# Computer Aided Color Appearance Design using Environment Map Based Lighting

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**Abstract**

*A BRDF approximation is developed that is suitable for interactive color appearance design in direct lighting provided by environment maps. The BRDFs are approximated as a linear combination of cosine lobes with a fixed set of specular exponents. A nonlinear optimization routine is used to fit the cosine lobes to BRDFs appropriate for a specific color appearance design application: automotive paint. Modification and rendering of the BRDF is made possible by linearly combining prefiltered environment maps for each cosine lobe in real time.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism-Color, shading, shadowing, and texture

## 1. Introduction

The recent development of pixel shading hardware and software has dramatically increased the control that a user has over the color appearance of a computer graphic object. Rather than being limited to a single simple hardwired reflection model, the shading model appropriate for the desired color appearance can be programmed, and it will automatically be evaluated at each pixel on the object's surface. In addition, it is possible to change the parameters of this reflection model in real time. The ability to interactively adjust the simulation of light reflection from a surface makes it possible to design the color appearance of an object. If the reflection model accurately simulates a real paint or surface coating then a new type of CAD, computer aided color appearance design or CACAD, becomes possible [Mey].

The evaluation of an object's color appearance is improved by making the lighting as realistic as possible. Correctly simulating the direct illumination provided by distant area light sources, including the sky, can have a major impact on an object's overall color appearance. This more realistic lighting can be introduced, while still maintaining interactive frame rates, by using pre-filtered environment maps [KM] or spherical harmonics [KSS]. Although it involves a time-consuming offline computation for each set of reflection model parameters, the extra overhead isn't a problem for many computer graphic applications because the reflection model doesn't change during the simulation. How-

ever, it presents a major obstacle for the interactive CACAD program described above.

The goal of the research described in this paper is to develop a CACAD program that combines the interactive control of a reflection model, implemented as a pixel shader, with the complex real-time lighting provided by an environment map. The approach begins with the assumption that the final tool is intended to solve a specific problem: the design of new automotive finishes [SMW03]. This leads to the selection of a reflection model appropriate for automotive paint in which just a few BRDF measurements are taken and a low order polynomial is used to interpolate the data [WM]. Given these important but practical restrictions, it is assumed that the space of bi-directional reflection distribution functions (BRDFs) generated by the automotive paint reflection model can be spanned by a set of basis BRDFs. If a basis BRDF can be rendered with global illumination interactively, then it is possible to render images of the combination of basis BRDFs interactively. If it is possible to rapidly compute how to combine the basis BRDFs to approximate a target BRDF, the target BRDF can be continually changed while generating images of it.

### 1.1. BRDF Design Suite

Automotive styling is an important aesthetic design problem. Because of the sculptural nature of vehicles and the
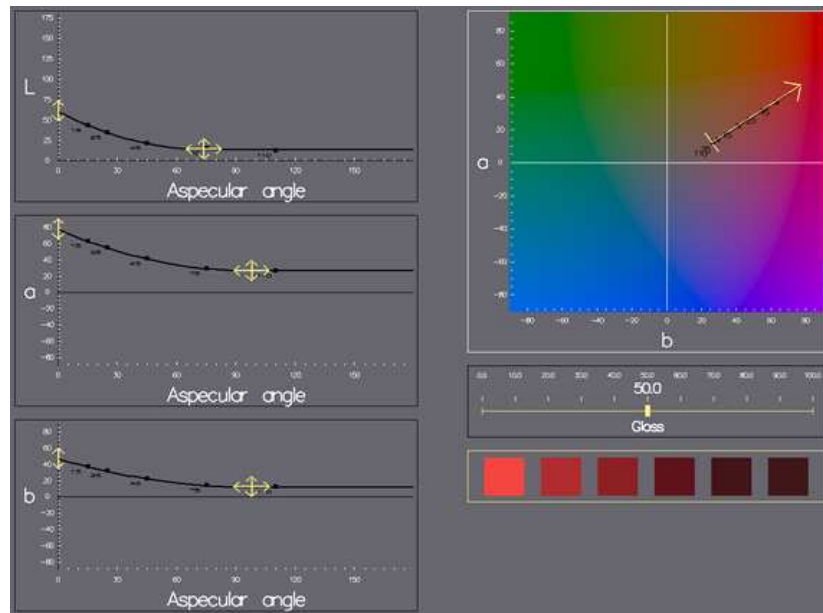
**Figure 1:** *User interface for automotive paint design.*

emotional aspect of styling preference, automobile design has always been at the leading edge of aesthetic design. The form, materials, and color used for the interior and exterior styling is equal to engine performance and handling as a driving force of sales. Automobile designers sculpt character and evoke emotional response by their differentiation of the aesthetic design. Finally, the avant garde designs of concept cars are frequently embraced as the new trend and their influence can eventually trickle down into other consumer product design such as house wears and appliances.

Since its conception, computer graphics and computer aided design has been used by the automobile industry to design the shape of vehicle surfaces and components. However, there were few computer tools for the design of color appearance and surface finish. This was because of two reasons. First, the standard reflection models in computer graphics were too limited to approximate metallic automotive finishes realistically. Second, for reasons discussed in Section 2 any system capable of generating realistic images was unsuitable for use as an interactive design tool.

Traditionally, the design and color forecasting of automotive paint requires mixing physical samples of paint, applying the paint to evaluation surfaces, tweaking the paint formulations, and remixing until the desired appearance are achieved. Advances in computer graphics hardware and software is now making CACAD possible. The opportunity exists for CACAD tools to help the color appearance industry in the same way that CAD tools has helped engineers.

The research presented in this paper is the rendering component of a larger software suite for the interactive design of automotive finishes. The software suite is called the BRDF design suite and it contains the following applications: BRDF designer, BRDF viewer, BRDF lobe visualizer, and BRDF color swatch.

The BRDF designer, shown in Figure 1, is a tool for manipulating a reflection model for car paint that is based on industry standards for measuring the appearance characteristics of the paint. These measurements include gloss for the clearcoat and three aspecular measurements for the metallic basecoat. This program interface provides a means for altering the reflectance properties of the paint. The desired aspecular measurements for the new paint can be input to a paint formulation system so that the paint can be manufactured. A test of the system showed good correspondence between the designed and the fabricated paint [GWM05]. The BRDF Designer is discussed in detail in [SMW03].

The BRDF Viewer uses the computer graphic rendering engine discussed in this paper for interactively rendering images of the designed reflectance on three dimensional surfaces and models of automobiles as the color is being designed. Lighting is important for evaluating aesthetic appearance of gloss, metallic, pearlescent, and color-shifting effects. The BRDF Viewer employs complicated lighting environments for evaluating these paint effects.

The BRDF Lobe Visualizer creates three dimensional graphs of the designed reflectance. Finally, the BRDF Color Swatch application provides a means organizing collections of metallic automotive paints in the form of a color palette.

## 2. Related Work

The appearance of a surface can be thought of as a convolution between the BRDF and the distant lighting environment. This convolution is costly but can be precomputed. The convolution between the lighting environment and the BRDF can be put into a prefiltered environment map [KM]. These maps can be used for fast rendering. However, the prefiltering needs to be done every time the BRDF changes. If brute force is used, the convolution can take minutes to hours or more on high resolution environment maps. However, a costly convolution in the spatial domain becomes a multiply in frequency domain. Spherical harmonics are the frequency space representation of functions on the sphere. By representing the BRDF and lighting environment as spherical harmonics, the convolution can be done in real-time [KSS].

Although the convolution is fast, every time the BRDF is changed it needs to be converted to the frequency domain before it can be used. This becomes one integral for each frequency needed to represent the BRDF. This is especially slow for glossy surfaces because hundreds to thousands of frequencies are required to properly represent these reflectances.

Precomputed radiance transfer is a technique that can render low frequency BRDFs with interreflections and shadows in real-time [SKS]. However, the BRDF must be "baked in" to the preprocessed transfer and can not be changed at runtime.

The Lafortune BRDF model in [LFTG] is used to fit a summation of generalized Phong lobes to BRDF data. The representation ends up being simple, yet very expressive. It can capture off specular, retro reflections, and anisotropic qualities in BRDFs. However, computing the fit uses a nonlinear optimization routine that does not run in real-time.

[MH] briefly mentions creating a prefiltered environment map for each lobe and using these to render images of the BRDF in global lighting environments. However, since the Phong exponent is a free variable in the BRDF fitting routine, the lighting environment must be prefiltered for each Phong lobe found.

Kautz et al. presented a hardware-accelerated prefiltering of environment maps that achieves interactive rates in [KVHS]. This may be the only existing technique that is suitable for interactive BRDF design in global lighting environments. The performance of prefiltering is dependent on environment map resolution and the BRDF being used. For example, a high gloss clear coat on a metallic automotive finish would need a high resolution environment map. This would push the limits of the hardware-accelerated system. Secondly, hardware used in the paper was not compatible with high dynamic range environment maps. It has yet to be shown that real-time rates can be achieved with high dynamic range environment maps.

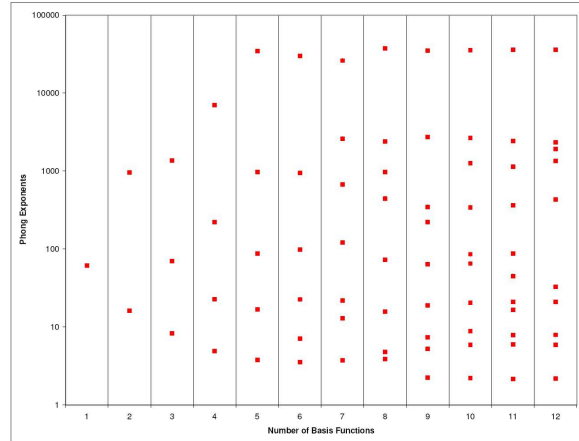Combinations of linear BRDF basis have been used to



**Figure 2:** *The cosine exponents chosen by the nonlinear optimization routine to be the optimal basis functions.*

synthesize new BRDFs. [MPBM03] presented a model for isotropic BRDFs based on densely acquired reflectance measurements from a database of BRDFs. A method for defining intuitive and perceptually meaningful parametrization was demonstrated that can be used to explore BRDFs.

McAllister et al. used a set of cube maps prefiltered with varying specular exponents to approximate the appearance of a spatially varying BRDF using the Lafortune representation [MLH]. By approximating the varying specular exponents as MIP-maps in a MIP-mapped cube map they achieved efficient rendering. However the goal of their approach was not design work and the fitting of the Lafourtune representation was done offline.

## 3. BRDF Representation

Given the objectives of CACAD, the approach taken in this paper is to approximate a designed BRDF as a linear combination of cosine lobes. The cosine lobes can be rendered under global illumination using prefiltered environment maps.

The BRDF is represented as a linear combination of basis BRDFs. The BRDF representation uses a set of cosine lobes [Pho75] with various specular exponents as the basis BRDFs. The cosine lobes are weighted and added together to approximate more complicated BRDFs. The BRDF representation is described in detail in Section 3.1.

The particular values for the cosine lobe specular exponents are chosen so as to best approximate the range of BRDFs that an existing CACAD system [SMW03] can design(see Figure 1). The technique for deciding the optimal basis lobes uses nonlinear optimization and is described in detail in Section 3.2.

### 3.1. Basis BRDFs

This section describes the BRDF representation that is used in this work. The BRDF is represented as three parts: diffuse, directionally diffuse, and gloss. This is sufficient to describe the class of metallic automotive BRDFs explored in this work. These three parts are represented as a linear combination of basis BRDFs. Cosine lobes with various specular exponents are chosen to be the basis BRDFs. The diffuse color of the object is represented by $K_D$. The intensity of the diffuse lobe is dependent simply on the dot product between the light $\vec{L}$ and the surface normal $\vec{N}$ as shown in Equation 1. The clamping of negative values to zero is not shown for simplicity.

$$Diffuse = K_D * \vec{L} \bullet \vec{N} \qquad (1)$$

The directionally diffuse and glossy components are represented as the sum of a set of *m* cosine lobes with various specular exponents. The cosine lobes are defined to be the dot product between the direction $\vec{R}$ of the light reflected off the surface and the view direction $\vec{V}$ taken to a specular exponent $E_i$. The glossy component of the BRDF is due to the light that reflects off the first surface of the object. This is represented by a summation of the cosine lobes, scaled by $K_{G_i}$ as shown in Equation 2.

$$Gloss = \sum_{i=1}^{m} K_{G_i} * (\vec{R} \bullet \vec{V})^{E_i} \qquad (2)$$

The directionally diffuse color is the result of the light that penetrates through the glossy layer of the object. This is represented by a summation of the cosine lobes, scaled by $K_{DD_i}$. Since the directionally diffuse color is a subsurface effect, the sum is scaled by the dot product between the light $\vec{L}$ and the surface normal $\vec{N}$ as shown in Equation 3.

$$Directional = (\vec{L} \bullet \vec{N}) * \sum_{i=1}^{m} K_{DD_i} * (\vec{R} \bullet \vec{V})^{E_i} \qquad (3)$$

The diffuse, directionally diffuse, and glossy components are added together to make the final color.

### 3.2. Optimal Basis Functions

This section describes a technique for choosing the optimal basis BRDFs. The particular values for the cosine lobe specular exponents need to be chosen so as to best approximate the range of BRDFs that are likely to be used in a CACAD application. Although it is possible to hand pick the specular exponents of the basis functions, more accurate results can be obtained by using an optimization routine to automatically pick the optimal basis functions that best approximate a database of example BRDFs.

The specular exponents will be used in Section 4 as the basis functions that are weighted together to approximate a wide variety of designed BRDFs. Thus, it is necessary to
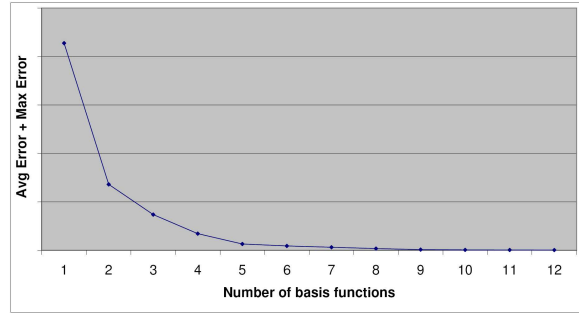


**Figure 3:** *The error the choice of basis functions used to fit the BRDFs in the database.*

have some cosine lobes with high specular exponents to represent glossy surfaces. In addition, some cosine lobes with low specular exponents are needed to represent rough surfaces with directionally diffuse reflectances. There is also the question of how many basis functions to use. There is a tradeoff between too many and not enough. A lot of basis functions can better approximate the range of BRDFs. However, too many will slow down the rendering system.

A database of example BRDFs is used to describe the range of BRDFs that are to be expected. The BRDFs in the database were created with a CACAD program for designing automotive paint. About thirty different paints were chosen to express the range of BRDFs that can be designed.

Principle function analysis can be used to pick the optimal basis functions that best approximate the range of BRDFs likely to be created with the BRDF designer. This is a similar concept to principle component analysis.

To find the best specular exponents, linear optimization routines can not be used. Changing the specular exponent to a cosine lobe is a nonlinear operation, therefore linear optimization and least squares fitting can not be used.

Nonlinear optimization has been used in graphics for finding specular exponents. Eric Lafortune et al. used nonlinear optimization to fit multiple generalized cosine lobes to a measured BRDF in [LFTG]. The technique used in this work is similar to Lensch et al.'s use of nonlinear optimization for finding the optimal basis functions to best represent spatially varying materials in [LKG*].

Nonlinear optimization is used to find the best basis functions to approximate the BRDF database. Instead of fitting a set of cosine lobes to one BRDF, a set of cosine lobes is fit to a set of BRDFs in a BRDF database. A nonlinear optimization routine is employed to find the specular exponents of the cosine lobes in the set of basis BRDFs. Levenburg Marquart nonlinear optimization is used for the search [PTVF92].

One drawback of nonlinear optimization is that it is not guaranteed to find the optimal solution. Nonlinear optimization is very dependent on the initial guess and gets stuck on

locally maximal solutions. Much supervision is required in order to successfully apply nonlinear optimization. By finding one optimal basis function for the BRDF database and adding lobes one at a time, the optimal basis lobes already found can be used as part of the initial guess when adding more lobes.

The function $f(E)$ that is minimized is a function that evaluates the error in the choice of basis functions. The set of $m$ cosine basis lobes $E_1$, $E_2$, …, $E_m$ is represented by $E$. Using the RMS error for the function is not enough. Although it can be used to obtain a low average error, it will leave regions of high error. This is an undesirable situation to have in a CACAD application. A slightly higher average error may be less distracting than the occasional high error. Choosing to minimize the average error plus the maximum error is shown in Equation 4. For each BRDF $B_i$ in the database of $n$ BRDFs, the weights of the cosine lobes are fit to the BRDF using the fast algorithm devoloped in the following section. Next, a function called $Error(E, B_i)$ evaluates the RMS error in using the cosine lobes $E$ to fit $B_i$.

$$f(E) = \max_{i \in \{1,2,...,n\}} (Error(E, B_i)) + \frac{1}{n}\sum_{i=1}^{n} Error(E, B_i) \quad (4)$$

This also gives an idea of how many basis functions are needed. As more basis functions are added, the max error should decrease along with the average error. Once both the average error and maximum error are within an acceptable range, there are enough lobes. Performance limitations of rendering hardware bound the number of basis functions that are useable.

The nonlinear optimization for choosing the optimal basis functions was run for one cosine lobe up to eleven. Figure 2 shows the actual exponents for a given number of basis lobes. Although the results are dependent on the BRDF database used, notice how the actual exponents are distributed somewhat regularly when graphed in log space. Figure 3 shows the error in choosing the optimal basis functions. The actual values are omitted, since the error was measured at only a few angles and thus useable only for self comparison.

## 4. Real-time BRDF Fitting

The set of basis BRDFs are combined to approximate a designed BRDF in real-time. This section describes the techniques used to fit the parameters of the reflectance model described in Section 3 to a BRDF. Because the application is interactive BRDF design, the fitting needs to be done at interactive frame rates using fast techniques.

First, the coefficients to the diffuse lobe are computed by lighting the BRDF at a 45 degree angle and measuring the outgoing light from an off specular angle, for example the surface normal.

Next, the glossy and directionally diffuse lobes are computed as a linear combination of the basis BRDFs found in
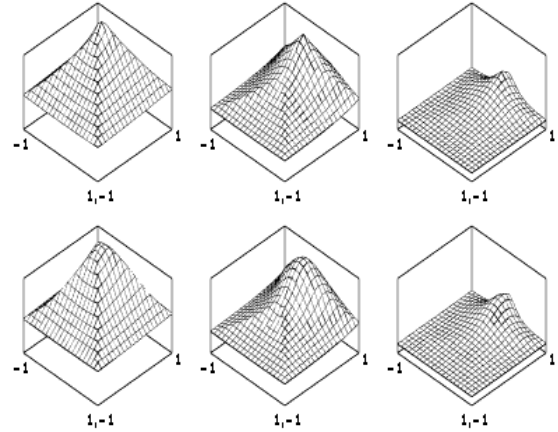


**Figure 4:** *Three slices of the target BRDF (above) are compared to the approximation using seven basis lobes(below) are lit from 10, 40, and 70 degrees(left to right).*

Section 3.2. The basis BRDFs are cosine lobes with fixed specular exponents; therefore only the coefficients $K_{DD_i}$ and $K_{G_i}$ that determine their weights can be changed. $K_{DD_i}$ is the directionally diffuse weight of basis function $i$ and $K_{G_i}$ is the glossy weight of basis function $i$. Equation 5 shows the concept in matrix form.

$$\begin{bmatrix} BRDF \\ Basis \\ Functions \end{bmatrix} \begin{bmatrix} BRDF \\ Basis \\ Weights \end{bmatrix} = \begin{bmatrix} The \\ Target \\ BRDF \end{bmatrix} \quad (5)$$

The basis functions and target BRDF are evaluated to fill in the matrix. The cosine basis lobes are evaluated as Phong lobes. The cosine functions are sampled at angles $\Theta_1$ to $\Theta_n$ and raised to the exponents $E_1, E_2, E_3$, through $E_m$, where $n$ is the number of sample angles and $m$ is the number of basis functions. $BRDF(\Theta)$ is the target BRDF sampled at the same angles. Equation 6 shows the matrix for directionally diffuse. The matrix for glossy component is handled similarly.

$$\begin{bmatrix} cos(\Theta_1)^{E_1} & cos(\Theta_1)^{E_2} & cos(\Theta_1)^{E_3} & \cdots & cos(\Theta_1)^{E_m} \\ cos(\Theta_2)^{E_1} & cos(\Theta_2)^{E_2} & cos(\Theta_2)^{E_3} & \cdots & cos(\Theta_2)^{E_m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ cos(\Theta_n)^{E_1} & cos(\Theta_n)^{E_2} & cos(\Theta_3)^{E_n} & \cdots & cos(\Theta_n)^{E_m} \end{bmatrix}$$

$$* \begin{bmatrix} K_{DD_1} \\ K_{DD_2} \\ \vdots \\ K_{DD_m} \end{bmatrix} = \begin{bmatrix} BRDF(\Theta_1) \\ BRDF(\Theta_2) \\ \vdots \\ BRDF(\Theta_n) \end{bmatrix} \quad (6)$$

This is in the form $Mx = b$, where the basis weights $x$ are the unknown parameters solved for. Matrix M is not necessarily square and invertible. However, $x$ can be simply solved with least squares. The solution produced by least squares may give negative weights for some of the cosine lobes. Nega-
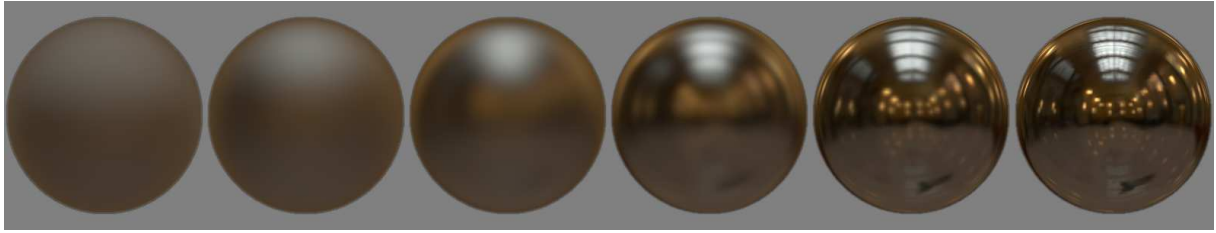
**Figure 5:** *The photographically acquired HDR environment map is prefiltered by the set of cosine lobe basis functions.*

tive weights are physically implausible for a BRDF [Lew] as well as produce distracting artifacts in the rendered images. If negative weights are clamped to zero, as in [KM], error accumulates from every negative lobe and cannot be corrected. Error may increase, rather than decrease, if more lobes are used in the approximation.

To prevent negative weights from occurring, linear programming is used to solve for the basis weights [NBE]. Linear programming has the advantage over least squares in that it allows constraints to be set on each variable as the minimum error is solved for. Each $K_{DD}$ and $K_G$ is constrained to be positive in the solver.

The absolute value of the error in approximating the BRDF is optimized to be minimal. Absolute value is nonlinear around zero and therefore incompatible with linear programming. The techniques that must be employed to convert the absolute value of error, which is nonlinear, to a linear function are beyond the scope of this paper, but are described in [Gas84].

Figure 4 shows the result of fitting seven basis lobes to a target BRDF's diffuse and directionally diffuse components. Gloss was omitted for clarity. Slices of the BRDF are mapped onto the unit square using the hemispherical mapping described in [SC94]. The mapping is responsible for the crease along the diagonal.

Since a linear programming solver computes the solution iteratively, there is no guarantee on the time it takes to find a solution. Occasionally, the solver may take a long time to settle on a solution. A time limit for finding a solution must be set to prevent pauses in interactivity. The only way the linear programming solver can compute the fit in real-time is to keep the matrix as small as possible. This is done by sampling the BRDF with as few measurements as possible.

Only a few BRDF samples are needed to capture most of the interesting aspects of the BRDF. The BRDFs for the metallic automotive finishes used in this research are generally smooth and well behaved. For these BRDFs completely sampling the BRDF from every incoming and exiting light angle is overkill. The color appearance industry uses only three to six tristimulus measurements across aspecular angles plus a single gloss measurement to successfully characterize them [WM]. Therefore, only a few samples are needed

to the approximate the BRDF. One sample is used to capture the diffuse aspect of the color, some are used to capture the directionally diffuse, and other samples in the near mirror direction are used to capture the magnitude and shape of the glossy first surface reflection. Using linear programming and a limited number of BRDF samples, the matrix in Equation 6 can be solved at real-time rates.

## 5. Rendering

To render the designed BRDF in a global lighting environment, all of the basis functions can be rendered with global illumination and weighted together using the coefficients found using the method described in Section 4. The illumination is represented by an environment map. The Uffizi environment map comes from Debevec's light probe gallery [Deb] and the Walter Library environment map pictured in Figure 5 was digitally photographed using a mirror ball. For each specular exponent in the set of basis functions, a prefiltered environment map is used to represent the appearance of the basis function in the lighting environment. The shader calculates the appearance of the surface, by summing the lighting environments, weighted according to their coefficient weights.

Section 5.1 discusses how the prefiltered environment maps representing the appearance of the basis functions in the lighting environment are computed. Section 5.2 describes the shader used for real-time rendering.

### 5.1. Prefiltered Environment Maps

A prefiltered environment map can be used to store the precomputed appearance of a BRDF in a lighting environment [KM]. Normally one would compute a prefiltered environment map for the designed BRDF. However, since the BRDF is represented as a linear combination of basis BRDFs, a prefiltered environment map is computed for each basis BRDF. The prefiltered environment maps represent the appearance of the basis functions in the lighting environment. Figure 5 shows a photographically acquired environment map prefiltered by the set of basis functions found in Section 3.2.

**Figure 6:** *Rendering a measured automotive paint BRDF.*



**Figure 7:** *Rendering a designed BRDF on a car.*

The prefiltering of an environment map can be done off-line. The prefiltering of an environment map is dependent on the specular exponent of the cosine lobe. Since the exponents are not free parameters in the fitting routine, the prefiltered environment map does not need to be computed every time the designed BRDF is changed. Software is freely available for prefiltering the lighting environment [DT].

High dynamic range (HDR) cube maps are used for the lighting environment. HDR images are helpful in capturing appearance phenomena contributed from the diffuse, directionally diffuse, and glossy components of a surface finish's appearance. Although an HDR display may be available for purchase in the not too distant future [SHS*04], traditional display devices will benefit from computing the image in HDR and then tone mapping the output.

### 5.2. Realtime Shader

A shader written in nVidia's CG programming language is used for rendering [MGAK03]. As the three dimensional surface is rendered, a shader computes the surface normal $\vec{N}$, view direction $\vec{V}$, and reflected view direction $\vec{R}$. The diffuse term is computed in the vertex shader. Glossy and directionally diffuse components are computed in the pixel shader. Finally, the color is tone mapped for display on the output device. Color plate Figure 6 shows the results of rendering measured BRDFs. Color plate Figure 7 shows designed BRDFs on cars.

The directionally diffuse and gloss aspects of the BRDF are rendered as a linear combination of prefiltered environment maps. The environment maps representing the appearance of each basis function in the lighting environment are weighted by the coefficients found by the real-time fitter.

For each basis function $i$ in the set of $m$ basis functions the following is done. The prefiltered environment map $CubeMap_i$ representing the appearance of $ith$ basis function is indexed in the direction of the reflected view ray $\vec{R}$. This is weighted by $K_{DD_i}$ and $K_{G_i}$. The directionally diffuse color is a subsurface effect and therefore also weighted by $\vec{R} \bullet \vec{N}$ ($\vec{R}$ in this case is an approximation of the light source direction.) The values are summed up in Equation 7 for directionally diffuse and Equation 8 for glossy.

$$Directional \;=\; (\vec{R} \bullet \vec{N}) * \sum_{i=1}^{m} K_{DD_i} * CubeMap_i(\vec{R}) \qquad (7)$$

$$Gloss \;=\; \sum_{i=1}^{m} K_{G_i} * CubeMap_i(\vec{R}) \qquad (8)$$

One issue is that for the directional diffuse color, the Lambertian scaling factor $\vec{L} \bullet \vec{N}$ is approximated. Normally it is $\vec{R} \bullet \vec{N}$ but since environment maps are used, the light direction is replaced with the central reflected view direction. For high specular exponents, the error is small. But the wider the directionally diffuse lobe, the more this affects the results. However, the error is not visually distracting. See [KM] for a more in-depth discussion of this.

To render the diffuse lobe, a diffuse map is used. This is done using the surface normal to index an environment map prefiltered with a Phong lobe specular exponent of one.

$$Diffuse = K_D * DiffuseMap_i(\vec{N}) \qquad (9)$$

The diffuse, directionally diffuse, and gloss are summed together. Finally, simple characteristic curve tone mapping and gamma correction are necessary to scale the final colors of the pixels to the range of the output device.

Increased specularity at grazing angles, also known as the Fresnel effect, can be simulated in two ways. One method is to increase the relative weights of the environment maps with high specular exponents at grazing angles. A second method is to run the BRDF fitting routine at multiple viewing lighting angles and interpolate between them in the renderer based on $\vec{L} \bullet \vec{N}$.

## 6. Conclusions

This paper has presented a computer graphic system for doing interactive color appearance design using environment map based lighting. The system can render BRDFs as they are being designed.

The system approximates designed BRDFs as a linear combination of a fixed set of cosine lobes in real-time. Non-linear optimization was used to find the optimal basis functions for use with the particular domain of BRDFs being designed. The renderer combines a set of environment maps prefiltered by each of the basis functions to render images of the BRDF in global lighting environments.

By creating a graphics pipeline that maintains interactivity during BRDF changes, this rendering system addresses the unique needs of the appearance industry in doing computer aided color appearance design work.

## Acknowledgments

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