Light and Materials in Virtual Cities

Julie Dorsey* Holly Rushmeier†

Yale University

ABSTRACT

The level of accuracy required for physical models of materials and their interaction with light in virtual city models is an open question. We consider work that has been done to date on modeling architectural materials, the measurement of such materials in situ, and modeling of natural materials found in urban environments (e.g. snow, ice, and mud). We identify gaps in currently available data, in current technology for specifying materials on large sets of buildings and rendering complex materials on a large scale. We also consider illumination of cities – both day lighting and the natural and manmade illumination at night. We identify issues related to night illumination, where assumptions about adapting to light source spectra and sensitivity to color that are made for daylight may not hold.

Index Terms: I.3.7 [Three-Dimensional Graphics and Realism]: Color, shading, shadowing and texture—;

1 INTRODUCTION

Realistic real time rendering of urban environments has application in architectural design, urban planning, emergency planning, driving simulators, defense, historical reconstruction and entertainment. While some applications depend on visibility "line of sight" calculations that only require geometry, applications that depend on visual detection or aesthetic judgments require accurate simulation of materials and lighting as well. Examples of applications where visual detection is important include simulating how well a driver can see traffic signs or pedestrians, how well an eye witness could have seen an event at night, or how an ancient building may have been configured to facilitate day-to-day activities. Examples where aesthetics are critical include evaluation of new building designs and generation of virtual sets for film. All of these are existing applications that could be enhanced and be more widely accessible by advancing the methods used for simulating light and materials on the scale of cities.

A considerable body of relevant research exists for simulating the illumination [7, 15, 28] and materials [5] used in man-made structures. Gaps exist though in data and models, methods for specifying materials, and techniques for efficiently rendering physically accurate illumination simulations. Currently available models for materials are incomplete, and the capture of existing materials in place is problematic. There is little data available for natural materials commonly found in urban environments. Current methods for specifying and applying materials are inefficient for large scale scenes. The rendering accuracy required for many applications has yet to be established. In particular, many applications require rendering conditions at night, where the characteristics of human vision are much different than in normal daylight.

*e-mail: dorsey@cs.yale.edu

†e-mail: holly@acm.org

Figure 1: An example of the wide variations in color, texture and geometry of brick materials.

2 MATERIALS

A material definition in computer graphics describes how the material redirects light as a function of wavelength, direction and position. Adequate data for describing the varieties of materials appearing in an urban environment is difficult to obtain. How to compactly represent materials and apply them to geometric structures is also an open issue.

2.1 Data from Material Samples

Initially it seems that there are only a few materials required for simulating the buildings and pavement that dominate urban scenes – stone, brick, concrete, wood, glass and metal. It also is often assumed that these are generally matte materials so that they can easily be simulated with texture maps. However, even disregarding the wide variety of complex materials needed to populate a city with people, automobiles and vegetation, just simulating architectural features requires much more than a library of a few hundred texture maps.

Figure 1 shows a small set of examples illustrating the variety of brick materials. Clearly size, layout and color vary. Most graphics systems allow varying these parameters (e.g. LightWorks `www.lightworks-user.com` brick plug-in allows 2100 variations to be specified). However there are also variations in small scale geometry and within-brick color variation. The regularity of the laying of the bricks also varies. These additional variations contribute to the appearance of a real, versus an artificially simulated, structure.

Furthermore, brick is not a simple matte material. Variations in the small scale geometry of bricks and their finish result in directional variations in their appearance. Figure 2 shows a brick wall photographed under two different lighting conditions. The bricks look different in each of the photographs, and in different locations within the photographs. The variations occur both because of the finish on the individual bricks, and because of the degree of indentation of the grout between them.

The variation in bricks is just an example of one small class of material. Figure 3 shows examples of the variations that occur in metals used in architecture. Materials that are often used are brushed metals with anisotropic reflectance, metals that are crimped into shape, treated to have small scale bumps or subtle variations in

Figure 2: An example of how the appearance of individual bricks, as well as a set of bricks changes with view and lighting.

Figure 3: A variety of metals used in architecture.

Figure 5: Examples of packed dirt.

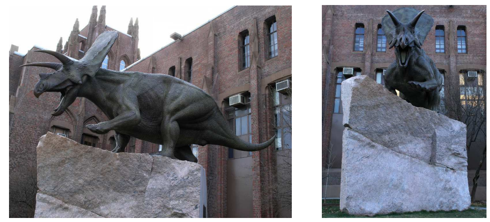

Figure 6: An example of varying incident light color.

color.

In addition to the variation in materials deliberately introduced by builders, natural materials, such as snow, dirt and mud, need to be introduced as well. While there have been models of snow [9, 23] developed, they have focused on snow as it would be seen freshly fallen in a more rural environment (Figure 4(a)), rather than as it appears in urban scenes (Figure 4(b)). Some aspects of mud have been simulated [13], but not a wide variety of packed dirt found in cities (Figure 5).

Many methods exits for measuring the data needed for city modeling either as bidirectional reflectance distribution functions (BRDF's) of spatial uniform materials [19], spatially varying BRDF [18] or bidirectional texture functions [3]. Some collections of definitions provided by vendors are available, such as Tostem roofing and siding materials available in the propriety LWA format for the LightWorks system. Partial data is available for some materials, such as the solar reflectance for various roofing materials at `http://eetd.lbl.gov/coolroof/`.

Collecting the large quantities of material definitions required for even a small city model is generally not feasible for one team to measure for a single project. Existing data is either incomplete or widely scattered at different sites in different forms. Unlike images and geometry, there are no widely used openly documented formats such as TIF and JPG or VRML and OBJ for materials that can be used by web crawlers for searches. Methods for querying for materials have not been developed – such as sets of common text descriptors or visual interfaces. While it is unlikely that the graphics community can agree on a specific format for even a subset of materials, one possibility is develop a file extension for some metadata description of materials that could be retrieved in searches.

Figure 4: Newly fallen snow (a), and snow in an urban setting (b).

2.2 Acquiring Material Data in Situ

Acquiring material data from real buildings is necessary to include particular important buildings in simulations, and to decompose into components that can be used in new building designs. Acquiring material properties for small opaque objects, where lighting can be controlled, is relatively straightforward [18]. However acquiring materials for objects on the scale of buildings remains problematic.

A small number of efforts have attempted to acquire material properties. Yu and Malik proposed a photometric method for buildings [34] that uses estimates of the directional illumination environment. This gives approximate solutions, because of the approximate estimates of variation of the illumination on the structure. In generating a model of the Parthenon [4], Debevec et al. took the approach of first measuring a collection of material samples, and then mapping the BRDF of the large structure by essentially identifying the material at each point as a combination of the samples. The identification proceeds by iteratively updating material definitions used to generating synthetic images of the structure with photographs augmented with light probe data to estimate incident illumination conditions. This method relies on the structure including a small set of materials, and that samples of the materials can be accessed easily for detailed measurement.

Xu et al. [33] used the laser return value to estimate the reflectance in a single channel to correct color images. This approach assumes that the incident light spectrum is spatially uniform. As shown in the figures of an outdoor sculpture in Figure 6, this is a poor assumption out of doors. Areas illuminated by direct sunlight, skylight and reflections from other structures and the ground are reflecting different incident spectra. An extension of the approach attempts to segment the color images into areas illuminated by different sources to appropriately apply different corrections. The disadvantages of this method are that it relies on the laser return, and assumes diffuse reflection only.

The development of efficient methods of estimating materials for existing buildings, in particular methods that don't require expensive laser time-of-flight scanner, remains an open problem.

2.3 Representations

While there are some materials that can be specified as a single BRDF, most of the materials in urban environments shown in Section 2.1 include spatial variations. Repeated use of the same sample of a BRDF/displacement map or BTF is easily spotted as artificial in a city simulation. Popular texture synthesis techniques based on sampling (e.g. methods inspired by Efros and Leung [8]) are far too slow to cover a city. Ideally, procedural textures should be used so that they can be generated rapidly, and with the appropriate variability as observed even in the regular brick patterns in Figure 1. Lefebvre and Poulin [16] proposed techniques for creating procedural models of bricks, tile and wood from sample data. These techniques need to be tested and extended to a wider range of materials.

The level of detail shown in the figures in Section 2.1 are only required for a small (several foot diameter) region around a pedestrian in a city environment. Level of detail management is needed for procedural textures. Becker and Max [1] developed a method for transitioning from displacement maps, to bump maps to BRDF's depending on the level of detail needed for a material in a particular view. Olano et al. [24] built on this idea to generate shaders that automatically adjust level of detail. These concepts need to be applied to the procedural methods generated for architectural materials. Further, they need to be combined with the management of geometric level of detail, exploiting the interaction of material and geometry that has been explored by several groups [2, 26, 31].

2.4 Specification

Assigning materials to individual structures is impractical on the city scale. To some extent this can be simplified by assigning materials to geometries that are assembled into structures by grammar rules [20]. However, to avoid generating masses of similar structures, methods are needed to assign different types of cellular patterns to structures in a plausible way. Initial work to perform this assignment was present by Legakis et al. [17]. This approach needs to be tested on a larger scale.

3 Illumination

Clearly direct illumination is most important in outdoor environments – buildings cast shadows on one another and structures look much different in cloudy conditions than they do in sunshine. In the late eighties and early nineties, researchers began producing methods for efficient daylight simulations for urban modeling [21]. These methods continue to be improved with studies of effects such as polarization [32]. Most rendering packages have the ability to adjust the environment and specify the sun direction based on time and geographic location.

While skylight and direct sun dominate day lighting simulations, the effect of structure-to-structure interreflections can not always be ignored. Figure 7 illustrates the effects of such interreflections. In the feature in the top left of the figure, the left side of the indentation looks redder than the right, despite the fact that there is no change in material. The color difference is caused by illumination from the red brick building shown on the right that faces the left side of the indentation. The dappled effect on the building facade on the lower left is not due to material variations. The irregular illumination of the facade is due to specular reflections from the mirrored building it faces, shown in the lower right.

The length scale of the effect of interreflections is relatively small compared to the scale of a city. Precomputed radiance transfer (PRT) [29] has been used extensively on small objects to encode the effects of interreflections of objects on themselves. Methods to adapt PRT efficiently to structures and to individual building components that can be reused are needed to realistically light large scale scenes in real time.

Simulations of scenes are needed for conditions other than clear daylight. Many years ago, Nishita et al. demonstrated a driving simulator for rainy night scenes [22]. Improved methods for various weather conditions and for night continue to be developed. Researchers at Columbia have recently focused on simulating vision under different weather conditions, such as rain [10, 11]. An accurate model of the night time sky and illumination was presented in [14].

Figure 7: The effect of interreflections between buildings.

Night scenes in urban environments represent problems both in computing illumination and in appropriately displaying the results. Figure 8 illustrates some of the problems. At twilight (upper image) both skylight and artificial light need to be accounted for. Twilight is a particularly critical time for evaluating road safety conditions, such as designing the round blue traffic signs with arrows to "pop out" in the cluttered visual environments. The range of very high to very low illumination levels bring into question either the need for specialized tone mapping algorithms or high dynamic range displays [27].

The lower two images in Figure 8 show the importance of correctly modeling light sources. The lower left image shows how large numbers of light sources dominate the scene. Some can just be treated as isolated emitters, but the effect of others illuminating facades and specularly reflecting off glass and metal need to be taken into account. The lower right image shows that more attention needs to be paid to the spectral properties of light sources. In daylight and indoors we adapt to the color of the dominant light source, and it appears white. At night, when there may be no single dominant source, we become sensitive to the variations in light source colors.

Early work in graphics in adaptation in different light levels is considered in [25]. A post processing algorithm to alter photographs to appear as though they are a night scene is given in [30]. Changes in visual acuity with change in light level is given in [12]. Temporal variations are described in [6]. Work is needed to validate these approaches for simulating vision in a complex night scene in an urban environment.

4 Summary

Existing work in materials and illumination needs to be tested and expanded for the successful simulation of urban scenes for many applications. Specific areas where work is needed include:

- Searchable urban material databases.
- Improved methods for acquiring building material in situ.
- Methods for deriving procedural material models from data.
- Level of detail management for materials with geometry.
- Assigning materials that adapt to building structures.
- Precomputed radiance transfer for large scale structures.

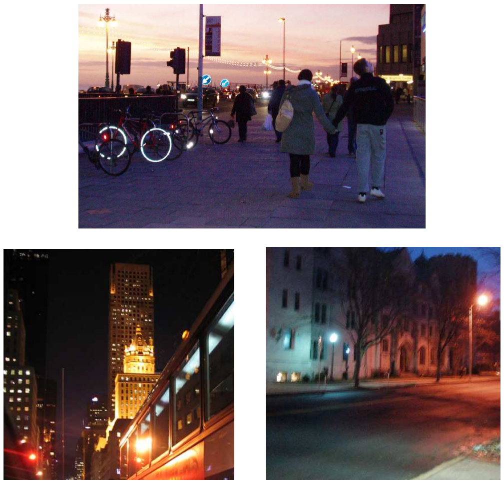

Figure 8: Twilight (top) and night (bottom).

- Improved perceptual models for twilight and night scenes.

References

[1] B. G. Becker and N. L. Max. Smooth transitions between bump rendering algorithms. In *SIGGRAPH '93: Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pages 183–190, New York, NY, USA, 1993. ACM.

[2] I. Cheng and P. Boulanger. Scale-space 3D TexMesh simplification. *Multimedia and Expo, 2004. ICME'04. 2004 IEEE International Conference on*, 1, 2004.

[3] K. J. Dana, B. van Ginneken, S. K. Nayar, and J. J. Koenderinck. Reflectance and texture of real-world surfaces. *ACM Transactions on Graphics*, 18(1):1–34, Jan. 1999.

[4] P. Debevec, C. Tchou, A. Gardner, T. Hawkins, C. Poullis, J. Stumpfel, A. Jones, N. Yun, P. Einarsson, T. Lundgren, M. Fajardo, and P. Martinez. Estimating surface reflectance properties of a complex scene under captured natural illumination. Technical report, USC ICT, December 2004.

[5] J. Dorsey, H. Rushmeier, and F. Sillion. *Digital Modeling of Material Appearance*. Morgan Kaufmann/Elsevier, 2008.

[6] F. Durand and J. Dorsey. Interactive tone mapping. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 219–230, London, UK, 2000. Springer-Verlag.

[7] P. Dutré, P. Bekaert, and K. Bala. *Advanced Global Illumination, Second Edition*. AK Peters Limited, Wellesley, MA, 2006.

[8] A. Efros and T. Leung. Texture synthesis by non-parametric sampling. *International Conference on Computer Vision*, 2(9):1033–1038, 1999.

[9] P. Fearing. Computer modelling of fallen snow. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 37–46, 2000.

[10] K. Garg and S. Nayar. Photorealistic rendering of rain streaks. *International Conference on Computer Graphics and Interactive Techniques*, pages 996–1002, 2006.

[11] K. Garg and S. Nayar. Vision and Rain. *International Journal of Computer Vision*, 75(1):3–27, 2007.

[12] G. Haro, M. Bertalmío, and V. Caselles. Visual acuity in day for night. *Int. J. Comput. Vision*, 69(1):109–117, 2006.

[13] H. Iben and J. O'Brien. Generating surface crack patterns. *Proceedings of the 2006 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pages 177–185, 2006.

[14] H. Jensen, F. Durand, J. Dorsey, M. Stark, P. Shirley, and S. Premože. A physically-based night sky model. *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 399–408, 2001.

[15] G. W. Larson and R. Shakespeare. *Rendering with Radiance: The Art and Science of Lighting Visualization*. Morgan Kaufmann, San Francisco, CA, 1998. ISBN 1-55860-499-5.

[16] L. Lefebvre and P. Poulin. Analysis and synthesis of structural textures. In *Graphics Interface 2000*, pages 77–86, May 2000.

[17] J. Legakis, J. Dorsey, and S. Gortler. Feature-based cellular texturing for architectural models. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 309–316. ACM Press, 2001.

[18] H. P. A. Lensch, J. Kautz, M. Goesele, W. Heidrich, and H.-P. Seidel. Image-based reconstruction of spatial appearance and geometric detail. *ACM Transactions on Graphics*, 22(2):234–257, Apr. 2003.

[19] S. R. Marschner. *Inverse Rendering in Computer Graphics*. PhD thesis, Program of Computer Graphics, Cornell University, Ithaca, NY, 1998.

[20] P. Müller, P. Wonka, S. Haegler, A. Ulmer, and L. Van Gool. Procedural modeling of buildings. *ACM Transactions on Graphics (TOG)*, 25(3):614–623, 2006.

[21] E. Nakamae, K. Kaneda, K. Harada, T. Miwa, T. Nishita, and R. Saiki. Reliability of computer graphic images for visual assessment. *The Visual Computer*, 7(2):138–148, 1991.

[22] E. Nakamae, K. Kaneda, T. Okamoto, and T. Nishita. A lighting model aiming at drive simulators. In *Proceedings of Siggraph 1990*, pages 395–404. ACM SIGGRAPH, 1990.

[23] T. Nishita, H. Iwasaki, Y. Dobashi, and E. Nakamae. A modeling and rendering method for snow by using metaballs. *Computer Graphics Forum*, 16(3):357–364, August 1997. ISSN 1067-7055.

[24] M. Olano, B. Kuehne, and M. Simmons. Automatic shader level of detail. In *HWWS '03: Proceedings of the ACM SIGGRAPH/EUROGRAPHICS conference on Graphics hardware*, pages 7–14, Aire-la-Ville, Switzerland, Switzerland, 2003. Eurographics Association.

[25] S. N. Pattanaik, J. A. Ferwerda, M. D. Fairchild, and D. P. Greenberg. A multiscale model of adaptation and spatial vision for realistic image display. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 287–298, New York, NY, USA, 1998. ACM.

[26] G. Ramanarayanan, J. Ferwerda, B. Walter, and K. Bala. Visual equivalence: towards a new standard for image fidelity. *ACM Trans. Graph.*, 26(3):76:1–76:12, 2007.

[27] E. Reinhard, G. Ward, S. Pattanaik, and P. Debevec. *High Dynamic Range Imaging: Acquisition, Display and Image-Based Lighting*. Morgan Kaufmann, 2005.

[28] F. X. Sillion and C. Puech. *Radiosity and Global Illumination*. Morgan Kaufmann Publishers Inc., San Franciso, CA, 1994.

[29] P. Sloan, J. Kautz, and J. Snyder. Precomputed radiance transfer for real-time rendering in dynamic, low-frequency lighting environments. *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 527–536, 2002.

[30] W. Thompson, P. Shirley, and J. Ferwerda. A Spatial Post-Processing Algorithm for Images of Night Scenes. *Graphics Tools: The JGT Editors' Choice*, 2005.

[31] P. Vangorp, J. Laurijssen, and P. Dutré. The influence of shape on the perception of material reflectance. *ACM Trans. Graph.*, 26(3):77:1–77:10, 2007.

[32] A. Wilkie, R. Tobler, C. Ulbricht, G. Zotti, and W. Purgathofer. An analytical model for skylight polarisation. *Proceedings of the EUROGRAPHICS Symposium on Rendering (EGSR 2004), Norrköping, Sweden*, pages 387–99, 2004.

[33] C. Xu, A. Georghiades, H. Rushmeier, and J. Dorsey. A system for reconstructing integrated texture maps for large structures. In *Third International Symposium on 3D Data Processing, Visualization and Transmission*, pages 822–829, 2006.

[34] Y. Yu and J. Malik. Recovering photometric properties of architectural scenes from photographs. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 207–217. ACM Press, 1998.