Bourke's realtime method in Blender and proposing other applications for panorama content in architecture visualization, (Felinto, 2010).

3 BEFORE RENDERING

Before to explain the rendering we need to have an idea of how the rendering algorithm fits in a production framework. So on, we shown a sketch of our production framework designed specially for full panoramic rendering of augmented scenes. The complete description of this framework can be found in (Felinto et al., 2012).

Production Framework:

1. Environment capture and panorama assembling

2. Calibration of the equirectangular panorama
3. Environment modeling
4. Modeling of the new objects
5. Rendering of the augmented reality panorama or restricted frustrum

One of the most important components in a rendering is the light. With out it we do not have any visible result. For photo-realistic rendering computationally designed lights do not offer the best results. Instead this is common to use light captured from real world.

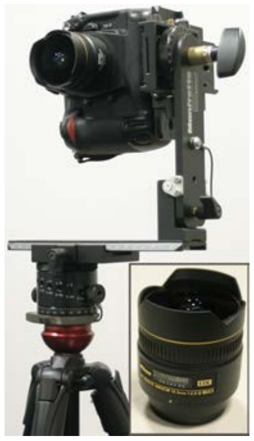
In order to obtain the light field of the environment, we need to resort to capture devices. Photography cameras can be calibrated to work as a light sensor with the right techniques and post processing software. For the ambit of this project we chose to work with semi-professional photographic equipment, considering this a good trade-off between consumer cameras and full professional devices. We used Debevec's method to produce HDR maps from bracketed pictures (Debevec and Malik, 1997). In total we took 9 pictures per camera orientation with the total of 7 different orientations to obtain the total of a 360° x 360° field of view from the camera point of view. The HDR stacks were then stitched together to produce an equirectangular panorama. We used a Nikon DX2S with a Nikon DX10.5mm fisheye lens, and a Manfrotto Pano head. For the HDR assembling we used *Luminance HDR* and for the stitching we used *Hugin*, both open source projects freely available in the Internet.

3.1 Environment Capture

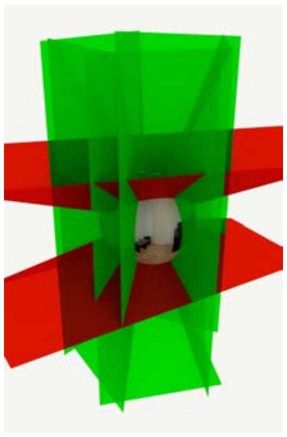
A common solution for light field capturing - mirror ball pictures - was developed to be used as reflection map and lighting (Debevec and Malik, 1997). However, when it comes to background plates, our earlier tests showed that a mirror ball picture lack in quality, resolution and field of view. Therefore, in order to maximize the resolution of the captured light field we opted to take multiple photographies to assemble in the panorama. We have used this idea before for test our production framework presented in (Felinto et al., 2012).

To use multiple pictures to represent the environment is a common technique in photography and computational visioning. For rendered images, when a full ray tracer system is not available (specially aggravating for real-time applications) 6 pictures generated with a 90° frustum camera oriented towards a cube are sufficient to recreate the environment with a good trade-off between render size and pixel distortion (Bourke and Felinto, 2010).

We chose a fisheye lens (Nikon 10.5 mm) to increase the field of view per picture and minimize the number of required shots. We used 7 pictures in total, including the north and south pole (see figure 1(b)).



(a)



(b)

Figure 1: (a): Equipment used to capture the full environment: Manfrotto Pano Head, Nikon DX2S camera and Nikon 10.5mm fisheye lens. (b): Space partition used for assembly the panorama, 5 photos around z-axis, 1 zenith photo and 1 nadir photo.

4 LIGHT-DEPTH ENVIRONMENT MAP

In this work we introduce a new type of space representation, the *light-depth environment map*. This map contains both radiance and the spatial displacement (i.e., depth) of the environment light. The traditional approach for an environment map is to take it as a set of infinite-distant or directional lights. In this new approach the map gives information about the geometry of the environment, so we can consider it as a set of point lights instead of directional lights. This second approach results in a more powerful tool for rendering purposes, because most common environment maps have their lights originally in a finite distance from the camera, such as an indoor environment map. With the depth we can reconstruct their original location and afford more complex and accurate lighting and reflection calculations. This enhanced map is no longer a map of directional lights but a conglomeration of lights points.

A *light-depth environment map* can be constructed from a hdr environment map adding the depth channel, as shown in figure 2. The depth channel map for a

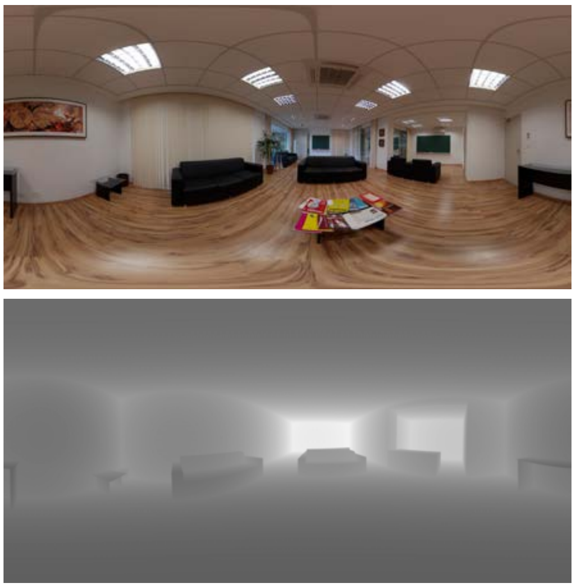


Figure 2: The upper picture shows the radiance channel of the environment and the lower one the depth channel used for reconstruct the light positions.

depth-of illumination light can be obtained by rendering from the shaping or also by scanning of the environment or other techniques. The production framework proposed in (Felinto et al., 2012) allow us to construct the *light-depth environment map* from the captured HDR light map using the modeled reconstruction of the scene.

For the following mathematic notations, a pixel sample from the *light-depth environment map* is denoted by $\mathbb{M}(\omega_i, z_i)$, where ω_i is the direction of the light sample in the map and the scalar value z_i denotes the distance of the light sample from the light space origin. The position of the light sample in light space is given by the point $z_i\omega_i$. We use too the simplified notation $\mathbb{M}(\omega_i)$ to represent the radiance of the sample located along the ω_i direction in the *light-depth map*.

5 RENDERING PIPELINE FOR AUGMENTED SCENES

The main problem in the traditionals rendering algorithms based in environment maps is that all light scattering calculations are performed using the environment map as a set of directional lights. This approach has the drawback that the environment map must be captured in the same position where the synthetic objects are inserted into the real scene, as did Devebec in his work (Debevec, 1998). If we need to introduce several objects in different positions of the scene, usually the positions of the shadows and reflections are wrong in the final render, as shown in figure 10, because the spatial location of the light is not considered in the directional approach.

Our proposal is based on modeling and synthesize the scene using a single large resolution environment map as input. This map is used for rendering the background, apply textures and model the environment geometry to keep photo-realistic light scattering effects in the final augmented scene to be rendered. In a parallel work (Felinto et al., 2012) we propose a production framework for render full panoramic scenes with augmented reality. This framework plus the rendering solution we are proposing makes possible add synthetic objects into a real scene using full panoramic cameras or conventional perspective cameras for render the output image.

Here we go describe the rendering pipeline used for process the augmented scenes modeled with this production framework.

We will start the description of the rendering pipeline introducing first some key ideas for the rendering process.

5.1 Primitives: Synthetic, Support and Environment Surfaces

Our rendering algorithm is based on a special classification of the scene primitives, where each category defines diferent light scattering contributions and visibility tests.

- ***Synthetic primitives:*** the objects that are new to the scene. They don't exist in the original environment. Their light scattering calculation does not differ from a traditional rendering algorithm.

- ***Support primitives:*** surfaces present in the original environment that needs to receive shadows and reflections from the synthetic primitives. Their light scattering calculation is not trivial, because it needs to converge to the original lighting.

- ***Environment primitives:*** all the surfaces of the original environment that need to be take into account for the reflections and shadows computations for the others primitives types. They don't require any light scattering calculation, because their color is computed directly from the *light-depth environment map*.

The level of detail of the environment reconstruction will depend on how you need the final render to be. For example, in a scene with no objects with glossy reflections, the environment mesh can be simplified to define only the main features that contribute with the lighting of the scene (e.g., windows and ceiling lamps) and a bounding box. Every ray starting at the light origin in world space must intersect with some primitive. We need to make sure the light field has the depth of all the rays. Thus it is important to model the environment mesh around all the scene without leaving holes/gaps.

5.2 Visibility Tests

Each light contributes illumination to the point being shaded only if the path from the point to the light's position is unobstructed. In a ray tracer we trace a ray whose origin is at the surface point and whose direction points toward the light. If there is no blocking object between the light and the surface, the light's contribution is included. These special rays are called *shadow rays*.

In augmented scenes where we have *support* and *synthetic* objects the traditiontal visibility test cannot solve all types of interaction between the scene objects. Consider a point p on a *support* surface. When we are computing the light contribution for this point we not consider obstructions given by other *support* object because all interaction between *support* objects are computed in the captured environment map. We only consider shadows generated by the *synthetic* objects and shadows over *synthetic* objects. To do this, we modified the visibility test to include the new special cases. We use a boolean variable *ignore_support* to turn on/off *support* objects during the visibility test. Table 1 shows the possible results for our visibility test for the possible values of the *ignore_support* variable and intersection types.

Environment primitives are ignored by the visibility test because they are associated with the *light-depth map* and used only for get correct computations of shadows and reflections (sections 5.6 and 5.7).

Table 1: Visibility test for augmented reality scenes, $VisTest(p, \omega, ignore\_support)$.

First intersection	*ignore_support*	
Object type	**true**	**false**
Synthetic	**false**	**false**
Support	**true**	**false**
Environment	**true**	**true**

5.3 Estimating the Direct Lighting Integral

The scattering equation (1) says that exitant radiance $L_o(p, \omega_o)$ from a point p on a surface in direction ω_o is the sum of emitted radiance from the surface at the point plus the integral of incoming radiance over the sphere times the BSDF for each direction and a cosine term.

$$L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{\mathbb{S}^2} f(p, \omega_o, \omega_i) L_i(p, \omega_i) |\cos\theta_i| d\omega_i. \tag{1}$$

As our scene has only the light-depth environment map as direct light source (L_d) and do not contain other emissive objects (i.e $L_e(p, \omega_o) = 0$) the equation (1) becomes

$$L_o(p, \omega_o) = \int_{\mathbb{S}^2} f(p, \omega_o, \omega_i) L_d(p, \omega_i) |\cos\theta_i| d\omega_i. \tag{2}$$

To compute this estimate, we need to choose one or more directions ω_j and apply the Monte Carlo estimator:

$$L_o(p, \omega_o) \approx \frac{1}{N} \sum_{j=1}^{N} \frac{f(p, \omega_o, \omega_j) L_d(p, \omega_j) |\cos\theta_j|}{pdf(\omega_j)} \tag{3}$$

where $pdf(\omega_j)$ is the probability of sampling the ω_j direction.

The computation of $L_o(p, \omega_o)$ depends on the primitive type of the point p. Thus for each type of primitive we have a particular way to compute the direct lighting contribution

- ***Synthetic primitives:*** $L_o(p, \omega_o)$ is computed using the traditional Monte Carlo estimator (3);
- ***Environment primitives:*** direct lighting contribution is obtained directly from the *light-depth map* as
$$L_o(p, \omega_o) = \mathbb{M}(\omega_p/|\omega_p|, |\omega_p|), \tag{4}$$
where $\omega_p = WTL(p)$. [1]
- ***Support primitives:*** $L_o(p, \omega_o)$ is computed by the estimator

$$\frac{1}{N} \sum_{j=1}^{N} \frac{\mathbb{M}(\frac{\omega_p}{|\omega_p|}, |\omega_p|) \cdot ES(p, n_p) \cdot \left\langle \frac{\bar{\omega}_j}{|\bar{\omega}_j|}, n_p \right\rangle}{p(\omega_j)}, \tag{5}$$

[1] $WTL(p)$ transform p from world space to light space.

where $ES(p,n_p)$ denotes a scale factor term used instead the bsdf term $f(p,\omega_o,\omega_j)$. We dedicate the next section to show the derivation of the $ES(p,n_p)$ scale factor and the Monte Carlo estimator for support primitives.

5.4 Direct Lighting for Support Primitives

Support surfaces need to be rendered to include shadows and reflections from the synthetic objects. The rendered value of a support point p that don't have any contribution from the synthetic objects must be converge to the radiance value stored on the light-depth map for his position. Thus we have that

$$L_o(p,\omega_o) = \mathbb{M}(\omega_p/|\omega_p|,|\omega_p|), \qquad (6)$$

where $\omega_p = WTL(p)$ [1] and the $L_o(p,\omega_o)$ term comes from the light scattering equation (2).

In order to get the equality from equation (6) is used a pre-computed scale factor

$$ES(p,n_p) = \frac{\int_{S^2} Lum(\mathbb{M}(\omega_s,z_s))\mathrm{d}\omega_s}{\int_{S^2} Lum(\mathbb{M}(\omega_j,z_j))\left\langle \frac{\bar{\omega}_j}{|\bar{\omega}_j|},n_p\right\rangle \mathrm{d}\omega_j}, \qquad (7)$$

where $\bar{\omega}_j = LTW(z_j\omega_j) - p$. [2]

The $ES(p,n_p)$ scale factor represent the percent of light contribution coming from the map to the point p and is used in the Monte Carlo estimator of equation (2). Thus we have the monte Carlo estimator for support primitives

$$L_o(p,\omega_o) = \frac{1}{N}\sum_{j=1}^{N}\frac{\mathbb{M}(\frac{\omega_p}{|\omega_p|},|\omega_p|)\cdot ES(p,n_p)\cdot\left\langle \frac{\bar{\omega}_j}{|\bar{\omega}_j|},n_p\right\rangle}{p(\omega_j)},$$

presented at the equation (5) in section 5.3

The $ES(v,n_v)$ value is estimated for all vertices v in support meshes. Thus, during rendering we calculate the scale factor for a point $p=(a_1,a_2,a_3)$ in the barycentric coordinates of the primitive triangle $T(v_1,v_2,v_3)$ as

$$\begin{aligned} ES(p,n_p) = \;& a_1\cdot ES(v_1,n_1) + a_2\cdot ES(v_2,n_2) + \\ & a_3\cdot ES(v_3,n_3). \end{aligned}$$

[2] $LTW(z_j\omega_j)$ transform $z_j\omega_j$ from light to space world space.

5.5 Computing BSDFs Scale Factor for Support Surfaces

The integral (7) can be calculated by computing the contribution of each light point, summing over the pixels of the entire light-depth map. This process is computationally expensive due to the size of the map (about 8k or higher). To simplify the accounts the map is discretized in a limited set of point lights whose radiance is equivalent to the total radiance of the whole map. So instead of summing over all pixels of the map we compute the sum on the small group of point lights to get a quick estimate of the illumination.

The discretization of the light-depth map is made using the median cut algorithm described in (Debevec, 2005). Computing the equation (7) over the discretized representation of the light-depth map by a set $L_d(i)$ of K point lights we have

$$ES(p,n) = \frac{\sum_{i=1}^{K} L_d(i)}{\sum_{i=1}^{K} L_d(i)\,\langle\omega_i,n\rangle}, \quad \textit{with}\ \ \langle\omega_i,n\rangle > 0, \qquad (8)$$

where

$$\omega_i = \frac{LTW(L_d(i)) - p}{|LTW(L_d(i)) - p|}.$$

5.6 Computing the Real Shadow Position

For every camera ray that intersects with the scene at a point p on a surface, the integrator takes a light sample ω_i by importance from the environment map to compute the direct light copntribution for point p. So, the render need to make a visibility test to determine if the sampled light is visible or not from the point p.

In the traditional rendering scheme, that uses environment maps as directional lights, the visibility test is computed for the ray $r(p,LTW(\omega_i))$, with origin in p and direction $LTW(\omega_i)$ of ω_i in world space. This approach introduces several errors when the object is far away from the point where the light map was captured. Note that for all object in the scene the shadows direction becomes in the same orientation because only are used directions for the light contributions accounts.

The *ENVPath* integrator works a little differently. Exploiting the light-depth environment map properties the visibility test uses the light sample position in real world and not only his direction.

The *ENVPath* visibility test use the direction ω_i of the light sample and multiply it by their depth value z_i obtaining the point $z_i\cdot\omega_i$ in the coordinate system of the light.

The point $z_i \cdot \omega_i$ is transformed to the world space to obtain $l_i = LTW(z_i \cdot \omega_i)$. Thus the calculation of visibility is made for the ray$r(p, l_i - p)$, whit origin p and direction $l_i - p$ as in figure 3.

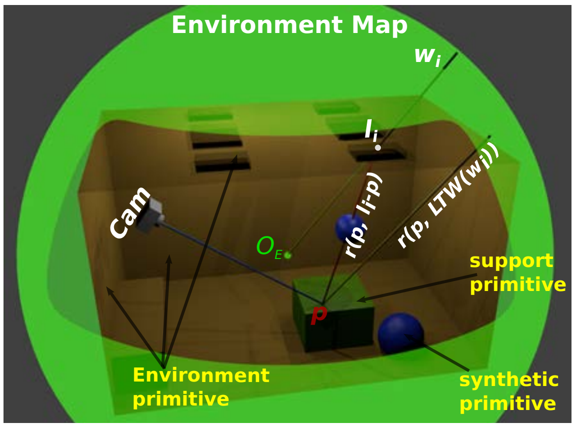


Figure 3: The visibility test used by the *ENVPath* integrator. The ray $r(p, LTW(\omega_i))$ used by the directional approach is unoccluded and thus light l_i contributes for the scattering account of point p. The ray $r(p, l_i - p)$ used for by our light-positional approach is occluded by a synthetic object and so gets the correct world-based situation.

5.7 Computing the Real Reflections

Given a point p on a surface, the integrator takes a direction ω_i by sampling the surface *BRDF* to add reflection contributions to point p. To do this, is computed the intersection with the scene of the ray $r(p, \omega_i)$ with origin p and direction ω_i. Note that the intersection exists because the environment was completely modeled around the world. If the intersection point q is over a synthetic or support surface his contribution must to be added to reflection account. Otherwise, if the intersection was with an environment mesh, we transform q from world space to light space by computing $q_L = WTL(q)$. position q for their position on the map lighting by computing the transformation $q_L = WTL(q)$. Finally the contribution given by the direction q_L in the environment map is added to reflection account. The figure 4 shows this proposal.

5.8 Environment Texture Coordinates

Environment texture coordinates are used to get some rendering effect such as apply deformation on support objects when synthetic objects interact with them. Other application its copy texture from one environment region to other. This can be a powerfull tool for texturing support meshes on regions where do you don't know the color directly by the environment because they is occluded by other support object. In

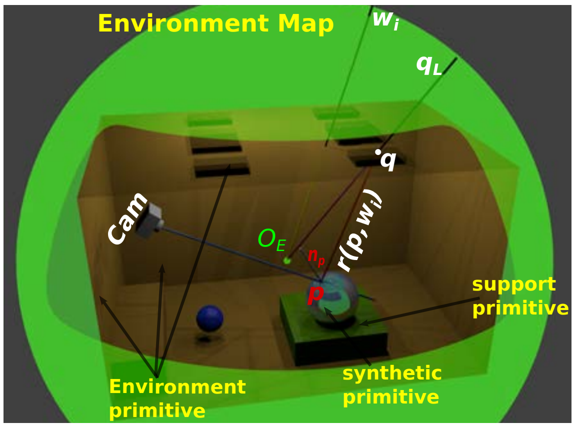


Figure 4: Reflection ray path account used by the *ENVPath* integrator. As shown, the ray $r(p, \omega_i)$ intersects the scene at point q, over the environment mesh. The radiance of q is stored at q_L direction in the environment map. Our aproach computes the correct reflection q_L, instead compute the directional ray ω_i that gives a wrong reflection mapping.

figure 5 we show the power of this tool for apply deformations on support objects when them iteracts with synthetic objects.

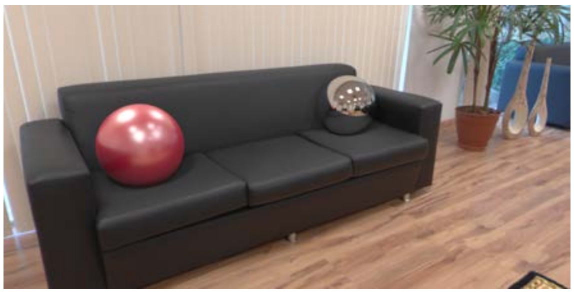


Figure 5: example of Environment texture coordinates.

6 LIGHT TRANSPORT THEORY

To understand the modified path tracing algorithm that we are proposing for augmented scenes it is necessary understand first the *light transport equation - LTE* (9), (Kajiya, 1986), that describes the phenomena of global interaction between the light sources and surfaces of the scene.

$$L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{\mathbb{S}^2} f(p, \omega_o, \omega_i) L(t(p, \omega_i), -\omega_i) |\cos\theta_i| d\omega_i. \quad (9)$$

Using a special form of the *LTE*, a sum over light carrying paths of different lengths, we can describe the incident radiance at a point p_0 from another point

p_1, where p_1 is the first point on a surface along the ray from p_0 in direction $p_1 - p_0$:

$$L(p_1 \to p_0) = L_e(p_1 \to p_0) +$$
$$\int_A L_e(p_2 \to p_1) f(p_2 \to p_1 \to p_0) G(p_2 \leftrightarrow p_1) \mathrm{d}A(p_2) +$$
$$\int_A \int_A L_e(p_3 \to p_2) f(p_3 \to p_2 \to p_1) G(p_3 \leftrightarrow p_2)$$
$$f(p_2 \to p_1 \to p_0) G(p_2 \leftrightarrow p_1) \mathrm{d}A(p_3) \mathrm{d}A(p_2) + \cdots$$

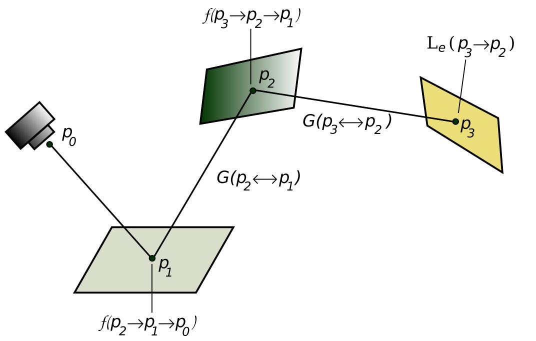


Figure 6: The integral over all points p_2 and p_3 on surfaces in the scene given by the light transport equation gives the total contribution of two bounce paths to radiance leaving p_1 in the direction of p_0. The integrand components are: the emitted radiance from the light, L_e; the geometric terms between vertices, G; and scattering from the *BSDFs*, f.

Each term on the right of this equation represents a path of increasing length. For example, the third term is illustrated in figure 6. This path has four vertices, connected by three segments. The total contribution of all such paths of length four is given by this term. The infinite sum can be written compactly as

$$L(p_1 \to p_0) = \sum_{i=1}^{\infty} P(\bar{p}_i). \qquad (10)$$

$P(\bar{p}_i)$ gives the amount of radiance scattered over path $\bar{p}_i$ with $i+1$ vertices, $\bar{p}_i = (p_0, p_1, \cdots, p_i)$ where p_0 is on the film plane and p_i is on the light source. So

$$P(\bar{p}_i) = \underbrace{\int_A \cdots \int_A}_{i-1} L_e(p_i \to p_{i-1}) T(\bar{p}_i) \mathrm{d}A(p_2) \cdots \mathrm{d}A(p_i),$$

where

$$T(\bar{p}_i) = \prod_{j=1}^{i-1} f(p_{j+1} \to p_j \to p_{j-1}) G(p_{j+1} \leftrightarrow p_j)$$

describes the fraction of radiance from the light source that arrives at the camera after all of the scattering at vertices between them.

Given equation (10) and a particular length i, all that we need to do to compute a Monte Carlo estimate of the radiance arriving at p_0 due to paths of lengths n is to sample a set of vertices with an appropriate sampling density in the scene to generate a path and then evaluate an estimate of $P(\bar{p}_i)$ using those vertices. More details about the *light transport equation* can be found in (Pharr and Humphreys, 2010).

7 ENVPATH INTEGRATOR: PATH TRACING FOR LIGHT-DEPTH ENVIRONMENT MAPS

We use a implementation of the path tracing algorithm that solves the light equation constructing the path incrementally, starting from the vertex at the camera p_0. At each vertex p_k, the *BSDF* is sampled to generate a new direction; the next vertex p_{k+1} is found by tracing a ray from p_k in the sampled direction and finding the closest intersection.

For each vertex p_k with $k = 1, \cdots, i-1$ we compute the radiance scattering at point p_k along the $p_{k-1} - p_k$ direction. The scattering computation for p_k on a synthetic, support or environment surface is performed using respectively the equations (3), (4) and (5) from section 5.3.

A path $\bar{p}_i = (p_0, \cdots, p_i)$ can be classified according the nature of its vertices as

- **Real path:** the vertices p_k, $k = 1, \cdots, i-1$ are on support surfaces.
- **Synthetic path:** the vertices p_k, $k = 1, \cdots, i-1$ are on synthetic objects surfaces.
- **Mix path:** some vertices are on synthetic objects and other on support surfaces.

There is no need to calculate any of the real path for the light. They are already present in the original photography. However, since part of the local scene was modeled (and potentially modified), we need to re-render it for these elements. The calculated radiance needs to match the captured value from the environment. We do this by aggregating all the real path radiance in a vertex p_1 as direct illumination, discarding the need of considering the neighbor vertices light contribution.

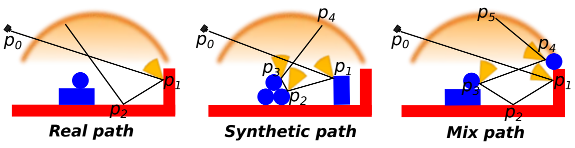
The synthetic and mixed light paths are calculated in a similar way, taking the individual path vertex light contributions for every vertex of the light path. The difference between them is in the Monte Carlo estimative applied in each case. In the figure (7) you can see the different light path types and the calculation that happens on the corresponding path vertices.

Because we are using an incremental path construction technique it is impossible know what kind of path we have before conclude it. So, the above classification is only theoretical.

For implementation purposes, during the incremental path construction we only need know if the partial path $(p_0, \cdots, p_k)$ contains some synthetic vertices or not. This allow us decide the Monte Carlo estimator to being use. To do this, we use a boolean variable *pt* (*path type*) that has a *false* value if the partial path do not have synthetic vertices and *true* otherwise.

Algorithm 1 ENVPath Integrator

```
 1: $L := 0$                                          ▷ Radiance contribution
 2: $r_0 := ray(p_0, -\omega_0)$                       ▷ Camera ray
 3: $pt := false$                                      ▷ Path type
 4: $T := 1$                                           ▷ Path throughput factor
 5: for $i = 0$ to $MaxLength$ do
 6:     $p_{i+1} = SceneIntersect(r_i)$
 7:     $T* = ThroughputAtenuation(p_i, p_{i+1})$
 8:     if $type(p_{i+1}) = ENVIRONMENT$ then
 9:         if ( $pt = true$ ) OR ( $i = 0$ ) then
10:             $L+ = \mathbb{M}(\frac{\omega_{p_{i+1}}}{|\omega_{p_{i+1}}|}, |\omega_{p_{i+1}}|)$    ▷ eq. (4)
11:         $break$                                    ▷ Terminate the path
12:     if $type(p_{i+1}) \neq SUPPORT$ then
13:         $pt := true$
14:     if $(i+1) = MaxLength$ then
15:         $break$                                    ▷ Terminate the path
16:     $L+ = DirectLighting(p_{i+1}, pt, i)$
                             ▷ Sample BSDF to get new path direction
17:     $r_{i+1} := SampleNewDirection(p_{i+1})$
18:     $T* = f(p_{i+1}, -dir(r_i), dir(r_{i+1}))$
19:         ▷ Continues the path construction or not ?
20:     if $Prob() < END\_PROBABILITY$ then
21:         $break$                                    ▷ Terminate the path
22:     else
23:         $T/ = Prob()$  ▷ Increase path contribution
24:     if $type(p_{i+1}) = SUPPORT$ then
25:         $T* = SupportAtenuation(p_i, p_{i+1})$
26: return $L$
```



🟥 Support surfaces 🟦 Synthetic objects 🔻 Direct lighting contribution

Figure 7: Path type classification. The yellow cones represents the direct lighting contribution from the vertices p_i that contributes with the illumination accounts.

Algorithm 2 Direct Lighting Estimator

```
 1: Procedure DirectLighting($p$, $\omega_o$, $PT$, $RD$)
 2: $Ld := 0$
 3: $mis := UseMultipleImportanceSampling(p)$
 4: $\omega_i := SampleLightDir(\mathbb{M})$
 5:                                   ▷ $\omega_p := LightToWorld(\omega_i)$
 6: if $type(p) = SUPPORT$ then
 7:     if ( $PT = true$ ) OR ( $RD = 0$ ) then
 8:         if ( $mis = false$ ) OR ( $RD = 0$ ) then
 9:             if $VisTest(p, \omega_i, true) = true$ then
10:                 $Ld+ = \frac{ES(p,n_p)\mathbb{M}(\omega_p)\langle\omega_p,n_p\rangle}{pdf(\omega_i)}$
11:         else
12:             if $VisTest(p, \omega_i, false) = true$ then
13:                 $Ld+ = \frac{ES(p,n_p)\mathbb{M}(\omega_p)\langle\omega_p,n_p\rangle}{pdf(\omega_i)}$
14:                 $Ld+ = \frac{f(p,\omega_o,\omega_p)\mathbb{M}(\omega_p)\langle\omega_p,n_p\rangle}{pdf(\omega_i)}$
                    ▷ Trace a second shadow ray by sampling
    the BSDF
15:         if $mis = true$ then
16:             $\omega_i := SampleBSDFDir(p)$
17:             $r := ray(p, \omega_i)$
18:             $q := SceneIntersect(r)$
19:             if $type(q) = ENVIRONMENT$ AND
    $DR > 0$ then
20:                 $Ld+ = \mathbb{M}(\omega_p)$
21: else                               ▷ $type(p) = SYNTHETIC$
22:     if $VisTest(p, \omega_i, false) = true$ then
23:         $Ld+ = \frac{f(p,\omega_o,\omega_i)\mathbb{M}(\omega_i)\langle\omega_i,n_p\rangle}{pdf(\omega_i)}$
            ▷ Trace a second shadow ray by sampling
    the BSDF
24:     if $mis = true$ then
25:         $\omega_i := SampleBSDFDir(p)$
26:         $r := ray(p, \omega_i)$
27:         $q := SceneIntersect(r)$
28:         if $type(q) = ENVIRONMENT$ then
29:             $Ld+ = \mathbb{M}(\omega_p)$
30: return $Ld$
31: end procedure
```

8 RESULTS

The rendering performance of our approach is equivalent to the rendering of a normal scene with the same mesh complexity using a physically based light rendering algorithm. There was no visible lost in that regard. Part of the merit of this, is that this is an one-pass solution. There is no need for multiple composition passes. And the rendering solution converges to the final results without 'adjustments' loops been required like the original Debevec technique (Debevec, 1998).

As explained during the paper, the core aspect of this process is to develop the rendering of full panorama images. More specifically the integration of a captured environment and synthetic objects. In the figure 8 you can see synthetic spheres integrated with the original panorama. The lighting and shadows on the floor are calculated with the light-depth map.

The mirror ball reflection calculation can be seen in more details in the figure 10. This is a comparison between the traditional direction map method and our light-depth solution. The spheres and the carpet are synthetic and render the same with both methods. The presence of the original environment meshes makes the reflection to be a continuous between the synthetic (e.g., carpet) and the environment (e.g., wood floor).

The proper calibration of the scene and the correct shadows helps the natural feeling of belonging for the synthetic elements in the scene. In the figure 11 you can see the spheres and the carpet inserted in the scene. The details are shown in a non panoramic frustum to showcase the correct perspective when seen in a conventional display.

Finally, we explored camera traveling for a few of our shots. In the figure 13 you can see part of the scene rendered from two different camera positions. The result is satisfactory as long as the support environment match is properly modeled. For slight camera shifts this is not even a problem.

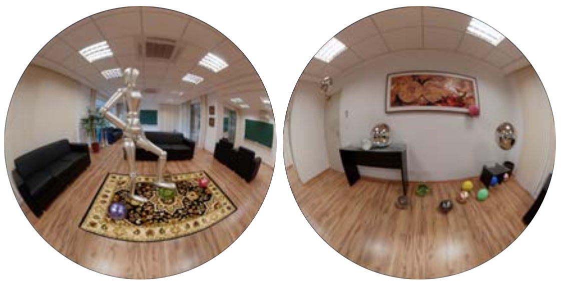


Figure 9: The top image is a full panoramic render of the augmented reality scene. The bottom images show the same scene rendered with fisheye lens.

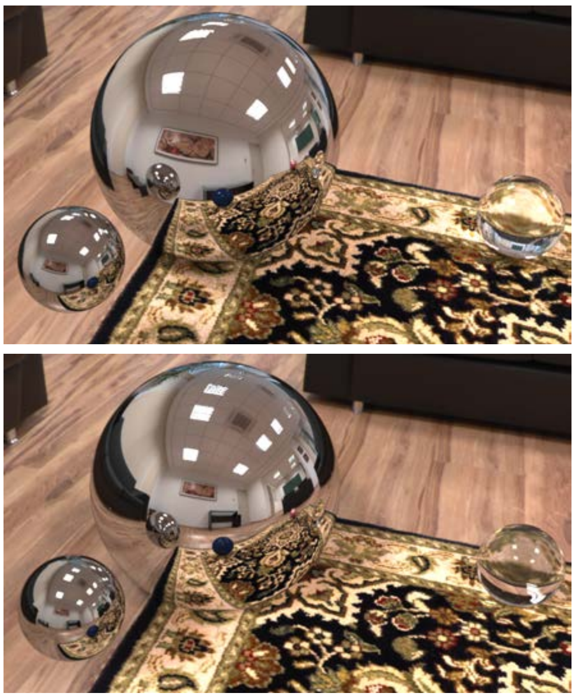


Figure 10: Comparison between reflections given by directional (upper) and light-depth (lower) maps approaches.

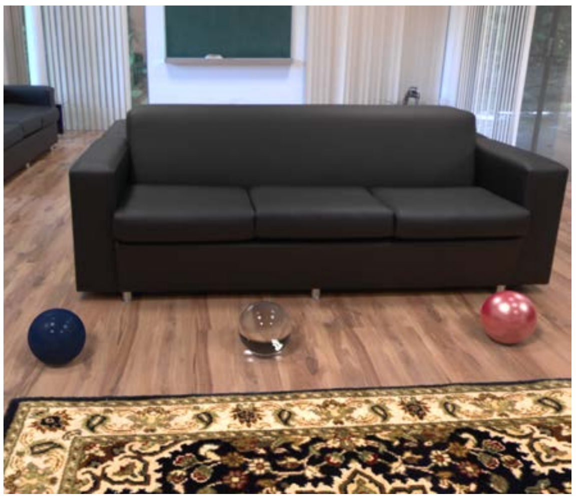


Figure 11: Shadows using light-depth maps. The red ball has different shadows directions than the blue ball.

9 CONCLUSION

We have presented a novel approach for rendering synthetic objects into full panoramic scenes based on illumination captured from real world and reconstructed depth. To show the feasibility of such a production workflow is essential to produce realistic immersive scenes for panoramic displays.

A key point of our method, until now unexplored for this means, is the use of light position in the environment map instead the directional approach to get the correct shadows and reflections effects for all synthetic objects along the scene.

Among the possible improvements, we are interested on studying techniques to recover the light positions for assembling the light-depth environment map and semi-automatic environment mesh construction for the cases where we can capture a point cloud of the environment geometry.

Outra extensao que estamos trabalhando no presente a combinacao do light-depth map de baixa res-

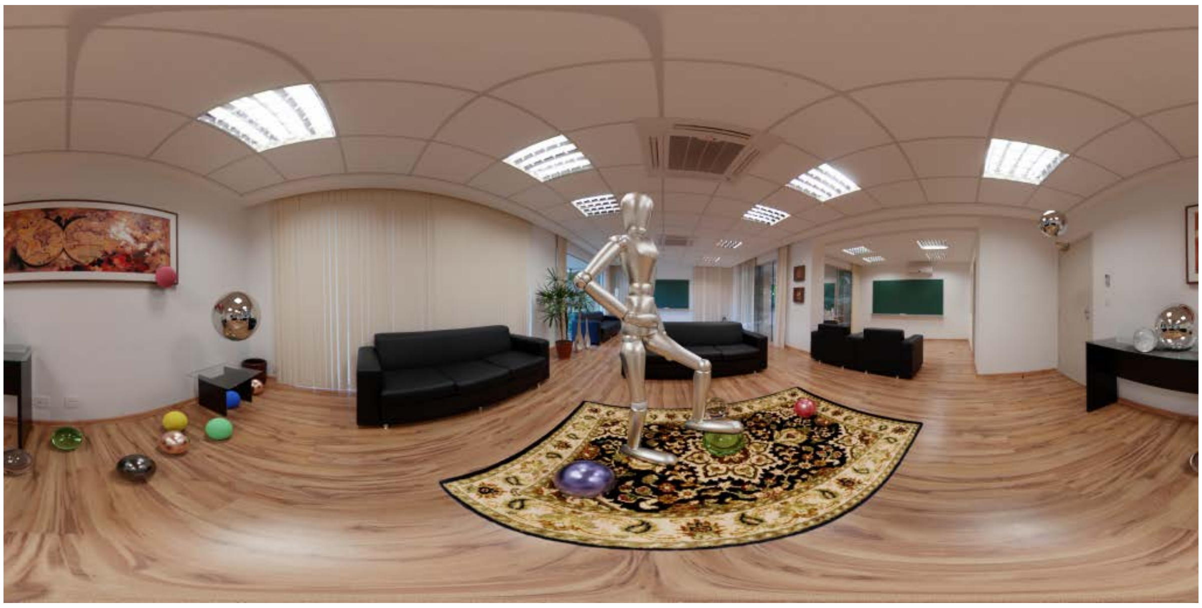


Figure 8: The top image is a full panoramic render of the augmented reality scene. The bottom images show the same scene rendered with fisheye lens.

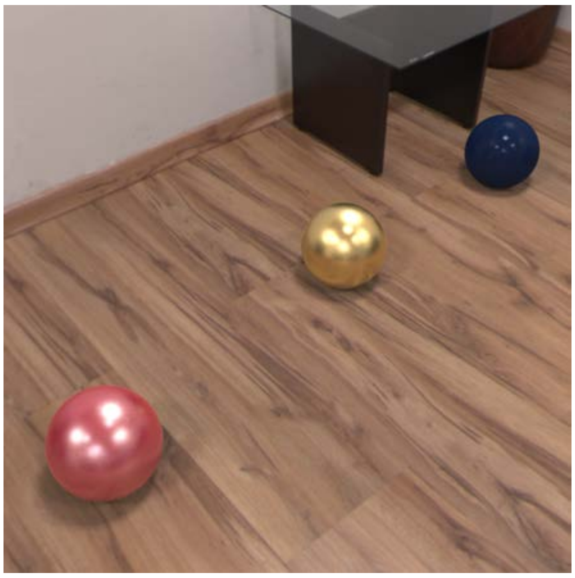


Figure 12: Shadows using light-depth maps. The red ball has different shadows directions than the blue ball.

oluco, por exemplo capturado com uma mirror ball, e um fundo capturado com camera convencional. Isto resulta interessante para renderizacoes que nao so full panoramicas mas precisam de um nivel apurados de sombras e reflexos.

Finalmente devemos destacar como mrito do presente trabalho sua usabilidade, dado que existe uma implementacao funcional e est disponivel no nosso site e no site do luxrender. Outro ponto interessante que existe um framework de modelagem especialmente disenhado para este tipo de renderizador e tambm est disponivel. Nosso trabalho open source.profissional a fim de abrangir um publico maior

Another thing to explore is the use more than one single environment capture to allow more complex camera traveling in the scene. The use of multiple environment captures helps too to have minor occluded regions of the real environment. This is important to avoid abuse on using environment texture coordinates. They are better fit for applying soft deformations on the environment instead of texture copy to complete unknown environment elements.

Finalmente estamos satisfeitos pelos resultados obtidos e pelas contribuioes que logramos tratando este tema. Mesmo vendo milhares de efeitos especiais utilizados nas producoe cinematogrfica, muitos das ferramentas e tcnicas esto fora do alcance deste reducido circulo de produtoras. Outra contribuio que consideramos importante a introduo dos mapas com profundidade que permitem obter efeitos mais prximos dos reais e permitir varios movimentos de cmera (traveling, zoom) que de outra forma no poderiam ser realizados com tanta naturalidade num processo de modelagem.

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