Chapter 19

Computer Graphics Techniques for Capturing and Rendering the Appearance of Aging Materials

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Computer graphics photorealistic rendering techniques are capable of rendering images that predict the appearance of yet to be manufactured objects. A challenge in computer graphics realism is creating the digital models of shape, materials, and lighting that are required for such rendering. Models for materials that have been aged by weathering or usage are difficult to produce. A recent trend in computer graphics is to attempt to capture aged materials in a form that allows them to be applied to arbitrary new shapes. We present the techniques used for capture and some sample results. Current techniques can be applied to various types of visual simulation, and we outline some future potential applications of rendering aged materials.

INTRODUCTION

Computer graphics is used in a wide variety of familiar applications, ranging from abstract representations of statistical and scientific data to synthetic characters in feature films and games. One important sub-area of computer graphics is the generation of realistic images. A key component in generating realistic images is creating digital models of the appearance attributes of the materials used in the scene being simulated. A variety of methods for modeling the attributes of pristine homogeneous materials have been developed in computer graphics over the past 30 years. However, many applications require simulating materials that have undergone spectral, spatial, and directional changes due to weathering and usage.

In applications, realistic images may be either required to be *plausible* or *predictive*. To be *plausible*, images must appear to an observer to be indistinguishable from a photograph of a physical scene, although the observer never needs to make a critical decision based on the image. Many applications such as computer games or synthetic props in film require only plausibility. To be *predictive*, images must appear the same to an observer as an image acquired of a physical scene. Unlike plausible images, predictive images are used by observers to make decisions, such as selecting a design or training for a task that requires target visibility. Methods for generating predictive images are based on physical models derived from work in other disciplines, and are subject to validation

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by physical and/or psychophysical experiment. While the requirements for a plausible image are lower, a difficult question to answer is whether a method can be relied upon to always produce a plausible result. Heuristics that produce plausible results in some cases may require a lot of manual tuning to obtain the desired output for a particular application. As a result, computer graphics researchers often focus on predictive techniques that have proven reliability. Generalizing predictive techniques to create reliable plausible results is easier than starting from pure heuristics that are not founded on physical models.

Most existing models for weathered materials in computer graphics are purely heuristic. Over the past 10 years various attempts have been made to generate models from first principles and from measured data. Existing methods are generally too slow or hard to control. Modeling aged materials continues to be a challenge in computer graphics research. Unlike other challenges that can be met with faster processors and increased memory, modeling materials requires new techniques and algorithms built on theory and data from other disciplines including chemistry and materials science.

Computer graphics has a history of borrowing from and contributing to other disciplines. An example of this interchange is radiative heat transfer and computer graphics lighting simulations. In the 1980s, techniques such as radiosity[1-2] from heat transfer were adapted to accurately compute visible light transfer in scenes for predictive rendering.[3] Subsequent work in computer graphics refined and improved the computational techniques and the results have been included in heat transfer texts.[4] Collaboration between chemists and material scientists and researchers in computer graphics clearly has the potential to improve graphics systems, and may also result in new methods for designing and evaluating the appearance of new materials.

We begin with a brief review of the elements of rendering images and capturing input that have become common in computer graphics. Next we give an overview of current methods that attempt to model aging materials. We conclude with an outlook for possible new work in this area, and the potential for new applications that could be enabled by improved material appearance models.

BACKGROUND—RENDERING AND CAPTURE

Material models are required to render realistic images. Specifically, in computer graphics the term rendering refers to the process of using numerical descriptions of three-dimensional scenes and a virtual camera and producing a two-dimensional image. The description of a three-dimensional scene may be produced entirely by a user interacting with a computer using mathematically based modeling software. However, over the past 10 years with the increasing availability of digital cameras, the use of captured data along with completely human specified models has become increasingly common.

Figure 1 illustrates the rendering process. A virtual camera specifies a viewer position and the viewing frustum. The image plane is perpendicular to the view direction, and is discretized into an array of pixel locations. The image is specified by defining an emitted (illuminated display) or reflected (for print images) color at each pixel location. Typically for computer images, values of red, green, and blue are specified, with the specifics of the element spectra taken into account for consistent appearance cross devices.[5] The view point and pixel locations define a set of rays in the three-dimension-

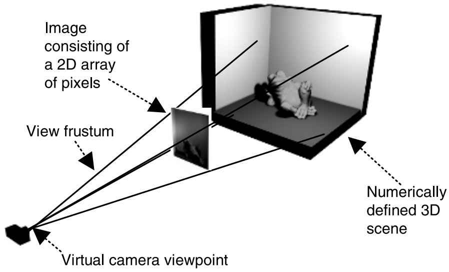

Figure 1—A 2-D image is defined by specifying a virtual camera and the lighting, shape, and materials in a 3-D scene.

al scene. A realistic image is formed by setting the pixel values according to the visible light that would arrive at the view point from the scene. The light arriving from a particular object visible along a ray depends on three things: shape, incident illumination, and properties of the object material.

The shape of an object can be defined in a variety of ways including triangle meshes, tensor splines, and subdivision surfaces. The specification of shape, computer aided geometric design, is a broad area in itself that is described in numerous texts.[6-7]

Computing the incident illumination is also an extended topic. Light may arrive at a point directly from a light source such as a lamp or the sun. Light may also arrive after one or more scattering effects in the environment. Accounting for all scattering events is referred to as "global illumination" in computer graphics. Methods for computing global illumination include the radiosity methods mentioned earlier, as well as many variations of ray tracing. Global illumination methods are described in detail in texts such as those by Larsen and Shakespeare[8] and Dutre[9] et al. Despite being a complex problem, current global illumination methods have been validated relative to ground truth as being reliable for being predictive, given accurate models of shape and materials.[10] Global illumination systems such as the freely available Radiance software[11] or commercial products such as Lightworks[12] are used in design applications requiring predictive results as well as for creating appealing and plausible imagery.

Material models in computer graphics have mainly focused on specifying the materials bidirectional reflectance distribution function (BRDF), or more generally the bidirectional scattering surface reflectance distribution function (BSSRDF).[13] The BRDF gives the reflected radiance as a function of wavelength, incident direction, and exitant direction. Both phenomenological models[14,15] that are constructed to fit measured data and first principles models that use surface roughness models and material index of refraction[16-17] have been developed and validated. For materials that are not spatially homogeneous, many systems depend on procedural methods that vary the BRDF parameters on a surface.[18]

BRDF specifications require some sort of measured data—either reflected radiances or surface roughness and index of refraction. Since microscopic surface roughness is difficult to measure, attention in graphics has focused on measuring reflected radiance. For spatial variations, procedural textures can be difficult to tune to achieve the appearance of specific materials. Interest has grown therefore in using digital cameras to capture spatially varying BRDFs.

A simple digital camera image is not adequate to model a material. As in the synthetic image, an image from a digital camera includes the effect of shape and incident illumination as well as material. The basic strategy for capturing materials with a digital camera is to control the lighting, measure the shape, and then process the image to estimate the mate-

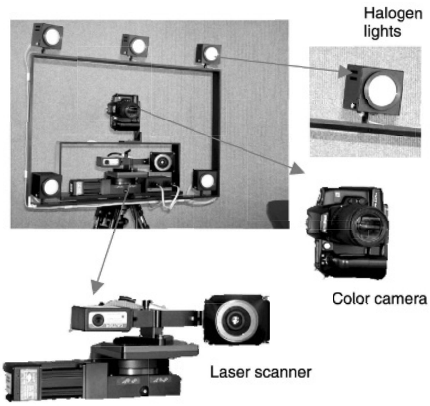

Figure 2—Object shape and appearance are captured by a hardware set-up including computer controlled range scanner, color camera, and lights.

rial appearance attributes. Since most methods for this processing in computer graphics do not include error estimates in this processing, we refer to this as "capture," rather than as "measurement." Several techniques have been developed with digital camera and controlled lighting for computer graphics to capture reflected radiance from simple known convex shapes.[14,19] These methods account for factors such as camera response nonlinearities and the spectrum of the illuminating source used, as well as novel geometric arrangements of objects and mirrors to reduce the number of images required.

For materials of interest on existing objects, more complex techniques are needed. *Figure* 2 shows one set-up for capturing the appearance of existing objects. The apparatus consists of a laser triangulation scanner (ShapeGrabber SG1002),[20] digital camera (Olympus C8080WZ),[21] and small computer controlled light sources (in this case, halogen bulbs in custom housings with custom control). The laser triangulation scanner is one of many optical devices developed over the past 20 years for measuring shape.[22] An emitter and sensor are mounted a known distance apart. Knowing the angle of the emitted laser spot and the angle from the sensor at which the reflection of the laser from the object is observed allows calculation of the distance from the object to the scanner. Scanning the object from a series of views produces a series of range images (images in which a depth, rather than a color, is recorded at each pixel) which can subsequently be geometrically registered and merged to form a three-dimensional model of the object shape.[23]

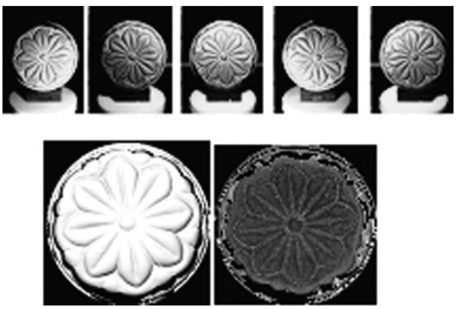

Figure 3—Hardware set-up captures images under five different lighting conditions (top row), which are processed with captured geometry (lower row left) and color corrected for the light source color to produce a map of the diffuse reflectance of the object surface.

The parameters of the color digital camera (position, orientation, focal length, and distortion correction) and position of the light sources can be calibrated in terms of the three-dimensional scanning system.[24-25] With these calibrations the projection of the captured image on the shape and the direction of the incident light are known. The image can be processed with this information to estimate either just the diffuse albedo[26] or, with assumptions about the similarity of the material viewed through different pixels, the BRDF at each surface point.[27] *Figure* 3 shows five images and geometry captured by the system in *Figure* 2, and the texture map of diffuse reflectance obtained after processing for directional lighting and accounting for the non-white spectrum of the incident light.

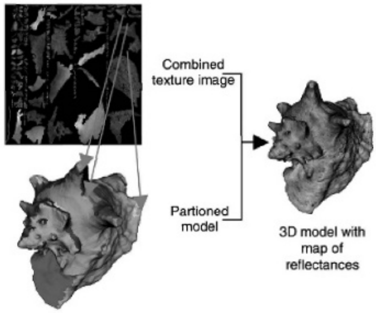

Figure 4—A 3-D object is partitioned into nearly flat regions to map texture images to the surface.

Analogous to the problem of aligning and merging all of the geometric range images, the individual processed textures need to be registered and combined.[23] The processed texture values are stored in images that are associated with the 3-D geometry via texture mapping. That is, each 3-D vertex on the object is mapped to a 2-D location in the texture image. To facilitate this mapping, the 3-D object is partitioned into approximately flat regions, and the textures for each region are stored in one combined large image. The result of this partitioning is illustrated for a captured complex natural object, a seashell, as shown in *Figure* 4.

CURRENT CAPTURE TECHNIQUES FOR AGING MATERIALS

Various methods have been developed for limited simulation of material aging. A complete summary is given by Lu et al.[28] Methods include modeling the mechanics of adhesion and cohesion of paint and substrates to simulate cracking and peeling,[29] and flow over objects resulting in the deposition of dirt and corrosive agents.[30] Most simulations methods are computationally slow, and can result in noticeable visual artifacts. Simulations have only been validated by general comparisons of synthetic results with photographs of the same phenomena that show similarities such as crack density. Because simulation has not proved efficient, most weathering effects in applications such as film and games are currently produced by hand painting of textures, or by artistically altering and manually applying photographs as texture maps. To reduce the labor involved in these applications and to enable predictive applications, researchers have turned to capturing physical aging effects.

The problem of capturing aging effects differs from the capture of full objects. Rather than capturing an image of reflectances that maps to a particular object, such as the mapping in *Figure* 4, a set of spatially varying reflectances is sought that can be mapped to a new object that is significantly different in shape from the original capture object.

Capturing the appearance of aging materials requires accounting for spectral, directional, and positional changes over time. Obtaining data for such a high dimensional problem in a transferable form is difficult. Four recent methods for capturing the effects each work by simplifying one or more dimensions. All of the methods can be applied to produce plausible results in some cases, but all are restricted to the extent they can produce predictive images.

Assumptions or restrictions in the different methods include:

(1) The effect of object shape on temporal appearance variations can be ignored.

(2) The end effect only, rather than temporal evolution of appearance, is of interest.

(3) Processes that can be reproduced in a reasonable length of time (weeks or less) are considered.

(4) Directional variations can be inferred from spectral variations on the material surface.

(5) The sequence of temporal effects acting on a sample can be inferred.

Assumptions (1) and (3) apply to the results by Gu et al.[31] who performed a series of laboratory experiments to capture the temporal variation of appearance on flat 1” x 1” samples of materials. Appearance was captured using an array of cameras and lights supported by a dome structure to capture the full BRDF across the sample. A library of data for 26 materials was captured, and has been made available online.[32] To apply the results, assumptions need to be made such as the effect of the object geometry and edge effects around the area where the object was exposed to the agent producing the weathering. An advantage of the data collected is that subtle variations such as changes in glossiness are captured using the full dome system. The output of this method is a temporal texture. That is, for each pixel in the texture rather than just having a BRDF, there is a time series of BRDF values. Gu et al.[31] also introduced effective mechanisms for storing this data in compact form.

Assumptions (1), (4), and (5) apply to the technique introduced by Wang et al.[33] Wang et al. begin with the assumption that a sample of material is found which has different areas that have been exposed to weathering effects for different periods of time. An example is a rusted plate with some original metal finish still exposed, some areas with flecks of rust, and some thoroughly rusted areas. The sample is scanned to determine the BRDF at equally spaced spatial positions (in general, pixel locations on an image of the sample). The BRDF samples are characterized by a seven parameter model. Three parameters each give the diffuse and specular reflectance in the red, green, and blue channels, and the seventh parameter gives the width of the specular lobe. A high dimensional manifold is formed by connecting each of the samples to each of its nearest eight neighbors. A human observer is asked to identify the most and least weathered areas of the sample. The samples identified are labeled as the end points of the weathering process on the manifold. All other points are assigned a degree of weathering based on their distance along the manifold between the greatest and least weathered samples. On the original spatial sample then, each sample can be assigned a degree of weathering. To capture the effect of spatial texture, the degree of weathering associated with each position is equal to the average degree of weathering of samples in a small surrounding region. Degree of weathering is roughly interpreted as the length of time an area has been exposed to a weathering process. The output is a space in which a texture can be extracted for any time in the assumed time history of the aging of a particular material.

Assumptions (2) and (4) apply to the approach by Mertens.[34] In this work, only the end appearance, or the “look and feel,” of an aged object is of interest. This has the advantage that the effect of the object shape at all length scales is accounted for, but the specifics of what caused the weathering and over what time period are not known. Mertens et al.[34] start with an object that has been captured with texture. Machine learning techniques (specifically canonical correlation analysis) are used to correlate texture variations with geometric measures such as curvature, surface orientation, and relative height of the position on the object. The result is a texture correlated with geometric quantities.

Finally, assumptions (3) and (4) apply to the method and data developed by Lu et al.[28] This work is similar to Gu et al.,[31] in that aging effects are produced in the laboratory. Unlike Gu et al.,[31] though, the effects of shape on the effects are captured, and directional effects are not. Lu et al. produced accelerated effects such as rusting of an ironing surfacing compound with exposure to vinegar fumes, molding of cheese, and cracking of a thick paste coating of plaster and paint. The shape of the objects with related texture was captured using the set-up shown in *Figure* 2. By being able to geometrically register the shapes captured at different times, it was possible to move the objects during the experiment, rather than keeping them still relative to the capture device. This extended the range of effects that were practical to capture to phenomena that required weeks to develop. Experiments were repeated on objects to study the reproducibility of the effects. Similar to Mertens et al.,[34] the texture variations were correlated to geometric parameters, although in Lu et al. geometric harmonic analysis was used to organize the data, and temporal texture series (similar to the series captured by Gu et al.[31] for flat objects) rather than static textures were used in the correlations. The same aging process was physically applied to different shapes, so that the predictive capabilities of the model derived from an experiment could be assessed by comparison of synthesized and physical results. The output of this work is temporal textures for particular aging effects, correlated with object geometry.

For all of these methods, the models are used on new synthetic objects by texture transfer methods inspired by the Markov random field methods introduced by Efros and Leung.[35] These transfer methods were extended to texture synthesis on non-flat surfaces in work such as Wei and Levoy.[36] In these methods a texture is transferred from an original sample while enforcing consistency and constraints. The process begins by selecting a location on the source object. For textures such as those modeled by Mertens et al.[34] or Lu et al.[28] a location in the original texture with the same value of the relevant geometric parameter (or parameters) is found, respecting the constraint on the texture. Either a pixel, or small patch of pixels, is copied from the source texture to the new target. The method proceeds to a new untextured location on the target. Once again, a location on the source is found with the same relevant geometric parameter value. However, on this and all subsequent

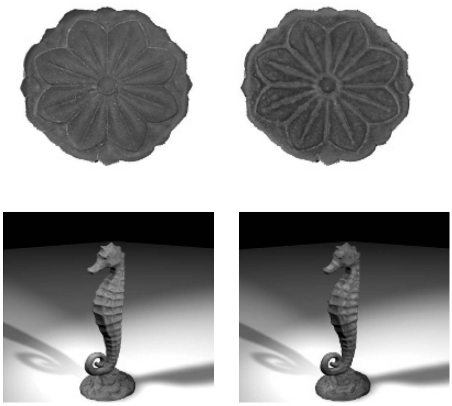

Figure 5—An example using data from Lu et al. of using a captured map of aging material to render a synthetic object.

transfers, consistency is enforced. That is, not only must the pixel or patch copied come from an area with the same geometric parameter, it must also be bounded by pixels with similar values to the pixels already transferred to the target object bounding the target location. An example of data captured by Lu et al.[28] applied to a synthetic object via texture transfer is shown in *Figure* 5.

FUTURE OUTLOOK

Captured textures of aging materials have been shown to be capable of producing rich visual effects on synthetic objects that add to the realism of synthetic images. Current methods are clearly very limited in the types of effects they can produce. Only very preliminary validation experiments have been conducted for assessing how reliable the methods are in predicting visual impression. More data sets, and suitable models for extending the application of the data, are needed for captured effects to be used in mainstream graphics applications.

In the literature from different fields there are many reports of long-term aging effects on materials. Examples include a two-year field test of painted frames,[37] and the 50-year stone wall test at NIST.[38] Since these tests, however, were not conducted for the sort of detailed simulation now possible, data reported for such work includes graphs of summary parameters rather than detailed colored imagery and/or geometric measurements. As future accelerated aging techniques are developed, it may require only simple modifications to acquire image data under documented conditions that could subsequently be used in visual simulations. Image data is required to track the spatial variations such as cracking that occur during aging. Shape and illumination data are needed to disambiguate changes in images resulting from shading, and changes resulting from changes in the material. A shape description may simply be that the sample is flat or spherical. For other shapes a CAD file for manufactured samples could be provided, or the sample could be scanned with a device such as the ShapeGrabber. Illumination data can be provided by including a standard object, such as a white diffuse sphere, into the image captured of the sample.

Any release of data or modification of procedures involves costs. Why should data be released to benefit another industry such as training, film, or computer gaming? One possibility is that such data could be packaged as a product for sale. Examples of such data are stock photographs sold as texture libraries for graphics applications, or product-specific content provided (for paints or furniture) through software rendering systems.

A more speculative benefit of capturing and releasing data is that the availability of synthetic material aging models could in the long term be used as a tool by material designers and manufacturers. One scenario would be the availability of differing products or procedures for preventing or retarding weathering effects. Realistic imaging could be applied to demonstrate the effect of choosing a set of products in a particular geographic and architectural setting. Results for several different treatments could be compared. The uncertainty in results could be illustrated by rendering results for several different cases of anticipated weathering conditions.

Another scenario is the design of materials that are meant to change in appearance to uniquely adapt to an environment. Faux finishes and rapid forming patinas are popular for applying to small decorative objects to give them a unique look. Materials to produce similar effects could be designed for larger structures. While the local effects of age and geometry could be predicted by experiment and modeling, computer graphics image generation could be used to predict the large scale visual effect on different geometries in different environments.

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