High Dynamic Range Rendering for Driving Simulations

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***Abstract*— Driving simulators, particularly low-cost ones, suffer from a lack of visual realism in comparison with real roads. In order to improve the immersion of the drivers in these simulators, and also to reproduce the visibility conditions of the road, we propose to improve the visual perception in simulators by integrating High Dynamic Range (HDR) rendering, followed by a tone mapping process. The gain is a better visual fidelity with respect to the simulated environments, especially when there are bright and dark areas at the same time on the screen.**

***Index Terms*— Driving Simulation, High Dynamic Range, Tone Mapping, Pixel shader.**

I. INTRODUCTION

Realistic images can be computed at interactive frame rates for Virtual Reality applications. Meanwhile, High Dynamic Range (HDR) rendering has a growing success in video games and virtual reality, as it improves the image quality and the player's immersion feeling.

We propose a new method, based on a simplified physical model of light propagation, to compute in real time the HDR illumination of a Virtual Environment [Petit and Brémond 2009]. Our method allows us to re-use existing Low Dynamic Range (LDR) virtual databases as input, and computes HDR images. Then, from these HDR images, displayable LDR images are rendered with a Tone Mapping Operator (TMO) and displayed on an 8-bit display device. The HDR scene computation and the operators are implemented in *OpenSceneGraph*, working in real time with pixel shaders.

The method is illustrated with a practical application where the Dynamic Range of the virtual scene is a key rendering issue: driving at night on a Driving Simulator. The Virtual Environment includes light sources such as road lighting and car headlights. The visual impact of these light sources is twofold: first, the light sources themselves may be included in the field of view; second, the objects luminance is due to the physical interaction between the light sources and the photometric properties of the surface (Reflectance and Specular properties).

Our framework is innovative because we propose a physical (photometric) interpretation of the image rendering pipeline. Due to the use of HDR Virtual Environments, the gain is a better visual fidelity, especially when there are bright and dark areas at the same time in the scene. Depending on the TMO, it is also possible to simulate the driver's visual adaptation to light and darkness. Another interesting point of the proposed rendering pipeline is that it allows to adapt existing virtual databases for HDR rendering.

II. PREVIOUS WORK

A. Motivations

The luminance gamut is among the main drawbacks of current display devices, with a luminance ratio between white and black pixels under 500:1 for most display systems, while the actual gamut may be over 1 000 000:1, both in daylight and at night. The recent development of High Dynamic Range (HDR) display device prototypes [Seetzen *et al*. 2004] did not lead, so far, to industrial developments (however see [Ward 2008] and www.dolby.com). Moreover, such display devices will not be available soon for large display surfaces, such as what is needed in most driving simulators.

Thus, building physical images from a simulation of light propagation faces the challenge of displaying the photometric and colorimetric images with a display device which cannot display the computed luminance.

B. Tone Mapping Operators

The increasing interest for HDR capture and imaging began in 1993 with the development of tone mapping operators (see [Reinhard *et al*. 05] for a review). These operators allow to convert HDR images (with a large gamut of luminance) in order to fit LDR display devices (with a very limited gamut of luminance), however keeping the main visual features in the images.

Moreover, some of these operators can process HDR videos, create glare and blooming effects on bright areas, and simulate the visual acuity and adaptation to light and darkness using criteria related to psychophysical data. These techniques are of great interest for the rendering of Virtual Environments because they make possible to use a HDR representation of the Environment far away in the rendering pipeline.

In the past 15 years, a number of tone mapping operators were proposed, with various results, and the focus of attention moved towards assessing the visual quality of the resulting images [Kuang *et al*. 2007]. The key issue is the difference, depending on the TMO, in terms of the resulting visual appearance. Thus, some choices have to be made, depending on the application, in order to choose a relevant TMO.

In the following, we selected an operator based on a psychophysical model of the Human Visual System [Irawan *et al*. 2005], taking advantage of the physical simulation of the light propagation in the Virtual Environment (see section III.B).

C. HDR Rendering

HDR Rendering is becoming a standard feature in many games, such as Half Life [Mitchell *et al*. 2006] and Crysis [Crytek 2009], which use HDR rendering to make participative media and bright light sources more realistic. HDR rendering is used with advanced lighting and post-processing effects, such as glare, which improve the apparent brightness of the light sources [Spencer *et al*. 1995]. However the TMO used in video games are generally very basic, due to the need for a fast rendering (e.g. a power function, a logarithm, or a sigmoid).

The difference between LDR and HDR rendering is the following: if a surface would normally reflect 25 % of the light to the viewer, a LDR light with a "radiance" value of 1.0 would set the surface to 0.25, which would not appear very bright. In contrast, with an HDR light source set to 10.0, the surface would become 2.5 and would appear extremely bright. Thus, HDR Rendering can take advantage of a physical description of the virtual environment (e.g. light intensity in candela, luminance in candela per square meters) to preserve the displayed contrasts and brightness of the simulated environment if we use a perceptually based TMO.

To perform a HDR Rendering, the eight light sources provided by *OpenGL* are not enough for most application, such as driving simulation at night. One popular method in videogames is to pre-compute light-maps with a global illumination algorithm, and to load them in the application, which avoids computing the lighting in real time. For instance, [Durand and Dorsey 2000] proposed an interactive tone mapping, including a street scene example, and [Brémond and Gallée 2002] proposed a pre-computed global illumination for a driving simulator application. The problem with these viewers is that the radiosity stage must be pre-computed (radiosity is far from real time), and thus cannot include moving light sources or moving objects passing under the light sources. Thus, most Virtual Reality applications need alternative rendering strategies.

D. HDR application/software

Recent advances in hardware enables to program *OpenGL* or *DirectX* applications that compute environment mapping (an efficient method to simulate a complex mirroring surface) using HDR Image Based Lighting. These applications simulate reflection, refraction, Fresnel effect, chromatic dispersion, blooming and glare [Debevec 2003, Kawase *et al.* 2003].

Some libraries for HDR rendering have emerged, notably in the open-source rendering engines *Ogre3D* [Luksh 2007] and *OpenSceneGraph* [Tevs 2009]. For instance, the Ogre3D tutorial uses three objects, illuminated by an HDR image with environment mapping. The application includes various tone mapping implementations in real time. The *OpenSceneGraph* library allows to load an object textured with an HDR image, and to tone map it in real time.

III. THE HDR RENDERING PROCESS

A. Framework

In the following, we propose a new pipeline for the computation and rendering of HDR virtual environments. Our framework is split in three steps:

1. The first one is the re-configuration of existing virtual environment databases in order to allow HDR rendering based on a physical model. This implies providing a photometric description of the light sources and of the reflecting surfaces.
2. The second step is the HDR computation in real-time with pixel shaders in *OpenGL* (the HDR Rendering).
3. The third step is the post-processing of the HDR images (tone mapping and glare), in order to compute displayable LDR images.

The following sections propose a practical solution for each of these steps, resulting in a HDR simulated environment rendered in LDR.

B. Physical Virtual Environments for HDR Rendering

The rendering pipeline was designed with two main goals. The first one was to compute HDR images with luminance and colorimetric values related to physical values. The second one was to re-use, when possible, existing LDR Virtual Environments, and to modify these environments only when the LDR description is irrelevant (e.g. for light sources).

To reach the first goal, we propose a physical interpretation of modified LDR databases, including light sources and reflection properties. The light sources intensities are described in photometric units (candela). One may either tune the intensity values, or use available photometric data from lighting designers or from existing databases [SE].

To reach the second goal and re-use existing databases, we were able to modify Virtual Environments with a modeling software in order to take into account the light sources, first for the direct lighting, then for the illumination, using a simplified real-time physical model. Thus, the light sources are described twice in the modified Virtual Environment:

- First, the light source is described for the lighting computation, using a per-pixel lighting in a pixel shader. The photometric intensity I is given in candela for each light source, and a directional lobe may be designed.
- Second, the light sources are described for the direct rendering, when they appear in the field of view (see Fig. 1). Three technical solutions are available:
  - using a HDR texture, created from a set of LDR photographs taken with various exposures (bracketing) [Debevec and Malik 1997];
  - using the `Emissive` coefficient of the OpenGL `Material;`
  - modifying the existing texture from the LDR database, and convert them into HDR textures.

A key idea in our rendering pipeline is to convert the LDR texture images into dimensionless reflectance maps, allowing further illumination computations. Namely, the textures of the LDR surfaces are converted into spatial distributions of light reflection.

Fig. 1 – Left: snapshot of LDR headlights for daylight. Right : HDR headlights at night.

Although the sensor settings of the texture photographs are usually lost, we made an assumption about the visual tuning performed by the computer graphics artist when creating the Virtual Database, assuming that the final tuning in the LDR Database (texture intensity and `Diffuse Material`) are set in order to get the right visual appearance of the surface, lighted with an `Ambient` light. Thus, given that these tuning are performed on a screen with a given γ (we set γ = 2.2 in the following), we converted the texture images into reflectance maps, on the three channels Red, Green and Blue, with:

$$R_{i,j} = T^{\gamma}{}_{i,j} \times D \quad (1)$$

where R is for Reflectance, T for Texture and D is the `Diffuse` component of the surface OpenGL `Material`.

C. HDR Rendering

From this modified Virtual Environment, it is possible to compute a physical luminance and color at each pixel in real time, with a simplified lighting model. We demonstrated this with a daytime virtual database from the LEPSIS Lab., the *Rivoli* database [Giannopulu *et al.* 2008] (see Fig. 2).

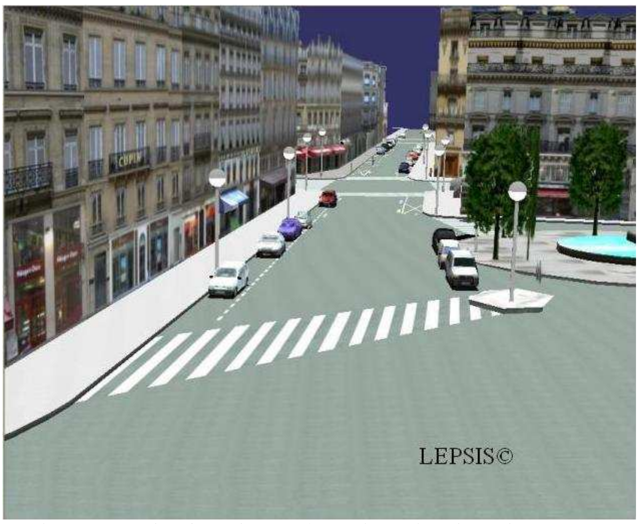

Fig. 2 – Snapshot from the *Rivoli* Daytime Virtual Database

Fig. 3 shows the proposed graphic pipeline. Following the physical laws of illumination, the luminance (the light directed towards the camera) is computed as the product (mode `MODULATE` in *OpenGL*) of illuminance E and reflectance $R_{i;j}$. The illuminance (the light send to the surface), in turn, is computed for each light source k as:

$$E_k = \frac{I_k \cos(\theta)}{d^2} \quad (2)$$

where I_k is the light intensity of source k in the pixel direction, θ is the illumination angle with the lit surface, and d the distance between the light source and the surface.

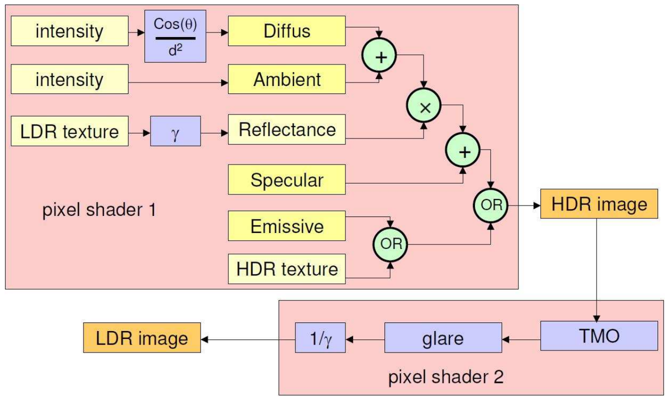

Fig. 3 – HDR Rendering pipeline based on a simplified physical model of illumination (shader 1), and LDR rendering (shaders 2).

In addition to this computation of the diffuse lighting, more terms are computed for the `Ambient`, `Specular` and for a possible HDR texture (e.g. light sources, sky-map). The `Ambient` term stands, for instance, for the sky illumination which cannot be neglected, even at night. Lastly, the `Specular` component is taken from the existing OpenGL `Material`.

Moreover, some textures are modified from LDR images to HDR images: this trick allowed to take into account the direct illumination of the virtual camera by the light sources in the field of view. The texture of a light source is set at a level far above 1.0, that is, to its physical luminance in candela per square meters. When such an emissive surface is found in the rendering process, this HDR texture is taken into account instead of the previous light reflection computation (the `Emissive Material` may be used if available, see the OR boxes in Fig. 3).

D. LDR rendering of HDR Virtual Environments

A number of TMO have been proposed in order to compress the dynamic range of HDR images into the 8 bits of usual digital images [Reinhard *et al.* 2005]. However, depending on the operator, the rendered images may be visually very different. For a virtual environment, only a few operators were proposed.

To choose between these operators, the main image quality criteria deal with immersion (visual appearance, e.g. [McNamara 2006]) and fidelity (visual performance, e.g. [Grave and Brémond 2008]). For our purpose, the more relevant TMO use psychophysical model of the Human Visual System (HVS).

In the following, we used Irawan *et al.*'s algorithm [Irawan *et al.* 2005], which is derived from the Histogram Adjustment method [Ward *et al.* 1997], however taking into account the temporal adaptation of the HVS, with a psychophysical model close to [Pattanaik *et al.* 2000]. We have restricted this TMO to the cone photoreceptor contribution, as even in the mesopic domain, the contribution of the rods has little effects on the luminance down to 0.1 cd/m², which is lower than the dark areas of most display devices.

To show the impact of the TMO on the displayed images, we have also implemented the global version of Reinhard *et al.*'s algorithm [Reinhard *et al.* 2002], derived from photographic art. It is clear from Fig. 4 that this operator is not well suited for outdoor night-time images.

Fig. 4 – Examples of tone mapped images of the same HDR virtual environment at night, however with two different Tone Mapping Operators. Left: [Reinhard *et al.* 2002]. Right: [Irawan *et al.* 2005].

IV. RESULTS

A. *The need for tone mapping in HDR physical rendering*

In order to show the practical advantage of using an HDR rendering approach for night-time road images, we have tested our physical-based rendering approach with a LDR rendering first.

Fig. 5 – Snapshot from the *Rivoli* virtual database, using only LDR rendering.

Fig. 5 show that with LDR light sources (that is, with a "radiance" set to 1.0) and no tone mapping, the images are non-realistic: the image is far too dark, except for the light source where the contrasts appear too sharp. This is due to the low radiance value, given that the light reflection on a given surface is proportional to $1/d^2$, where d is the distance to the light source (see Eq. 2), and then decreases quickly. In the *Rivoli* database, the light sources are 6.50 meters above the ground, and most surface reflection coefficients are below 0.5. Even at a street lamp's foot, only 7% of the light remains.

This first example showed that an HDR description of the light sources is mandatory in a physically-based rendering approach. With this in mind, another solution was tested: computing an HDR pre-rendering image, and threshold it before rendering with a linear tone mapping between the Minimum and Maximum values. Unfortunately, this strategy fails too, as one can understand from Fig. 6.

Fig. 6 – Snapshot from the *Rivoli* virtual database, using HDR parameters for sources and LDR rendering

First, it was not easy to choose a "good" threshold, and one may doubt whether a given threshold value would be optimal all along the navigation in the Virtual Environment. In some way, one may argue that computing the right threshold for every image is some kind of elementary TMO.

Second, whatever the threshold, the resulting image includes strong artefacts (e.g. see the saturated road surface on the bottom right of Fig. 6). The trade-off of this threshold approach is between low threshold values, which avoids saturation at the cost of darkening the image, and high threshold values, with more pleasant images, except for the saturated areas.

Finally, these two preliminary results demonstrate the need for a true HDR computing, followed by a non-trivial tone mapping.

B. *Computing with a HDR rendering pipeline*

In order to demonstrate the proposed rendering pipeline, a video was computed in the *Rivoli* Virtual Environment at night. Fig. 7 shows snapshots of this video. It is clear from the images that our proposal outperforms the LDR techniques of Fig. 5 and 6.

One advantage of the proposed technique is that its design makes it easy to re-use existing LDR databases, where each surface is described using an OpenGL `Material` and/or a texture image. In the example of Fig. 7, a limited list of changes was needed in order to render the daylight scene by night in HDR:

Fig. 7 – Snapshots from the *Rivoli* virtual database, using the HDR rendering pipeline of Fig. 3 under night-time conditions.

- The car light Texture images were replaced by HDR Texture images. These HDR images were the previous LDR Texture, normalized with a maximum value equal to the light source intensity.
- The road lighting light sources were modified, using `Emissive` values above 1.0 in the OpenGL `Material`. These values were set to photometric values.

Only one pixel shader computes the HDR rendering, but a bunch of pixel shaders is needed to compute the LDR rendering. At this stage, two TMO are fully implemented with pixel shaders: the global version of Reinhard *et al*.'s operator [Reinhard *et al.* 2002] (see Fig. 4., left), and Irawan *et al.*'s operator [Irawan *et al.* 2005], which gives better results (Fig. 4, right and Fig. 7).

To reach real-time with Irawan *et al*.'s algorithm, we used mipmapped textures to compute the adaptation luminance, as well as for the histogram adjustment. The scenario runs up to 60 frames per second with 100 bins in the histogram, using the fifth mipmap level, and 1680 ×1050 images.

In order to improve the performance of the pipeline, both in terms of speed and visual appearance, several issues are to be addressed. For instance, an accurate rendering of glare effects may be implemented following [Spencer *et al.* 1995, Rischel *et al*. 2009], however with a computational cost. In the current state of our work, we only used a LDR rendering of the glare effect: the tone mapped images are thresholded, and then convolved by a normalized Gaussian Filter. Then, the result is added to the tone mapped image.

V. Conclusion

We have proposed a real-time HDR rendering framework for interactive Virtual Environments, working in *OpenScenegraph*. Our framework allows to use a slightly modified version of a daytime LDR database in a new rendering pipeline, with pixel shaders in cascade. The HDR images are rendered using a simplified photometric model of light propagation, and then processed by a tone mapping operator, which simulates eye vision. A dynamic TMO was chose for this purpose [Irawan *et al*. 2005], however the temporal adaptation to light and darkness is not implemented in real time at this stage of our work.

The rendering needs HDR light sources such as headlights and street lighting in the HDR virtual database. A photometric description of these light sources is needed for the simulation of light propagation.

The light distribution, in our example, was build from a naive description of the light sources. However the same pipeline may be used with measured photometric data, as was done by Renault for car lights: in [Lecocq *et al.* 1999], a pixel shader computed (in LDR) the displayed luminance with a pixel shader, using intensity maps provided by photometric measurements. The sky-map could also use a HDR texture, as well as a HDR light source for the `Ambient` material.

At this stage, the final rendering is computed in real-time. Future work includes the computation of the glare effect on the HDR images. This should lead to a better visual appearance of the displayed images. As the use of mipmapping for the adaptation luminance and the histogram adjustment in the tone mapping process is a key point for real-time, we next have to study the influence of the mipmap level on tone mapped images.

Another idea, in order to save computing time while keeping the image quality, would be to interpolate luminance values in the tone mapped histogram in Irawan *et al.*'s TMO. We expect that this trick may allow us to lower the number of bins in the histogram (saving computing time), while keeping the output image quality.

The light transport simulation proposed in our model is far from perfect. To our sense, the main improvement which could lead to a better visual realism would be to take into account the BRDF of the surfaces, providing that physical data is available (e.g. see [Dumont 2007] for road surfaces).

Another important issue about HDR rendering is to assess the visual quality of the displayed images. This may be done, either, based on subjective assessments [Winkler 2005], or on objective criteria, such as visible differences [Mantiuk *et al.* 2005] and visual attention [Petit *et al.* 2009].

For a driving simulation application, our understanding is that subjective judgments on the "realism" of the displayed images is the main issue for the immersion assessment in a driving simulator. Meanwhile, visual attention (e.g. using eye tracking techniques) and visual performance (e.g. visibility of other drivers/pedestrians) may be the main issues about the ecological validity of the simulator in terms of visual perception [Hoc 2001].

We hope that our work may contribute to enlarge the validity domain of driving simulators to transportation research studies where visual perception is a key issue. In any case, due to the dominance of the visual channel for information collection while driving [Sivak 1996], providing a driving simulator more realistic in terms of visual input is a true challenge for Computer Graphics.

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