Practical Precomputed Radiance Transfer for Mixed Reality

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Abstract. Mixed Reality and its concept of virtual superimposed on real space interplay invoke such interactive experiences that promote new patterns of believability and presence for cultural heritage applications. The seamless integration of virtual cultural artifacts with 'real lights' or images of real scenes, is an important step towards believability and consistency in synthesized MR scenes. That synthesized world termed Augmented Reality allows seeing the real scene with virtual augmentations superimposed onto it, but often fails to produce a real-time image that as a whole is a believable integrated experience. Furthermore, often Virtual Reality cultural heritage reconstructions are not physically correct rendered in real-time. Our main research efforts are twofold: adding believable and realistically simulated real-time virtual artifacts superimposed on real video sequence images, as well as employ dynamic 'area lights' for real-time large scale VR site reconstructions. The main novelty of this combined effort is a new adaptation of a physically correct illumination model for virtual cultural heritage artifacts as well as large scale reconstructions based on 'real area light', captured via light probes and employed in an extended graphics hardware accelerated Precomputed Radiance Transfer algorithm.

1. Introduction

Attaining a high quality believability and realism of a real-time seamless integration between real images and virtual objects lit with 'real light', requires two main aspects for consistent matching: geometry and illumination. First, the camera position-orientation and projection should be consistent; otherwise the object may seem too foreshortened or skewed relative to the rest of the picture (geometrical consistency). Secondly, the lighting-shading of the virtual object needs to be consistent with the other objects in the

real environment (illumination consistency). In the past, consistency of geometry has been intensively investigated [2]. On the other hand, few methods have been proposed so far for real-time illumination consistency registration to superimpose virtual objects onto an image of a real scene: [12], [7] and even less research in the area of superimposing real-time, dynamic-deformable virtual objects on real-time video streams. Furthermore, pursuing bridging the lighting of virtual objects with real ones, we harness the research graphics domain of global illumination, the physically-correct simulation of light transport [19] [3].

Figure 1 Virtual augmentation in AR: Normal diffuse shading(far left) and extended Precomputed Radiance Transfer with varying exposure of both h/w camera and captured HDRI scene real area light (center, right)

2. Background

With the advent of sixth generation graphic programmable units (GPUs) as massive parallel powerful streaming processors, research on real-time ray tracing has recently made tremendous advances [19]. Recent algorithmic improvements together with optimized GPU based implementations allow now for limited interactive ray tracing. Furthermore, as most of today's global illumination algorithms heavily build on top of ray tracing, real-time performance of the latter is giving rise to new interactive global illumination algorithms for complex dynamic scenes [3]. However, the application of such models is still far away from MR and dynamic virtual cultural heritage, due to their heavy computational requirements. Recently a new real-time theory-methodology for physically correct area-light global illumination simulation of rigid objects in VR has been introduced, termed Precomputed Radiance Transfer(PRT) [16], which provided the most realistic and believable real-time VR illumination model up to date [11]. In the current work we propose an extension on this algorithm for a) MR (matching exposures of real light captured from real-time

AR camera and real-light captured from light probe) and b) multi-geometry meshes and a categorization of the radiance transfer based on the type of sub-geometry in the mesh: occluder or receiver (Figure 1). In [14] a radiosity based solution with irradiance maps was presented for photorealistic virtual heritage static object simulation, but allowed only static, predefined objects, lights where the currently introduced VR PRT algorithm allows for real, dynamic High Dynamic Range Image (HDRI) lights in a physically correct simulated environment (Figure 2).

The new proposed fusion of developments in this area of real-time physically-correct simulation of light transport (low frequency shadows, reflections, indirect illumination) with the previous topic of illumination registration in Augmented Reality environments, we believe will become a mandatory feature of future Mixed Reality simulations, similar to the introduction of real-time texture mapping a few years ago.

Figure 2 VR Reconstruction of the Aspendos theatre with applied PRT (diffuse unshadowed occluder) and precalculated irradiance maps with dynamic HDRI area lights (variable exposure)

The theatre of Aspendos (Figure 3) is the best preserved roman theatre in Asia Minor, and it is calculated that it was built around 161-180 A.D. during the reign of emperor Marcus Aurelius. In 1078, the greater area of Pamphylia was claimed by the Seljuk Turks. Certain remains in the theatre of Aspendos and oral sources imply that the theatre was used as a caravanserai (Merchants' Inn) by the Seljuk's. In 1392 ottoman reign sat in and, by the declaration of the Republic of Turkey in 1923, Aspendos took its place within the boarders of the Turkish province of Antalya.

Figure 3, Aerial views of the Aspendos theatre under variable real light exposure

It was only after the rediscovery of the theatre by European archeologists in the 19th century, after long centuries when the theatre was forgotten to all but a few locals, that an architectural evaluation of the structure became an issue. In the second half of the 19th century, the building caught the attention of scientists. It was the works of researchers such as Lanckoronski [6] and Texier [6], although occasionally contradicting with each other on certain assumptions, which helped to gradually sweep away the mist of centuries that shadowed Aspendos. In this paper we provide results based on our ongoing VR restitution research results on the Aspendos theatre, related to possible restorations related to its roof. Furthermore, specific Greek-Roman statues used to be placed in various locations within the theatre (statues which were removed are not yet discovered) and as part of an envisaged mixed reality simulation; we are simulating a possible virtual statue in a real environment under laboratory conditions (maquette). The AR-Life Mobile Simulation prototype that was demonstrated in [13] is planned to perform the AR demo on site using the advanced illumination registration algorithm defined in current work, while harnessing the previously defined MR Character Simulation Framework and Markerless camera tracking solutions of the AR-Life prototype.

3. Methodology

We propose two physically correct illumination registration methods based on precomputed radiance transfer [16] adapted for mixed reality diffuse cultural heritage multiple-geometry artifacts as well as virtual reality large-scale virtual reconstructions. A new categorization is proposed that takes into account the different radiance transfer vectors per mesh

vertex. A uniform grid acceleration structure preprocessor is utilized in order to determine the self shadowing factor by ray-casting, based on specific criteria analyzed further below. Graphics hardware is finally used for fast, per vertex final radiance estimation, based on the Spherical Harmonics projected "real" area light captured from a light probe and the local transfer vectors. At the last stage, a tone map operator matching the h/w camera exposure setting with the HDRI exposure of the already captured area light of the same real scene which is used to illuminate the virtual augmentations.

Spherical Harmonics Theoretical background

Spherical Harmonics (SH) define an orthonormal complex basis over the sphere, S, analogous to Fourier Transform over the 1D circle. However, as we are interested in approximating real functions over a sphere (light intensity fields) we will be working only with real spherical harmonics.

Using a spherical coordinates parameterization:
$S = (x, y, z) = (\sin\theta \cdot \cos\phi, \sin\theta \cdot \sin\phi, \cos\theta)$, the basis functions are defined as: $Y_l^m(\theta, \phi) = K_l^m e^{lm} P_l^m \cdot (\cos\theta)$ for $l \in N, -l \leq m \leq l$ where P is the Associated Legendre polynomial and K the normalization constant: $K_l^m = \sqrt{\dfrac{(2 \cdot l + 1) \cdot (l - |m|)!}{4\pi \cdot (l + |m|)!}}$. The real-valued SH basis is given by the transformation:

$$Y_l^m(\theta, \phi) = \begin{cases} \sqrt{2} \cdot K_l^m \cdot \cos(m \cdot \phi) \cdot P_l^m \cdot \cos(\theta), m > 0 \\ \sqrt{2} \cdot K_l^m \cdot \sin(-m \cdot \phi) \cdot P_l^{-m} \cdot \cos(\theta), m > 0 \\ K_l^0 \cdot P_l^0 \cdot \cos(\theta), m = 0 \end{cases}$$

Low values of l (called *band* index) represent low-frequency basis functions over the sphere. The basis functions for l reduce to polynomials of order l in x, y, z. Evaluation is done with specific recurrence formulas[8]. Our CPU preprocessor, precalculates the SH basis for each direction in the assumed sphere of jittered sample direction points surrounding each vertex in our models.

*Spherical Harmonics GPU per vertex Projection -
Reconstruction*

As SH is an orthonormal basis, a scalar function f defined over **S** can be *projected* into its coefficients via integral (synthesis): $f_l^m = \int f(s) \cdot y_l^m(s) \cdot ds$ i.e. calculating how much of f is like the basis function y ('s' is a sample point). We estimate this integral employing Monte Carlo integration since we assume the unit sphere pre-allocation of jittered sample points-directions. These calculated coefficients provide the n-th order reconstruction function (analysis): $\tilde{f}(s) = \sum_{l=0}^{n-1} \sum_{m=-l}^{l} f_l^m \cdot y_l^m(s)$ which approximates f as the number of bands n increases. [Ramamoorthi01] has proved analytically that 3 SH bands (9 bases) can accurately represent low-frequency signals. It is often convenient for GPU final calculation to re-write the reconstruction function as: $\tilde{f}(s) = \sum_{i=1}^{n} f_i \cdot y_i(s)$ where $i=l(l+1)+m+l$. Thus evaluation at s of the reconstruction function is a simple dot product of the n^2-component coefficient vector f_i with the vector of evaluated basis functions $y_i(s)$.

Precomputed Radiance Transfer overview and Mixed Reality Extension

As we aim for a physically based light transport and reflectance simulation the starting point is the rendering equation [10] and its approximate solution that is amenable to real-time simulation of concave objects, as defined in the original Precomputed radiance transfer algorithm [16]:

$$L_o(\bar{x}, \bar{v}) = L_e(\bar{x}, \bar{v}) + \int_\Omega f_v(\bar{x}, \bar{l}_\omega, \bar{v}_\omega) \cdot L_{in}(\bar{x}, \bar{l}) \cdot (\bar{l} \cdot \bar{n}) \cdot dl$$
,

Where v is the view vector direction in global coordinates (ω is the local direction), l is the light direction, L_{in} the incident radiance, L_o the reflected radiance and f the BRDF (isotropic or anisotropic expressed in local coordinates). PRT allows for simulating diffuse & glossy objects in low frequency lightning environments, by capturing

6

interreflections, soft shadows, caustics and specific BRDFs by approximating the rendering equation above. A pre-processor creates 'transferred radiance' functions (vectors) over object (object's shaded response to environment: mapping incoming to outgoing radiance) and at runtime these functions are applied to incident lightning.

Both lightning & transferred functions are represented using the low-order Spherical Harmonics linear basis, exploring linearity of light. Thus shading integral reduced to a dot product between their coefficient vectors (diffuse receivers) or a linear transform of lighting coefficient vector through transfer matrix(glossy receivers). The original PRT algorithm was aimed to be applied on single mesh, static objects; we extend this assumption to our case study of meshes containing multiple geometries. Thus we categorize them into 'Occluders' (participate in the final rendering but only cast and don't receive shadows) and 'receivers' (receive and cast soft shadows).

The basic illumination assumption is concave diffuse objects lit by a distant environment map. Such an *environmental map* **stores the radiance incident from all directions at a single point.** Then the object's shaded 'response' to environment is defined as a *transfer function*, mapping incoming to outgoing radiance. The expensive transport simulation is precomputed and stored as vectors/matrices over surface vertices. A static uniform grid structure is employed, traversed using the [1] algorithm for fast grid traversal and the [9] ray-triangle algorithm for intersections of the casted ray with the grid-voxel included triangle. Besides the original barycentric coordinate criteria on whether the point of intersection lies within the tested triangle, a further criteria on distance from origin is employed based on an intuitive ε value. Furthermore, for faster performance and correct intersection results, all faces that share the current vertex are ignored from ray casting as, where back facing triangles are not ignored as they could too contribute on the vertex self-shadowing despite orientation.

The incident radiance is not precomputed but sampled dynamically from the supplied HDRI environmental map and projected to SH (thus allowing for light exposure modification, as well as rotation). Then for diffuse objects,

the transfer vector at each vertex is dotted with lighting's coefficients (input luminance) for self-scattered shading, which gives the approximated lighting at that point.

Hence Radiance self transfer:

- ➢ Encapsulates how an object O shadows and scatters light onto itself.
- ➢ To represent it, we parameterize incident lighting at points p of O, denoted $L_p(s)$, using the SH basis thus representing it as a vector of n^2 coefficients $(L_p)_i$.
- ➢ We then sample the lighting dynamically at a point and also precompute and store densely over O transfer vectors/matrices.

A Transfer vector $(M_p)_i$ for diffuse surfaces is calculated, which is the linear transformation (influence of basis $(L_p)_i$ on shading at p) on lighting vector producing scalar exit radiance L'_p.

Diffuse Unshadowed Occluder Transfer (DUO transfer)

After creating pairs of vertices-normals (light points) we proceed into calculating a transfer function for each. In the case of DUO, the transfer vector for a point p is defined as:

$$T_{DUO}(L_p) = \left(\frac{\rho}{\pi}\right) \cdot \int_\Omega L_p(s) \cdot H_{NP}(s) \cdot ds$$ producing an ideal

diffuse, view angle invariant exit radiance. The ρ term is the albedo constant (emitted radiance/irradiance), L_p is the incident radiance (from the SH projected environment map) and H_{NP} is the geometrical term accounting for Lambert's law, i.e. the cosine weighted hemispherical kernel about the vertex p normal N. Projecting both integral terms in SH, the integral becomes a dot product of the projected coefficients, thus fast to calculate in GPU for every sample direction in the hemisphere surrounding the vertex p. It has to be noted that this type of transfer is applied also to MR 'blue box' geometry [13], i.e. the depth-buffer not frame-buffer rendered geometry that is often use when real objects should occlude virtual augmentations, since we still require that they cast virtual shadows on other virtual augmentations in their proximity.

Diffuse Shadowed Receiver Transfer (DSR transfer)

In order to calculate this function we use our list of precalculated rays and SH coefficients, dotting each one with the surface normal at sample point to check if it lies in upper hemisphere. Then to include self-shadows we add a visibility function for *shadowed diffuse transfer*, defined

as: $T_{DUO}(L_p) = \left(\dfrac{\rho}{\pi}\right) \cdot \int_{\Omega} L_p(s) \cdot H_{NP}(s) \cdot V_p(s) ds$ where Vp

is calculated by ray-casting: trace a ray from current point through the polygon database to find any hits (just a Boolean that it occurred). The ray traversal is accelerated with eh uniform grid structure and the algorithms mentioned before; examples are depicted in following Figure 4 The Uniform Grid acceleration spatial structure for ray casting (left-centre) and detail on differences between DUO (right top) and DSR (right bottom)

Figure 4 The Uniform Grid acceleration spatial structure for ray casting (left-centre) and detail on differences between DUO (right top) and DSR (right bottom) transfers

HDRI Area Lights

The real world contains a lot more brightness variation than can be captured by digital sensors found in most cameras today. The radiance range of an indoor photograph can contain as many as six orders of magnitude between the dark areas under a desk to the sunlit views seen through a window. Typical CCD or CMOS sensors capture only two to three orders of magnitude. The effect of this limited range is that details cannot be captured in both the dark areas and

9

bright areas at the same time. This problem has inspired many solutions in recent years. One method of capturing greater dynamic range of still scenes is to shoot multiple exposures, which appropriately capture tonal detail in dark and bright regions in turn. These images can then be combined to create a high dynamic range (HDR) image. [5] Presented a simple technique for recovering this response function, up to a scale factor, using nothing more than a set of photographs taken with varying, known exposure durations. With this mapping, we then use the pixel values from all available photographs to construct an accurate map of the radiance in the scene, up to a factor of scale as defined in [4][20] and visualized via GPU fragment shader based on the RGBE file format (`Figure 5`).

Figure 5 Custom captured HDRI Light probe for AR (left) and various MR PRT DS precomputed radiance transfer results on right based on the captured HDRI

3.1 Proposed Virtual Restoration(s): The two different historical hypotheses:

Two models of the Aspendos theatre were developed in order to visualize the site in its present state and as it was back in the III century. The main difference between these two versions of the model resides in the elements that were present at the Roman time and that are now no longer present, such as the Velum, the roofing of the theatre and all the decorative features of the scene building (general view presented in `Figure 6`).
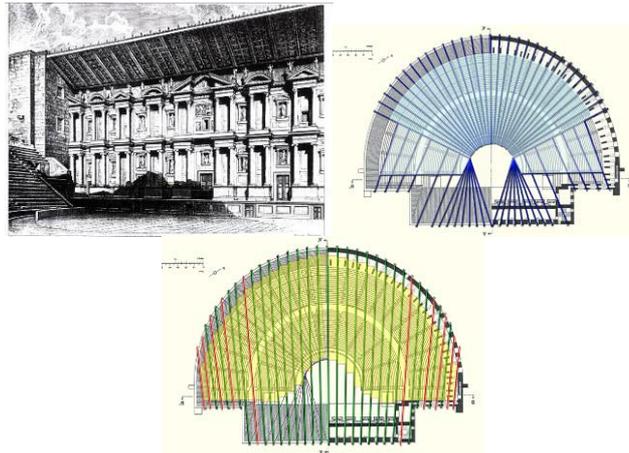
Figure 6, Restitution of the scene building by Lanckoronski and Velum plan by Izenour (center) and by de Bernardi (right).

Concerning the Velum two contradicting sources were available (`Figure 6`), namely the restitution plans by Izenour and the ones by de Bernardi.In order to proceed in our virtual restitution (`Figure 7`) the hypothesis presented by Izenour was kept as reference because his assumption, based upon a parallel with the Rome Coliseum Velum, uses and explains all the ropes anchor points still existing at the exterior of the theatre.
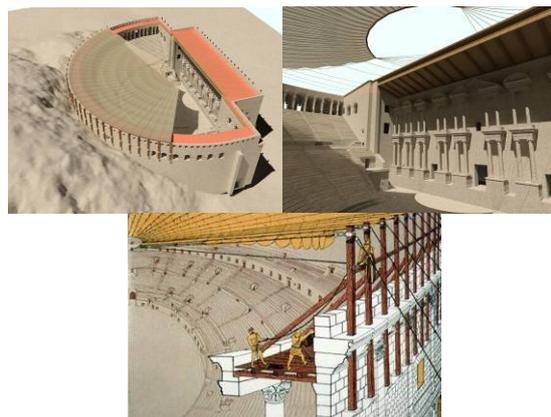
Figure 7, 3D virtual restitution of the Aspendos Velum according to Izenour hypothesis (left-center) and Detail of the Velum structure (right)

The hypothesis of de Bernardi on the other hand implies the creation of additional anchor points in order to keep the symmetry of the Velum and allow a correct placing of the sliding sections of the Velum (details depicted in `Figure 7` right). Concerning the Roofing of the Theatre, Izenour restitution drawings, presenting some differences between front and lateral sections, do not seem to consider some

11

issues and their repercussions regarding a height difference between the Cavea roofing and the scene building lateral structures. Moreover, these drawings (Figure 8) also depict the roofing of the Theatre as a contiguous structure covering both the Cavea upper arcades and the scene buildings, thus impeding access to the upper arcades roof where the ropes used to open and close the sections of the Velum where operated.
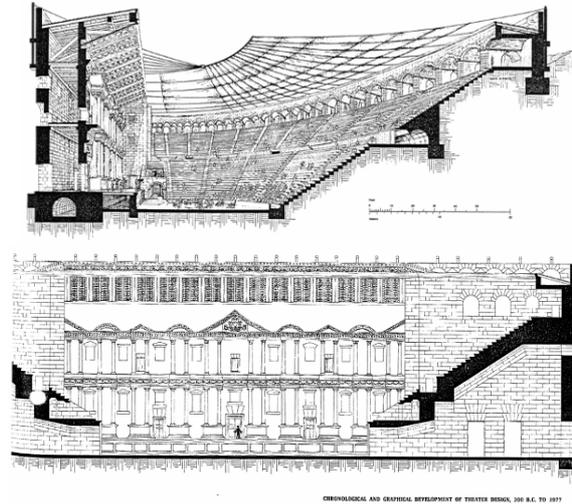

Figure 8, Izenour Velum restitution

Therefore a modified model (Figure 9) based upon Lanckoronski restitution drawings, has been prepared in order to address these specific issues, namely evening the induced slope of the section of the roof connecting the lateral building to the Cavea upper arcades, and flattening the covering of the upper arcades in order create the necessary room to operate the Velum ropes.
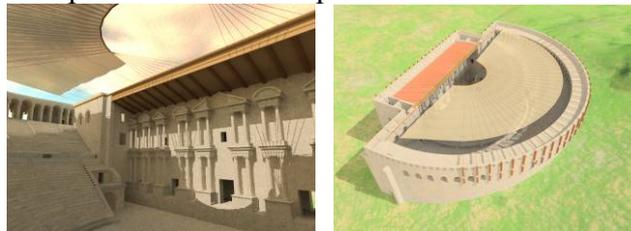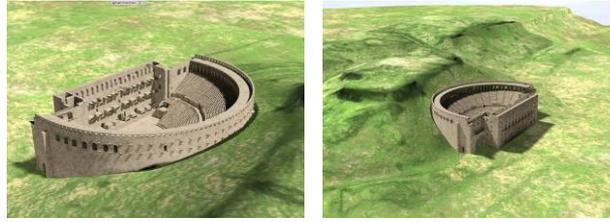

Figure 9, Lanckoronski Roof restitution

Figure 10, Screenshots from the 3D real time simulation of the Aspendos theatre in its present state

4. Quantified Results

A novel extension to the PRT[16] algorithm has been proposed in order to be applied in Mixed Reality Multi-mesh geometries based on the categorization of the underlying geometry segments into 'occluders' and 'receivers'(Figure 1, Figure 2, Figure 5). The illumination model was based on 'area light sources' based on either custom captured 'real light' as HDRI light probe or based on custom made 'HDRI virtual light probes'. Two case studies were presented for cultural heritage artifacts and large scale site reconstructions with different approaches to final PRT simulation:

➢ Large Scale Sites in VR
- o Radiosity-based low frequency irradiance maps pre-calculation
  - ▪ PRT DUO transfer for projecting light transport and HDRI light to SH and evaluating them
  - ▪ HDRI Area based on virtual Light Probe
  - ▪ Performance: For 286.000 triangles and DUO transfer on P4 3.0 Ghz, preprocessing SH projection with 9 SH bases, and GPU fragment shader radiance evaluation took 126 seconds and real-time simulation with dynamic light(variable exposure via vertex shader) and variable exposure yield 70 fps

➢ Static Cultural artifacts as virtual augmentations in AR
- o PRT DSR transfer
  - ▪ Static Voxel-Based Grid [1] with fast ray-triangle intersection [9]
    - • Extra relaxation tests for ray-triangle intersection:
      - o Proximity of hit to origin

13

- o Ignore faces containing origin
- o Include back/front facing polygons
- 'Real Light' captured HDRI probes
- Performance: For 76.800 triangles and DSR transfer on P4 3.0 Ghz, preprocessing SH projection with 9 SH bases, self-shadow ray casting with 512 rays per vertex and GPU fragment shader radiance evaluation took 126 seconds and real-time simulation with dynamic light and variable exposure(variable exposure via vertex shader) yield 70 fps

PRT with HDRI Area Lights based on Virtual Light Probes

In order to visually restitute a more convincing virtual illumination of the scene, the use of High Dynamic Range Image Based Lighting has been investigated, to allow the rendering of diffuse lighting and soft shadows, in conjunction with the previously extracted Radiosity irradiance maps, by means of multi-texturing, in order to render at the same time the hard shadows caused by direct lighting (i.e. the virtual sun). In the first tests undertaken, HDR IBL was first used to create the lighting solution used to perform the texture baking of the virtual diffuse lighting, while the extracted lightmaps were used on the self-illumination channel of the corresponding baked materials to render hard shadows.
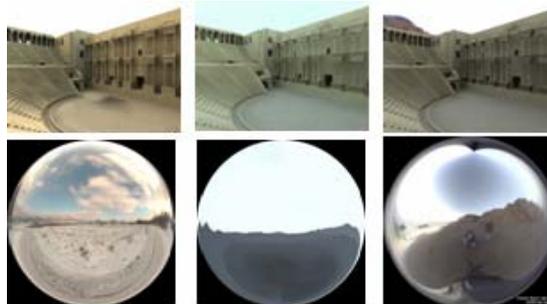

Figure 11, Aspendos Theatre rendered using HDR IBL with different photographic light probes

In an earlier stage of the project the use of photographic light-probes has been attempted (examples depicted in `Figure 11`), but it became soon clear that, due to the fact

that the Aspendos virtual model had to be simulated under specific lighting conditions at different dates and hours of the day, and under different weather conditions, the use of on-site taken photographic light-probes as source for the IBL computation would have been less than practical: therefore the creation of virtual light-probes has been chosen in order to easily allow a total control over the positioning of the sunlight and over the climatic conditions present in the simulation. In order to produce the virtual light probes two approaches were used:

1. the combination of several LDR panoramic images rendered at different exposures,
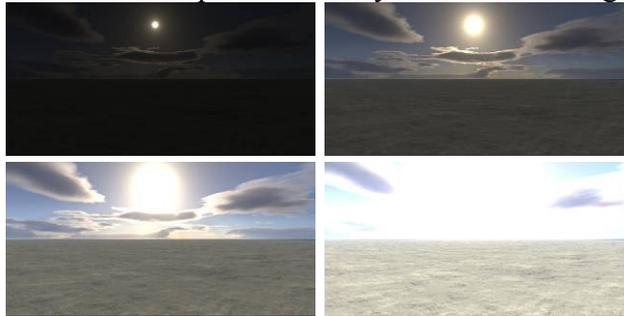2. the direct computation of a synthetic HDR image

Figure 12, Excerpt from the set of panoramic LDR rendered images used to create a virtual light probe.

For the first approach the sunlight system of 3D Studio MAX was used in the modeled scene to determine the sun positioning using temporal and spatial parameters (i.e. geographical position of the model and date and time of the simulation), than the atmospheric simulator of the Dreamscape plug-in was used to produce the volumetric clouds and a correct representation of the sun set to the previously determined position, finally a set of panoramic LDR images (`Figure 12`) at different exposures was rendered and combined with HDR Shop to produce the final virtual HDR image to be used to light the scene.
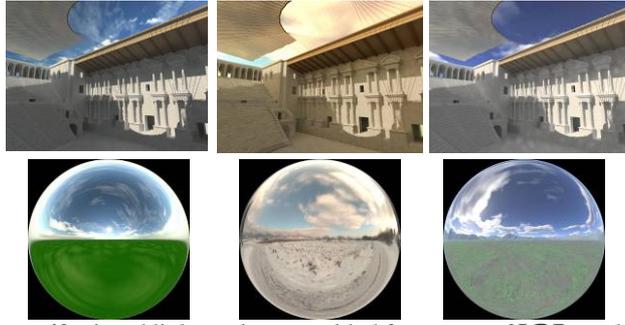
Figure 13, virtual light probe assembled from a set of LDR rendered images (left), photographic light probe (center), computed HDR virtual light probe (right)

For the second approach (`Figure 13`), Terragen environment simulator was used in conjunction with the SOPack Plug-in, in order to directly output rendered HDR cube-maps, and with the Solaris Plug-in, to set the date, hour and location of the computed sunlight.

5. Future Work

The current tome map operator for exposure matching between the real camera response curve and the HDRI light probe exposure is ad hoc experimental and an analytical representation is envisaged. Furthermore, we aim to extend the above approach to deformable characters in MR by parameterising the ambient occlusion of the precomputed diffuse radiance transfer, according to the degrees of freedom and posture dependence of the associated bone segment. Furthermore, we aim to allow for variable multi-material, multi-mesh BRDFs for physically correct materials simulation for virtual humans, such as cloth (Minnaert, Oren-Nayar, Cook-Torrance) and skin (BSSRDF-Jensen).

7. Acknowledgements

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