Optimal Sampling for Efficient BRDF Acquisition

Asad Ali[1,a)] Imari Sato[2,b)] Takahiro Okabe[1,c)] Yoichi Sato[1,d)]

Abstract: In this paper we propose a novel method for measuring reflectance of isotropic materials efficiently by carefully choosing a set of sampling directions which yields less modeling error. The analysis is based on the empirical observation that most isotropic BRDFs can be approximated using 2D bivariate representation. Further a compact representation in the form of basis is computed for a large database of densely measured materials. Using these basis and an iterative optimization process, an appropriate set of sampling directions necessary for acquiring reflectance of new materials are selected. Finally, the measured data using selected sampling directions is projected onto the compact basis to obtain weighting factors for linearly representing new material as a combination of basis of several previously measured materials. This compact representation with an appropriate BRDF parameterization allows us to significantly reduce the time and effort required for making new reflectance measurements of any isotropic material. Experimental results obtained using few sampling directions on the MERL dataset show comparative performance to an exhaustively captured set of BRDFs.

1. Introduction

Materials can be classified based on their optical properties as they modulate light differently depending upon the nature of surface. These properties provide us with a variety of clues about how a particular material will appear under different illumination conditions. Physically as well as computationally the optical properties of materials are effectively represented using a Bidirectional Reflectance Distribution Function (BRDF)[1].

Typically BRDF helps us characterize scene radiance, more formally it is a function of four variables $f(\theta_i, \phi_i, \theta_o, \phi_o)$, where θ_i, ϕ_i are polar and azimuthal angles of the incident light direction and θ_o, ϕ_o of the reflected direction respectively. It tells us how bright a surface patch will appear when viewed from one direction while light falls from another. There are several advantages of measuring the optical properties of materials in the form of 4D BRDF as it can be used for photo realistic rendering, preservation of historical heritage, analysis of remote sensing data, movie production and in computer vision it is often used for material and object recognition tasks. Moreover measured BRDF data can be helpful for the development and validation of analytic BRDF models.

This work focuses on an important sub-class of BRDFs called isotropic BRDFs for which rotations about the surface normal does not need to be considered. This generalization reduces the BRDF from a function of four variables to three $f(\theta_i, \theta_o, \phi_i - \phi_o)$. Even with this generalization uniform sampling still requires a huge amount of measurements i.e. suppose with an angular spacing of ψ the number of measurements necessary would be approximately $\pi^3/(4\psi^3)$[2].

Many researchers have attempted to make the traditional measurement process more efficient by proposing solutions which attempt to measure many different samples at once by using mirrors [6][7] or use spherical samples of the materials [10] which requires the material to be homogeneous. However optical elements usually do not allow measuring reflectance at near grazing angles and can be a source of indirect illumination resulting in incorrect measurements [3].

To overcome some of these issues, we propose a reflectance measurement procedure that significantly reduces the number of necessary measurements by carefully selecting an optimized set of few sampling directions using compact basis in this paper. This is achieved by using the observation that most isotropic BRDFs can be approximately represented by 2D bivariate form and further the variations in the data can be minimized by representing it in the form of basis. This appropriate representation significantly reduces the number of unknowns in the linear system which directly influence the reduction in number of necessary measurements for acquiring BRDFs of isotropic materials. Obtained results using the proposed method demonstrate that by using such an approach a new material can be acquired using 100 or fewer measurements with a fair amount of accuracy.

The proposed method explicitly differs from [3] as it uses 2D bivariate approximation [5] for isotropic BRDFs and further compression using compact basis. Also few sampling directions are selected robustly using basis representation by performing iterative optimization in a dimensionally reduced space which is significantly fast compared to an exhaustive search over all samples. We are motivated to use bivariate approximation as it reduces the dimensions of isotropic BRDF from three to two due to general-

1 Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan
2 National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda, Tokyo 101-8430, Japan
a) asad@iis.u-tokyo.ac.jp
b) imarik@nii.ac.jp
c) takahiro@iis.u-tokyo.ac.jp
d) ysato@iis.u-tokyo.ac.jp

ization of bilateral symmetry and the use of basis enables us to compactly capture variations present in broad category of materials which directly contribute towards our goal of reducing sampling directions.

2. Related Work

Ward [6] did the pioneering work by introducing the use of digital cameras as part of measurement setup. The key optical instruments of his device were a half silvered hemisphere and a camera with a fish eye lens. In his arrangement the light source and the sample holder are movable over all the incident angles and allows the measurement of anisotropic reflectance for a material sample.

However the first large collection of sparsely sampled BRDFs of 61 materials originated as part of the CUReT project by the work of Dana et al.[7]. Their system was able to measure spatially varying BRDF's also referred as Bidirectional Texture Functions (BTF). They simultaneously measure the BTF and BRDF of the material at 200 different combinations of viewing and illuminations directions. Later in [8] they introduced a improved version of the BRDF/BTF measurement device allowing simultaneous measurements of multiple viewing directions which used curved mirrors to eliminate the need of hemispherical positioning of camera and illumination device.

Marschner et al.[10] developed an improved BRDF measurement system using two cameras, a light source, test sample of known shape and assume known geometry. Matusik et al.[3] based their BRDF measurement setup on the work of [10] for measuring reflectance of about 100 different materials. Marschner et al.[10] were not able to take into account the local spectral characteristics of BRDFs resulting in dense uniform sampling of the acquisition hemisphere. This was one of the main issue addressed in the work of Matusik [3] to significantly reduce the time and measurements necessary for acquiring BRDFs. They also analyzed the local signal variations in the BRDFs using wavelets and showed that good reconstruction can be performed using 69000 measurements by using wavelet basis. Further they went on to show that it was possible to represent reflectance of an arbitrary material as a linear combination of reflectance of several other material samples using linear representation. They showed that 800 sampling directions are enough to represent new BRDFs using this framework.

Mukaigawa et al.[11][12] developed a high speed method for BRDF measurement using ellipsoidal mirrior and projector arrangement without a mechnical drive for changing incident angles. They can measure reflectance of a material in about 50 minutes. However the accuracy of the measured BRDFs was not evaluated and the use of fixed sampling interval without taking into account characteristics of BRDFs results in increased measurements. Similarly Gosh et al.[13] described a fast method for acquiring the BRDF directly into basis representation which results in capturing reflectance in 1-2 minutes. However obtained results show that there is still significant need for improvement specially in the direction of what kind of illumination basis functions can be ideal for the task.

Other existing methods like Lawrence et al.[14] focus on interactive editing of materials and introduce the use of inverse shade trees for representing arbitrary BRDFs non-parametrically using weighted sum of small number of materials. Similarly, Sato et al.[15] focus on modeling object appearance analytically and show that a set of suitable lighting directions for sampling images can be determined based on objects BRDF.

3. Proposed Technique

We propose the use of 2D bivariate approximation for representing isotropic materials based on the empirical observation that such materials are bilaterally symmetrical and further show little change when the light and view directions are swapped about the half vector thus transforming the dimensions of the isotropic BRDF from three to two. Besides the variations present in a large database of such materials are robustly captured using basis and are used for efficiently selecting an optimized set of few sampling directions in an iterative manner for acquiring new BRDFs of previously unknown materials. Captured materials using these 100 or fewer selected samples are then linearly represented using the compact basis for recovering complete BRDFs robustly.

3.1 Overview

In order to achieve the desired goal of reducing the number of necessary measurements, the BRDF is first transformed into an appropriate representation then all materials are arranged together in a matrix and dimensionality reduction is performed followed by the selection of suitable sampling directions using an iterative procedure. Each of these processes are explained in detail in a stepwise manner in the sections ahead followed by the detailed experimental evaluation of the proposed framework.

3.2 Data Representation

As this work deals with reducing the acquisition time of isotropic BRDFs of new materials so we opted to base our analysis on an already measured BRDF dataset of Mitsubishi Electric Research Lab (MERL)[4]. Acquired by Matusik [3][4] there are 100 materials in this dataset with BRDF measurements made for all three color channels i.e. Red, Green and Blue.

These measurements were made using Rusinkiewicz half vector parameterization [9] of the BRDF instead of the original 3D isotropic parameterization $f(\theta_i, \theta_o, \phi_i - \phi_o)$. They argued that the original representation requires dense angular sampling over the acquisition hemisphere to accurately measure the specular peaks otherwise resulting in poor highlight representation in the form of an ellipse depending upon the orientation of light source.

3.3 Rusinkiewicz BRDF Parameterization

Figure 1 shows the original as well as the half vector Rusinkiewicz parameterization [9] of BRDFs. In this parameterization four angles are used to describe the BRDF namely: theta half (θ_h), theta difference (θ_d), phi difference (ϕ_d) where as phi half (ϕ_h) is not considered for isotropic BRDFs. The advantages gained by re-parameterizing the BRDF in this form are significant as the storage requirements are reduced allowing for fewer basis for robust representation besides important BRDF phenomenon

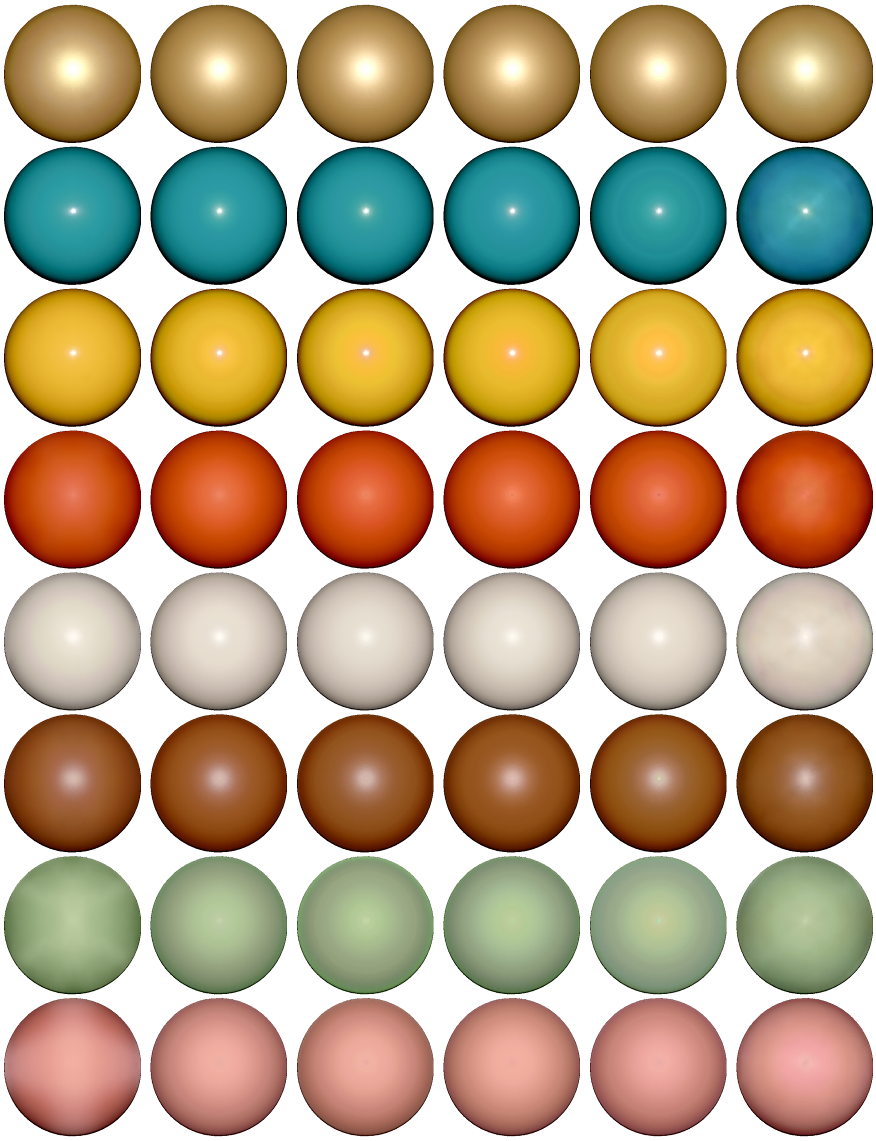

Fig. 6 Visual comparison using several materials between the original renderings and proposed method. (a) Original Measured Data. (b) Reconstruction with 170 Samples 45 Basis. (c) Reconstruction with 120 Samples 40 Basis. (d) Reconstruction with 80 Samples 35 Basis. (e) Reconstruction with Random 80 Samples 35 Basis. (f) Matusik [3] 800 Samples. Materials (along rows from top) are: gold paint, plastic, yellow phenolic, red fabric, rubber, maple, green latex, pink fabric.

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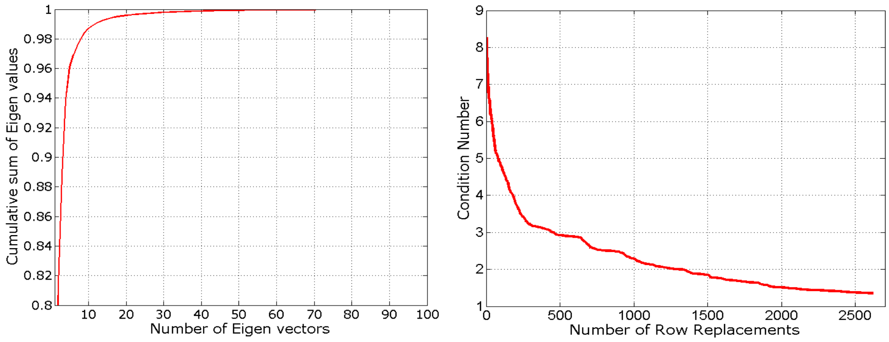


(a) (b)

Fig. 2 (a) Plot of cumulative sum of Eigen values for the 2D Bivariate data of matrix H. (b) Convergence plot demonstrating the decrease in condition number as row replacements are performed using the optimization process of section 3.8.

in fact the coefficients which need to be estimated as part of the projection. But before moving forward let us represent this in a form of linear equation:

$$H\boldsymbol{c} = \boldsymbol{b} \quad (2)$$

where H is the matrix of all BRDFs with dimensions M x N, $\boldsymbol{c}$ represents the coefficients vector which are to be estimated with dimension N and $\boldsymbol{b}$ corresponds to the BRDF of a new material which in this case must equal to M.

There are N material in H so at least N coefficients need to be estimated for each new material $\boldsymbol{b}$ by projecting it on H and then use the calculated coefficient $\boldsymbol{c}$ to reconstruct the new material sample as a linear combination of BRDFs of existing material using the linear generative model of equation (2) .

However, having seen earlier in section 3.6 that fewer basis can capture majority of the variance in BRDFs of matrix H, so instead of using H for computing the linear projection, top K Eigen Basis V_K can be used to represent all the BRDFs. The linear equation with this change can be expressed as:

$$V_K\boldsymbol{c} + \boldsymbol{m} = \boldsymbol{b} \quad (3)$$

$$\boldsymbol{c} = (V_K^T V_K)^{-1} V_K^T(\boldsymbol{b} - \boldsymbol{m}) \quad (4)$$

where matrix V_K represents the top K Eigen basis of matrix H and $\boldsymbol{m}$ represents the mean vector of matrix H which must be subtracted from the new material measurements before computing its projection and then added back after the reconstruction step.

Moreover the above system of equations is highly over constrained. Suppose with $K = 35$, there are 35 unknown coefficients and the number of linear equations equals $M = 24300$ for each newly acquired BRDF of which majority are linearly dependent. This means that the number of necessary BRDF measurements can be significantly reduced for a material by selecting an appropriate sub-set from this large number of equations which can help us efficiently estimate the desired coefficients $\boldsymbol{c}$. If such a small subset of equations can be found which can represent a newly acquired BRDF as a weighted combination of BRDFs of several materials then any new material can be measured by using the combination of only a few light source and view directions corresponding to the selected set of equations (sampling directions / rows) in an efficient manner.

3.8 Selection of Suitable Directions for Acquisition

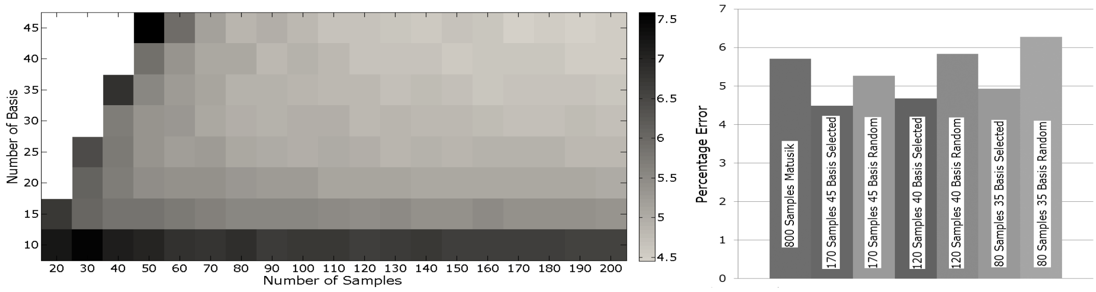
In order to estimate a subset of rows of Eigen Basis V_K, iterative optimization needs to be performed which attempts to reduce the condition number of the linear system of equations described above. The condition number is used here to find out how inaccurate the solution will be after an approximation using selected set of rows is obtained.

Normally for well conditioned matrices all the diagonal terms are of same order and for ordinary matrices the Eigen values will have the same order of magnitude as the diagonal terms of the original matrix. So the Eigen values will be close to diagonal terms for a diagonally dominated matrix. This means that the ratio of the highest to the smallest Eigen value should give a smaller number if the matrix is well-conditioned, since all the diagonal terms are of the same order. However if this ratio is large i.e. the order of difference among the diagonal terms is more, then the matrix is ill-conditioned.

Now let us go into the details of this optimization process in a stepwise manner:

(1) Select a subset of L rows from V_K randomly. Let us represent this row subset with matrix X.
(2) Select one row from subset X and one row from outside of set X and swap them by inserting the row from outside into set X.
(3) Then perform PCA on the covariance matrix $X^T X$ to obtain Eigen values.
(4) Calculate the ratio between the highest and the lowest Eigen value (Max / Min) which approximates the condition number of the system.
(5) If new condition number is less than the previous condition number then keep the newly inserted row in set X otherwise discard the new row and restore set X to its previous state.
(6) This process is repeated iteratively from step 2 to step 5 until no more rows can be swapped for successive tests of all rows.
(7) Repeat procedure from step 1 to step 6 several times and finally select the solution which has the lowest condition number among all obtained solutions.

The iterative procedure described above allows us to obtain an optimal solution over multiple runs and produces a stable set of rows



(a) (b)

Fig. 3 (a) Experimental results obtained using the proposed method with different combinations of basis and sampling directions. Sampling directions vary along the x-axis and basis vary along the y-axis. Gray color indicates average percentage error. (b) Comparison of the proposed method with Matusik et al.[3] and a randomly selected set of sampling directions.

in set X at the end of optimization which guarantees the system to be numerically well conditioned. Figure 2(b) plots the change in condition number with row replacements for a sample case. Sampling directions obtained in set X are based on the statistics of 2D BRDFs of different kinds of materials. These sampling directions are thus general and can be used for modeling various types of materials without the need for calculating them for each material.

The obtained set of equations can also be referred to as the most informative set and are selected irrespective of the red, green and blue channels. However selecting equations equal to the number of unknowns in our system may not generalize well over the set of known BRDFs so while performing row reduction we make sure to select the rows appropriately. Finally having selected a subset of equations the linear system can be updated to represent this fact as:

$$\boldsymbol{c} = (X_K^T X_K)^{-1} X_K^T (\boldsymbol{b}_X - \boldsymbol{m}_X) \tag{5}$$

where X_K represents the Eigen Basis with selected set of rows, $\boldsymbol{b}_X$ is the acquired BRDF of a new material using selected sampling directions and $\boldsymbol{m}_X$ is the mean vector of H corresponding to selected directions.

4. Experimental Results

In order to test the effectiveness of the proposed method with few sampling directions several experiments are conducted using MERL dataset [4] besides the obtained results are compared with that of Matusik et al.[3] and a randomly selected set of samples. We compute the percentage error between the actual measured BRDF of a material and its approximation obtained using very few selected set of sampling directions suggested by our method for evaluation:

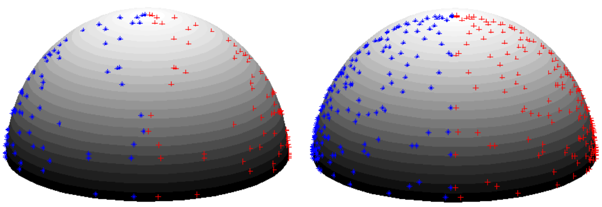


Fig. 4 Plot of selected sampling directions in 4D BRDF form for 80 Samples 35 Basis (left) and 170 Samples 45 Basis (right) visualized as pairs of light source (red+) and view (blue*) positions across the hemisphere.

$$Error = \left(\frac{\sqrt{\frac{1}{N} \sum_{\theta_h, \theta_d, \phi_d} \left(\frac{1}{C} \sum_{R,G,B} (\rho_{org} - \rho_{approx})^2 \right)}}{\sqrt{\frac{1}{N} \sum_{\theta_h, \theta_d, \phi_d} \left(\frac{1}{C} \sum_{R,G,B} (\rho_{org})^2 \right)}} \right) * 100 \tag{6}$$

where ρ_{org} represent the original measured BRDF in logarithm space and ρ_{approx} is its approximation using selected sampling directions, C is the number of color channels, N is the total number of sampling directions in 3D Rusinkiewicz parameterized data, while computing the error using 3D data with 2D bivariate approximation we evaluate approximated data against each ϕ_d value for a given pair of θ_h and θ_d.

First, to find out a suitable combination of basis and samples for representing arbitrary BRDFs, all possible combinations are densely evaluated. To perform such experiments the MERL [4] dataset is divided into two groups, a basis set and a test set of materials. The basis set is used for computing compact basis whereas the test set contains material from which selected set of samples will be taken as a representation of actual BRDF acquisition process using the sampling directions selection process described in section 3.8. Since there are 100 material in the dataset, we divide them into two sets as: 80 materials for calculating basis and 20 materials for testing and 10 such configurations of 80-20 combinations of basis and test set are constructed randomly.

Detailed results obtained using the procedure described above are shown in Figure 3(a). In the figure it can be seen that as we increase the number of basis to 35 and onwards little improvement in reconstruction is observed by increasing the number of samples beyond a certain level. For 35 basis, only a 0.3% improvement occurs when number of samples are increased from 80 to 200. Similarly for 40 basis 0.2% improvement occurs as number of samples are increased from 120 to 200. Specially no improvement occurs at all in reconstruction error by increasing the number after 170 samples for the case of 45 basis. Based on these observation it seems that as few as 35 basis and 80 samples will be sufficient for capturing the variations presents in a large class of isotropic BRDFs quite effectively.

However to generalize well we select three combinations of basis and samples for further analysis and comparisons i.e. 35 basis 80 samples, 40 basis 120 samples, 45 basis 170 samples. Figure 4 visualizes the selected sampling directions for two combinations. A value of $\phi_h = 0$ and $\phi_d = \pi/2$ is used for the mapping from 2D bivariate to 4D BRDF representation which allows us to com-

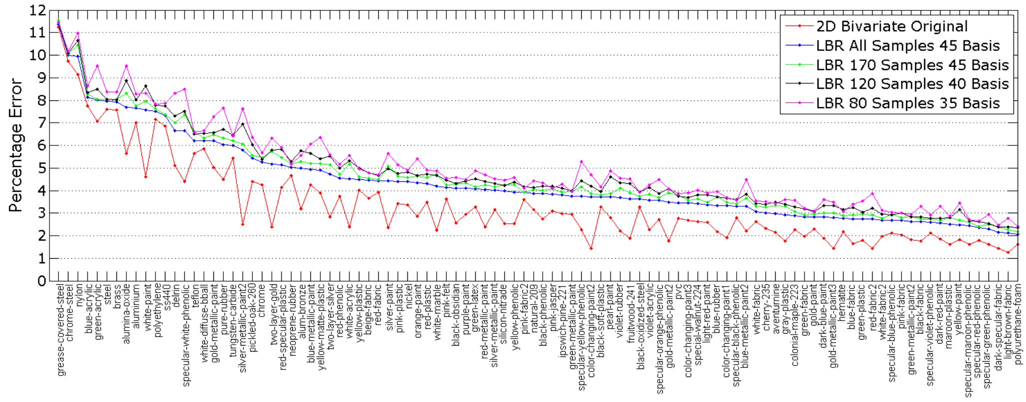


Fig. 5 Detailed Results of 100 materials from the MERL dataset. Comparison of three selected sampling directions (80,120,170) using the Linear Basis Representation (LBR) is shown with all samples and 2D Bivariate BRDF to demonstrate the effectiveness of the proposed method. (Image embedded at high resolution. Please zoom in.)

pactly display the sampling directions in the form of pairs across the hemisphere.

Using these three combinations the proposed method is compared with the work of Matusik et al.[3] using 800 samples and a randomly selected set of samples. We use our own implementation of their work described in [3]. Figure 3(b) shows the comparison using averaged results for all methods. From this comparison it becomes quite evident that by using bivariate representation and basis approximation significant reduction in the number of necessary sampling directions is possible for a large variety of materials which show little change for rotations of the light and view direction about the half vector. Further these results show that the use of sophisticated sampling method described in section 3.8 allows considerable improvement over a randomly selected set with similar basis combination. We also explicitly compare results of four materials with the method of Matusik et al.[3]. It is important to mention here that their method uses 3D Rusinkiewicz parameterization [9] of the BRDFs while our proposed method uses 2D bivariate parameterization and further compression via PCA. Results format is: Material Name(Results of [3], Proposed method with 170 samples and 45 basis): Dark Red Paint(4.5%, 2.6%), Gold Paint (3.2%, 2.9%), Aluminum-Bronze(5.7%, 5.2%), Red Plastic (4.9%, 4.5%).

Detailed results of the proposed method on 100 materials from the MERL BRDF dataset [4] are also shown in Figure 5 using the selected combinations. The reconstruction achieved with fewer samples is also compared with the maximum achievable reconstruction using all samples and 45 basis combination to demonstrate how closely fewer samples compare to an exhaustively selected set of sampling directions. The results have been obtained by projecting a single material on basis computed from 99 materials from the dataset. Besides an explicit comparison of 2D bivariate representation of all materials with original 3D MERL data is also shown in Figure 5, with an average of 3.36% over the MERL database it can adequately capture the variations present in different materials.

In order to further demonstrate the effectiveness of reconstructing with fewer samples a visual comparison of reconstructed BRDFs is shown in Figure 6 for several materials. Renderings using original ground truth, randomly selected set of sampling directions and [3] are also included in comparison. Tone mapping algorithm of [16] is used for these renderings. Besides Figure 7 shows comparison between the original and reconstructed BRDFs of three materials rendered using [17] under different environment maps. This visual comparison highlights the fact that by using very few sampling directions it is possible to recover the original BRDF of an arbitrary material with a fair amount of accuracy.

5. Conclusion

In this paper we proposed a new method for acquiring BRDFs which significantly reduces the number of necessary measurements for isotropic materials. Our method achieves this by exploiting the inherent similarities present in materials using bivariate parameterization alongside a compact basis representation of a large database of materials. The detailed experimental results demonstrate the effectiveness of the proposed method with few measurements against an exhaustively captured set for a large set of materials from the MERL database. In future we plan to extend this framework to anisotropic and spatially varying BRDFs in an appropriate manner which can enable there acquisition efficiently.

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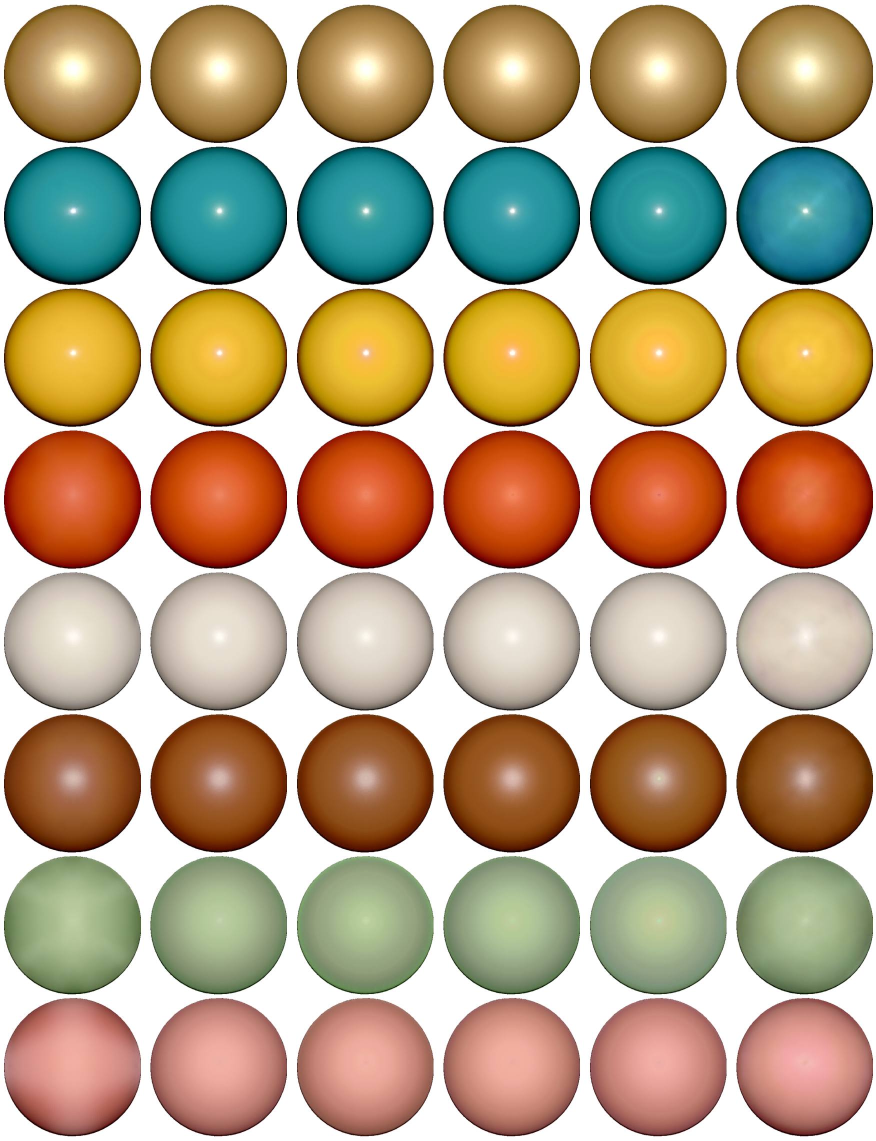

(a) (b) (c) (d) (e) (f)

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(a) Original Measured Red Metallic Paint

(b) Reconstruction with 80 Samples and 35 Basis

(c) Original Measured Green Acrylic

(d) Reconstruction with 80 Samples and 35 Basis

(e) Original Measured Blue Rubber

(f) Reconstruction with 80 Samples and 35 Basis

Fig. 7 Visual comparison between the original measured and reconstructed BRDFs using selected 80 samples and 35 basis for three different materials from the MERL dataset.