Conditioning Anisotropic BSDF Measurements for Lighting and Daylighting Simulation

Gregory J. Ward

Anyhere Software, 950 Creston Rd., Berkeley CA USA

Abstract

This report describes the requirements for utilizing bidirectional scattering distribution function (BSDF) measurements produced by the PAB-Opto goniophotometer and similar devices in simulation tools such as *Radiance*, and describes progress to date in implementing these methods. An interpolation technique has been identified for resampling the measured data, and an initial implementation has been produced. Work continues on improving this technique and software so it may be employed in a streamlined process for reducing BSDF measurements to a usable form and distributed as variable-resolution XML data. This data may then be employed by lighting simulation software to model complex fenestration systems.

Introduction

The challenge is that BSDF measurements are of necessity sparse, irregular, and incomplete, whereas simulation software requires a full description of this 4-dimensional function blanketing every incident and outgoing direction. Simple approaches such as bilinear interpolation fail to capture BSDF behavior from sparse measurements, as they are unable to track specular lobes that rotate in the output with changing incident directions [BvdPPH11]. A more sophisticated data reduction technique is required.

A common approach is to fit the measured data to a mathematical BSDF model [War92], but this works only for "typical" surface materials, failing for exotic or purpose-designed materials such as those employed in complex fenestration systems. Our goal is to model arbitrary BSDFs, without resorting to a model that assumes a particular behavior.

To date, we have only measured *isotropic* materials at relatively low sampling resolution (i.e., 145 Klems directions). Because isotropic BSDFs are invariant to rotation about the surface normal, a single plane of incident directions is sufficient to fully characterize their behavior. However, sharp peaks in the output will not be captured using the "full Klems" basis, which averages angles within 10° (approx.) regions. Moving to a higher-resolution basis is prohibitive, since it requires denser measurements over the entire hemisphere, rather than simply near the specular peaks.

The PAB-Opto goniophotometer is capable of changing its measurement density near specular peaks, which makes it an ideal device for capturing variable-resolution BSDF representations such as the tensor tree described in [Ward et al. 2012]. However, this leaves open the problem of adequately sampling the incident directions. Because outgoing peaks track incident radiation directions, even isotropic materials must have their incident angles sampled at the maximum output resolution to capture the highlight movement. This becomes impractical very quickly, since each incident measurement takes an hour or so to complete. For *anisotropic* materials, covering the entire incident hemisphere at this maximum resolution would require months or years to measure a single surface.

The goal of this work is to identify an interpolation method that takes the sparse, irregular samples produced by the PAB-Opto goniophotometer, and produces a complete, variable-resolution BSDF representation sufficient to simulate the measured material with high fidelity. The method must work for anisotropic as well as isotropic materials, and will be employed as a data reduction step between the raw measurement capture and the sharing of data in a standard XML format. Thus far, we have implemented an experimental version of the interpolation software, and are in the process of tuning a final version for internal use. Upon further testing and validation, the software will be shared with other measurement labs, which should greatly improve the availability of BSDF data for simulation.

Advanced BSDF Interpolation

A survey of reflectance measurement and reduction techniques led us to only one method that addresses our problem of interpolating BSDF data [BvdPPH11]. However, the authors had only considered the case of interpolating between similar BRDFs, which is not the same as interpolating portions of a sparsely sampled BRDF. While it was clear that the method could be extended, it was already fairly complicated and expensive, so we knew such an extension would not be straightforward. Luckily, the principal author of the paper, Nicolas Bonneel, was interested and willing to help us out.

The identified method, *Lagrangian mass transport*, processes a BSDF in the following stages:

1. Divide the incident hemisphere using Delaunay triangulation on measured directions.
2. Interpolate outgoing BSDF at each incidence with a sum of Gaussian radial basis functions, $\sum_j G_j(r(\theta_o, \varphi_o))$.
3. Along each edge of the Delaunay mesh, compute the optimal mass transport matrix that moves one set of radial basis functions to another.
4. For each desired incident direction during interpolation, compute a new set of radial basis functions based on the three surrounding vertices of the corresponding triangle.
5. Use this new RBF sum to compute all desired outgoing directions.

Each of the above steps brings with it challenges, which we discuss in the following subsections.

Delaunay Triangulation on the Sphere

By definition, a Delaunay triangulation ensures that no point is contained within the circumcircle of any triangle. For points on a sphere, the Delaunay triangulation is congruent to the *convex hull*, which is the minimal volume convex polyhedron enclosing all points. Using a Delaunay mesh minimizes errors from interpolating distant incident measurements. We are currently testing a simplified method of Delaunay triangulation on the sphere that does not require iterative edge-swaps. An example result over a quarter sphere is shown in Figure 1.

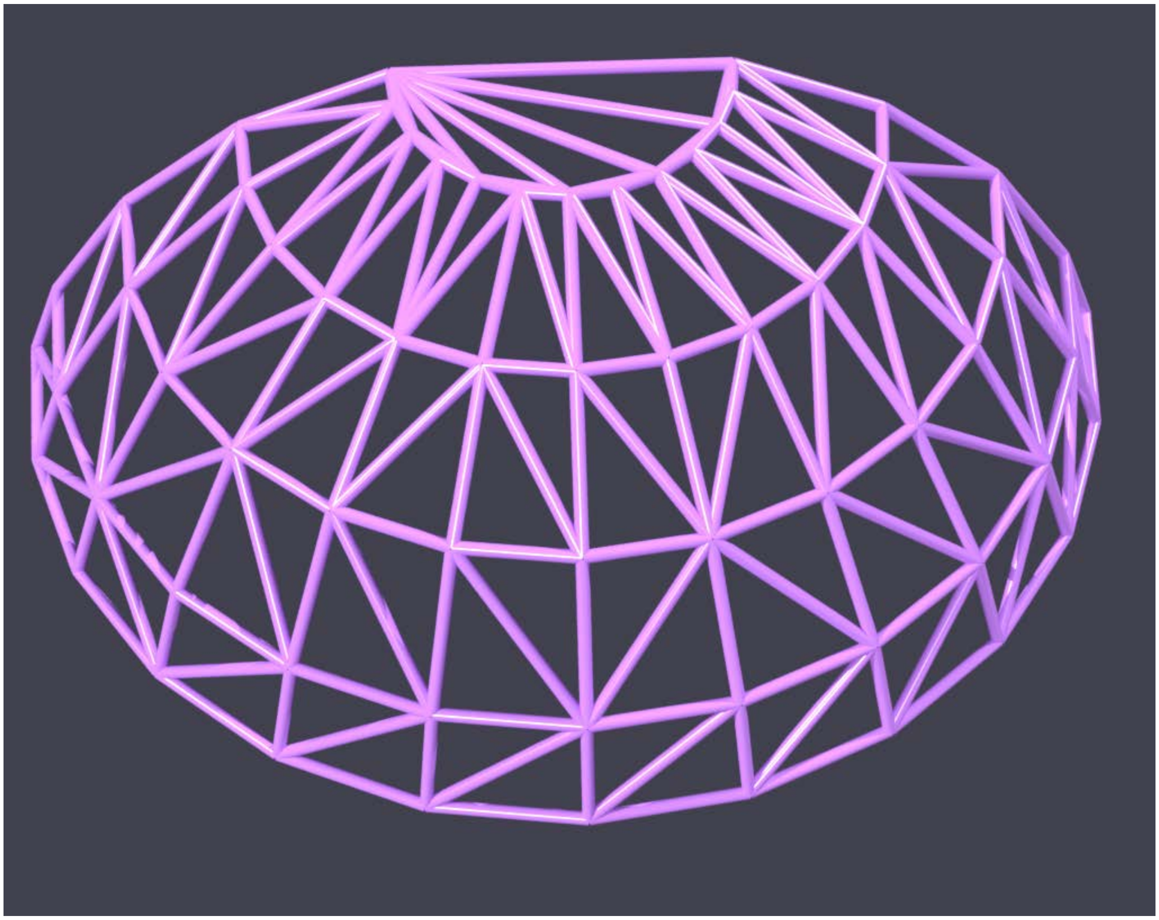

Figure 1. Delaunay mesh from PAB-Opto incident measurements of sawtooth metal profile.

Radial Basis Function Representation

A given set of outgoing measurements on the hemisphere can be interpolated using a sum of Gaussian lobes of differing center, magnitude and spread. These are called Radial Basis Functions (RBFs) because their evaluation reduces the two outgoing directions (θ and ϕ) into a single, radial value, which is the distance from the center of a given lobe, $G_j(r(\theta_o, \varphi_o))$. Computing an optimal set of RBFs is difficult due to the non-uniform sampling of the PAB-Opto device. (See Appendix A.) The first step is therefore to reduce the original samples to a more regularly-spaced sample set, which can serve as the centroids of our Gaussian lobes. The final step is then to optimize the lobe magnitudes and spreads to best fit the original data, as shown in Figure 2.

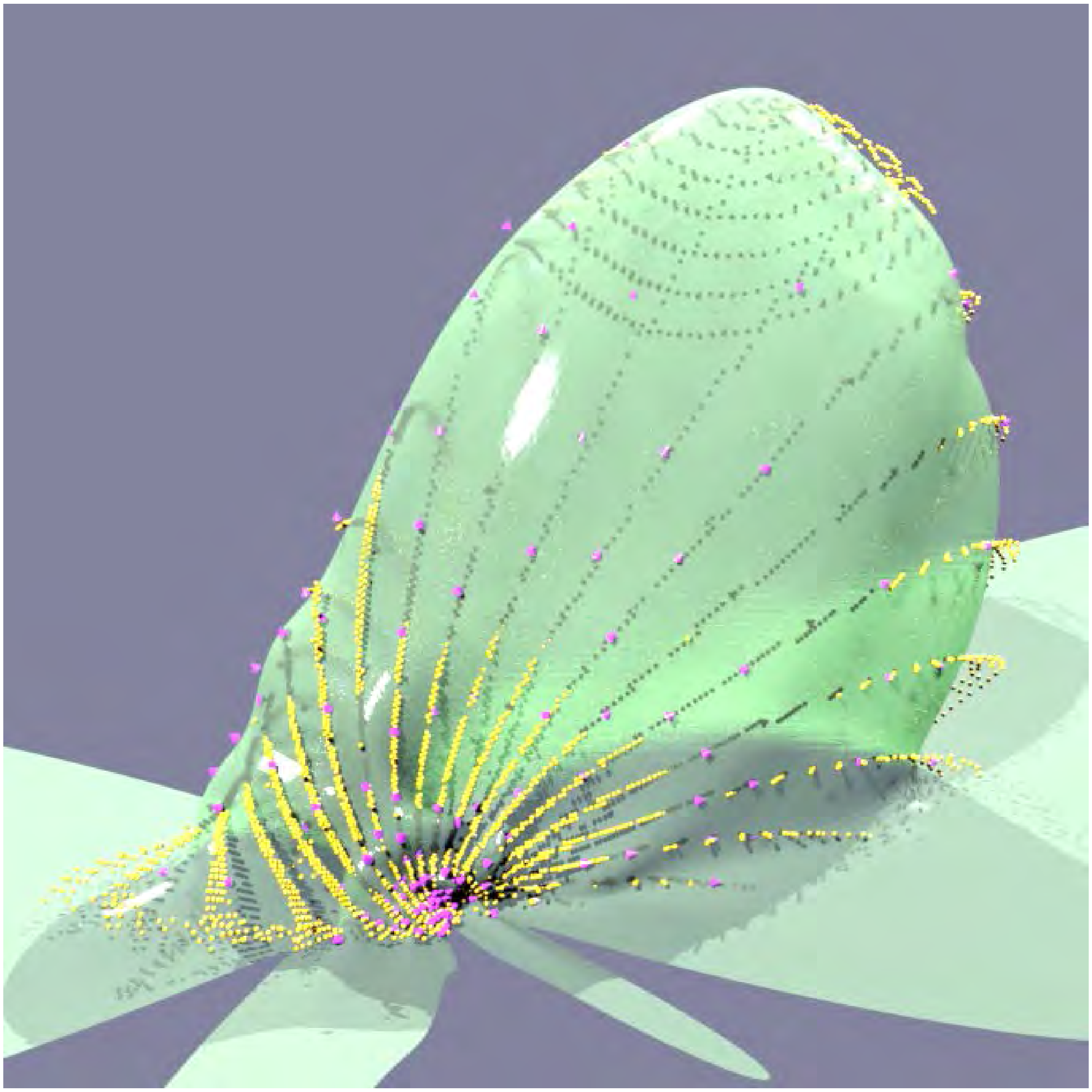

Figure 2. A radial basis function interpolation of outgoing BSDF directions for a single incident direction. Yellow points indicate the original measurements. Pink points are the resampled centroids for the Gaussian lobes. The green surface is the sum of our radial basis functions, approximating the BSDF.

Lagrangian Mass Transport

The most difficult and expensive step in the calculation is minimizing the Earth Mover's Distance (EMD) for the migration of RBF lobes from one incident direction along a Delaunay edge to its neighbor. This is critical to maintaining the character of the BSDF, since it allows the lobes to shift direction rather than to fade in and out as typical of other interpolation schemes.

Given two RBF outgoing distributions (i.e., two sets of Gaussian lobes that sum to the BSDF for those incident angles), we start by computing the "cost matrix," which assigns a price for moving a unit of energy between any two Gaussian lobes. This is simply the distance between the two lobes plus the difference in their spread in our implementation. The migration computation then proceeds in steps, where a bucket of energy is moved along the cheapest route until all the mass is accounted for. Our hope is that this direct calculation will be less expensive than the network optimization problem solved by [BvdPPH11], which proved intractable for typical data set sizes. Testing continues on this module.

Interpolating RBF for New Incident Direction

Since our goal is to evaluate our interpolated function at arbitrary incident and exiting directions, we need a method for arriving at an RBF representation for any angle of incidence. Initially, we believed that the Lagrangian Mass Transport problem would need to be solved again for each interpolated incidence as well as every edge in the mesh (Figure 1), and this proved to be very expensive, indeed. Subsequently, we arrived at a formula for interpolating the RBF at any point within a mesh triangle using the edge migration matrices alone. This makes RBF interpolation fast and efficient, but further testing is required to verify the method.

Evaluating Interpolated RBF

This step is the simplest and the quickest, which is fortunate since the interpolated RBF must be evaluated hundreds of thousands of times in creating the final BSDF representation. In effect, a function similar to the green surface shown in Figure 2 is computed for each interpolated incident angle, and the peaks in this distribution are sent to a separate data reduction program. This separate program (**rttree_reduce**, fully developed and tested), then creates the final variable-resolution BSDF data included in our XML output.

Implementation and Testing

The initial implementation of our interpolation method built and relied heavily on the code developed by Nicolas Bonneel for his 2011 paper. Nicolas did most of this implementation, with some help in testing from Murat Kurt, the other co-author of [Ward et al. 2012]. This code base built upon multiple libraries developed by Nicolas and third parties, and was deemed too unwieldy for a final deliverable. Plus, there were some outstanding bugs that Nicolas did not have time to track down, as his work was taking a new direction as he moved to a different institution. The results presented in our paper present the ideas and the not-quite-working output based on BRDF measurements from [NDM05].

It was therefore decided to start fresh with a new implementation, customized to our particular problem and not reliant on third-party software. This is the code we have briefly described in this report, which is currently undergoing testing. Our plan is to complete this development effort in the next two months and start reducing additional BSDF measurements over the course of this fiscal year.

There is another issue we have yet to fully address, which is incorporating symmetry. As shown in Figure 1, many measurement sets rely on symmetry to complete the data. The sawtooth profile that was measured for this dataset has left-right symmetry that makes half of the incident directions redundant. (See Figure 3.) We can save time and effort by measuring only half of the incident directions, as was done by Peter Apian-Bennewitz when he provided this data. We then need a means to detect or specify this symmetry when performing our interpolation. We have already implemented automatic detection for isotropic (i.e., radially symmetric) data. We plan to add detection of bilateral and quadrilateral symmetry, handling each case appropriately.

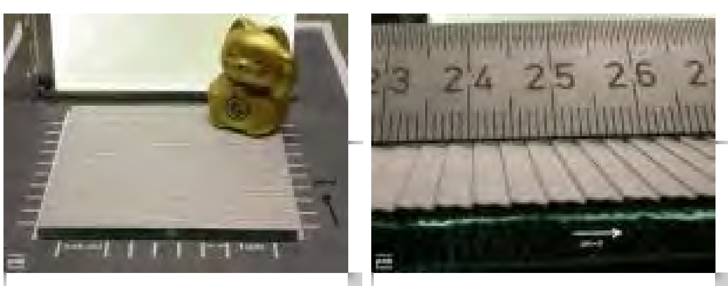

Figure 3. Sawtooth profile material used in our BRDF measurement example.

Summary

We have identified and developed a new method for interpolating measured BSDF data that takes a set of irregular, sparsely sampled points and produces a continuous function. This function may then be resampled as appropriate for the desired, final representation. In the case of a measured material with strong specular peaks, this might be an XML file describing a tensor tree structure that is suitable for ray-traced simulation. This will allow arbitrary, anisotropic materials to be used in the simulation and design of complex fenestration systems.

Next Steps

Work is not completed on this task. Although the code is written, it has not undergone the necessary testing. Also, the cost of computing the migration paths from one incident angle to another is high, and we need to leverage parallel computation to reduce running times to something reasonable. Even with multiprocessing, it may take nearly as long to reduce the data as it does to collect it. A method for recording the interpolating matrix would therefore be of value, and this will be added to the task list for the next fiscal year. By recording the interpolant, we will be able to later resample the data for any desired BSDF representation without compromise. Finally, extensive testing and validation must be performed on the method.

Aknowledgments

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References

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Appendix A

The attached set of measured BRDF data corresponds to the metal profile shown in Figure 3. Measurements were conducted by Peter Apian-Bennewitz on his PAB-Opto device with sample rotator. Higher resolution measurements were taken near the specular peaks, which are subdued in these renderings because the values have been multiplied by the cosine of the exiting polar angle. The magenta dots are the actual points measured, showing the inherent non-uniformity of the data capture.