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Observing and Transferring Material Histories

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Figure 1: A synthetic object with a material history captured from a physical object.

Abstract

We consider the problem of modeling objects composed of materials that change over the course of time. First principles simulation of the processes that cause material change are either extraordinarily time consuming or impossible because the processes are not thoroughly understood. We take the approach of capturing the time variation of materials undergoing particular changes in appearance. We control and/or measure the relevant parameters that produce the changes. Some parameters may be independent of the object shape, such as thickness of a coating applied, while others depend on the shape. We use the data collected to generate synthetic objects composed of the same materials. The objects can be rendered at different steps in their history, with the material changes being unique to the shape and conditions of that object.

1 Introduction

Real materials are rarely spatially uniform. Natural appearance is characterized by spatial variations in reflectance and in small-scale surface structures. Real materials also frequently change with time as a result of various external effects such as wetting or drying, deposition of corrosive materials, or gravity. For a particular object composed of a particular material, the extent of these effects is determined either directly, or indirectly, by the shape of the object and the properties of the material. In this paper, we seek an efficient method to compute unique spatially and temporally varying material textures on synthetic shapes. We introduce a new approach to this problem that combines using knowledge from existing literature, and observations and physical capture of appearance under controlled conditions.

One approach to produce the appearance of weathering or aging that adapts to a particular object is to numerically simulate the effects on the object from first principles of materials science. Such first principles simulations are computationally demanding to produce the variations observed on real objects that occur at both small and large spatial scales. The variety of mathematical models for such simulation is also limited by what has been developed in materials science for engineering applications. In engineering applications, the interest in phenomena, such as corrosion or cracking, is to determine the strength of a material, or the conditions of a material failure. The modeling of detailed processes that produce variations in appearance for many phenomena generally has not been addressed.

An alternative to first principles simulation is to physically capture appearance data. In the general area of reflectance and texture modeling, much recent research has focused on the capture of databases of bidirectional reflectance distribution functions (BRDFs) or bidirectional texture functions (BTFs), in place of first principles modeling of reflectance from surface microstructure and optical properties. Simply capturing the BRDF or BTF of a single weathered flat plate or sphere, however, is not adequate to provide the data to generate material textures that vary spatially and temporally based on a particular object's shape, history and environment.

In this paper, we introduce a new approach to appropriately capture material variations due to weathering and aging effects, so that they can be applied to new synthetic shapes. Rather than using the existing materials science literature to find detailed models for running simulations, we use this literature to isolate important parameters that control effects. With the knowledge of the key parameters, we conduct controlled experiments to capture the change in material appearance as a function of time. In our approach, we only need to understand what are the major parameters involved, leading to a significant reduction in the number of parameters and hence in complexity. We do not need to understand the detailed mechanisms that make these parameters important, and we do not need to model their detailed interactions that cause small-scale variations. Instead, we capture such variations by example.

Using the gathered data, we demonstrate that new objects can be synthesized with realistic material histories. A new object can be rendered at different steps in its history and, although composed of the same captured materials, the synthesized material changes are unique to the shape and conditions of that object, i.e., the rendering is not just a simple transfer of the texture from a planar sample.

Current texture synthesis techniques largely ignore the relationship of texture to shape and other underlying physical parameters, hindering their broad application in current production systems. Unlike previous methods, our approach demonstrates texture synthesis that adapts to the shape and conditions of the object (e.g. exposure to chemicals, or paint thickness), and also exhibits consistent evolution of a texture in time. Figure 1 shows an example of a synthetic object with a material history captured from a physical object. It demonstrates synthesized patination that is unique to the shape of the new object and is consistent in time.

2 Background

The work presented in this paper draws on many different efforts to model complex material appearance in computer graphics.

Simulation of Aging/Weathering Effects: A variety of different weathering simulation techniques have been developed for computer graphics applications [3, 6, 7, 5, 11, 12, 17, 24, 27]. These have been highly successful and have increased interest in methods to produce aged, imperfect objects. However, these methods can be computationally expensive. Further, they are either restricted to those factors that have been well understood in materials science, or are only loosely physically-based and not necessarily robust for all applications. We build on this previous work however by using existing models in the selection of key parameters that control weathering/aging effects.

Replication of Aged Appearance: Another class of approaches does not attempt to simulate the processes that result in complex appearance, but rather to replicate their effects. As an example, Miller introduced a set of algorithms for accessibility shading; this type of shading yields visual effects that resemble tarnish on surfaces [25]. Wong et al. described a framework for applying imperfections to surfaces by first computing a geometry-dependent tendency distribution and then applying patterns generated from abstract sources [32]. While this approach yields a range of interesting effects, it cannot handle changes due to complex environment-surface interactions. We build on these geometric approaches by extracting the relationship between geometry and appearance and thereby facilitating the transfer to arbitrary shapes.

Manual Specification: The most commonly used technique for applying aging effects to models is to paint patterns onto surfaces [14]. While this approach avoids a costly simulation, it is ad hoc and time-consuming, as it relies on an artist to specify the complex relationship between appearance and geometry. This can be challenging, even for a single instance in time, and is exacerbated when considering time-varying effects. However, a designer wants to have control over appearance, just not at the detailed level. In the approach we present, a user can specify shape, conditions and parameters that control appearance, and then the details can be generated on the object coherently in both time and space.

Texture Synthesis: To generate synthetic objects with realistic spatial variations in surface color and finish, the area of texture synthesis has been extensively explored, with much recent work inspired by [10, 9]. The work in [1, 21, 20, 22, 26, 33] describes recent representative techniques. Most of the previous work in this area has focused on homogeneous textures. As most textures vary continuously over the geometry, these approaches have found limited applicability. A notable exception is the work on progressively-variant textures by Zhang et al., which supports local variations in texture elements [34].

Gorla et al. [13] developed a method for generating textures that are adjusted according to the curvature of the object. In general, their method produces a texture that is oriented with any vector field mapped on the surface. Our approach to mapping materials has in common with their approach taking into account the properties of the underlying geometry and of parameters mapped to the geometry. However, in our approach, the texture is not just resized or reoriented based on geometry, but actually different textures may evolve over different parts of the object based on its shape and environment.

Capture: Recently the capture of accurate appearance models from existing objects has received a great deal of attention [4, 19, 23, 28]. The work has focused, though, on either materials with variations captured from entire objects to be used only on those objects, or materials captured from small examples to be reused uniformly over new objects. In our approach, we capture appearance from full objects that can be applied to new, different full objects.

Non-photorealistic Rendering (NPR): Sloan et al. used the shading from an image of an object and transfer it to a new shape, using a sphere as an intermediate representation [30]. Here, the transfer is based on a correspondence between light source and surface normals. In other work on NPR, Hertzmann et al. [15, 16] use analogies either between images or between curves to transfer learned filters or styles to new images or curves. In this case, the transfer is based on a correspondence that is implicitly learned from the input data. In our work, we build on this basic idea by capturing material histories directly from real objects and then using the explicit correspondence between the material variations and other properties, such as accessibility and the spatial distribution of material thickness.

3 Experimental Framework and Procedure

The relationship between weathered appearance and shape cannot be determined by capturing an object at a single point in its history, as it is not clear what features of the texture have been applied by external, possibly deliberate means, and what are the effects of the interaction of specific atmospheric conditions with the material and the object geometry. We therefore introduce the approach of controlled observation of the spatiotemporal variation of texture with shape and conditions of the object. Only through controlled experiments can we identify and isolate important parameters that affect appearance.

In this paper, we present a general framework for capturing material histories, and give two detailed, representative examples, demonstrating our approach. The basic framework is as follows:

- Isolate a basic phenomenon that results in material appearance changes over time. The two example phenomena we will present in this paper are paint crackling and copper patination. Other possible phenomena that could be handled by the proposed approach include wetting/drying, accumulation of dirt, dust, or ice on a surface, fading due to UV radiation, and bacteria propagation.

- Identify potential controlling parameters for the phenomenon. This is selected by casual observation, followed by a survey of the relevant literature. We then conduct a series of preliminary experiments on a particular phenomenon.
- Select a small set of key parameters to control and measure. This is critical, as nearly all phenomena that impact appearance are potentially affected by many parameters, e.g. air temperature, object temperature, humidity, atmospheric composition, fluid flow, solar radiation, etc. It is impractical to attempt to develop a model from observation to reproduce the effects of all factors in all combinations. After identifying important parameters, the method for dealing with more than one variable is to conduct experiments where only one parameter is allowed to vary. For example, in subsequent experiments on drying we have started with flat surfaces with no geometric effects in order to isolate other, non-geometric effects.
- Perform a set of preliminary tests on a variety of objects. This is required because there are no automatic ways for creating the test samples. Preliminary studies on everyday objects inform the design of the more formal, controlled experiments, which are tailored to a particular phenomenon.
- Perform final tests, measuring control parameters and capturing a series of images recording the material history.

Within the context of our approach, we do not suggest that the chosen control parameters can each one by itself explain all possible effects, including visual ones. The parameters used are indicative of a proof of concept and should not be considered as the only way to vary the appearance. As mentioned above, we only choose the major parameters involved, and do not require an understanding of the detailed mechanisms that make these parameters important. It should also be noted that currently many of these physical variations have not been fully characterized in materials science, because the number of actual parameters is very large and their interactions are too complex.

3.1 Experimental Procedure: Crackling

An example with an interesting spatial and time variation in appearance is crackling paint. It has been reported in the literature, e.g. [29], that an important parameter governing the evolution of appearance of crackling paint is the thickness of the paint layer. (There are, of course, other parameters that matter, such as adhesion to the substrate, temperature, as well as the homogeneity of the paint.) In the pilot tests, we also noted with some surprise that geometry did not have a direct effect on the crackling pattern. Instead, paint thickness was the main controlling parameter. If, as it is usually done, geometry were directly correlated with texture appearance, we would not have observed the effects of paint thickness.

The paint thickness is measured along with the captured appearance history and is then used as a control parameter to guide the synthesis of appearance. In this section, we describe the preparation of the sample, the acquisition of its appearance history, and the measurement of its spatial variation with respect to paint thickness.

Sample Preparation: We used an off-the-shelf kit, by Crackle Creations, to create artificial crackle patterns. This is a two-step process: first, a yellow base layer is applied on the surface; its purpose is to reduce the adhesion, or friction, of the top layer. Next, a white layer of paint is applied with varying thickness over the first. In order to facilitate the measurement of the paint thickness after the formation of the crackle patterns, the sample was prepared on a letter-size transparency. This allowed us to use a back-light projector (like the one used to view x-rays) to measure the amount of light transmitted through the paint. The amount of light transmitted was assumed to be inversely proportional to the thickness of the paint.

Acquisition of Appearance History: The appearance of the evolving crackle pattern was captured with an Olympus C8080WZ digital camera set at its highest resolution and at the lowest compression rate for the JPEG format. (We chose to capture JPEG images because of a faster acquisition cycle for each image compared to TIFF images.) A total of 92 images were captured with approximately 7-8 seconds of delay between each image. The lighting, which was close to diffuse, was kept constant throughout the whole acquisition. The rightmost three images in the top row of Figure 3 show samples from the acquired sequence. As evident during the acquisition, the crack formation and growth were fast at the beginning, but then slowed significantly as time progressed. Note that small cracks generally form first and are located in the regions where the paint was fairly thin. See the leftmost image in the top row in Figure 3 for relative paint thickness. The large cracks required more time to develop and were generally located in regions where the paint was relatively thick.

More importantly, the appearance of the crackle pattern between regions of thin and thick paint is qualitatively different. The small cracks seem more irregular (wavy) and appear to meet at 120° angles. The large cracks (e.g. see the bottom left region of the rightmost image in the top row of Figure 3) tend to be more regular (straighter) and to meet at 90° angles. This was also observed in [29].

The above demonstrates that paint thickness does not just control the speed of crack formation or the relative scale of the pattern. This implies that one cannot simulate the effects on appearance due to paint thickness by simply rescaling image patches, or by increasing or decreasing the speed of crack formation and growth. Paint thickness affects the whole image appearance function $f(x, y; t)$ in a much more complicated way, which necessitates either the development of complex and generally inaccurate and ad hoc models, or the use of appearance transfer techniques, such as ours, that utilize meaningful control parameters that can be measured along with the appearance history.

Measuring Paint Thickness: As the crackle pattern was painted on a transparency, we were able to use a back-light projector to measure the amount of light transmitted through the paint. The yellow base layer appeared almost translucent before the application of the top layer, hence we assumed that it absorbed almost no light. This can be verified by looking at the prefiltered raw image of light transmission, where the interior of the cracks was almost translucent compared to the other parts of the pattern. Although visually one can discern which parts of the pattern correspond to thick or thin initial paint application, the problem we faced during the measurement of the paint thickness map was the presence of the gaps of the cracks themselves, which could potentially pose problems for our algorithm. To avoid this problem, we applied bilateral filtering [31, 8], with the special requirement that it find the mode in the neighborhood of a pixel position (as opposed to finding the nearest mode, or the bilaterally weighted average). The inverted result of this filtering operation is shown in the leftmost image in the top row of Figure 3, which shows the relative thickness estimate of the *original* paint application, even where cracks eventually formed. (As mentioned above, we assumed that the amount of light transmitted is inversely proportional to the thickness of the paint.) Note the spatial correspondence of the paint thickness to the differences in the crackling pattern shown in the top-row images of Figure 3. These images and the corresponding paint thickness map are used as input data in the appearance transfer algorithm presented in Section 4. Note that the paint thickness map is relative, since we do not know the actual light transmittance of the paint. Nevertheless, this issue can be circumvented by rescaling the map in order to match the dynamic range of the destination paint-thickness map.

3.2 Experimental Procedure: Patination

The chemical reaction of metals, such as copper or brass, with solutions of compounds, such as chlorine-containing substances, produces interesting patterns of color that lead to an aged appearance, or patina. The development of a patina depends on the spatial distribution of the solution, the geometry of the object and the atmospheric conditions. For our experiment, we chose to work with copper, and experimented with various geometries and solutions. We selected a solution that produced a substantial color change within a relatively short, two-week period. The sample object was kept indoors, for complete control of the atmospheric conditions.

Sample Preparation: We chose as our test object a copper kitchen mold, with a raised geometric pattern on its base. This allowed us to apply the solution consistently to a generally horizontal surface with shape variation. We used a solution documented in [18] for developing a blue-green patina. The solution consisted of 10 grams of ammonium chloride and 10 grams of ammonium acetate dissolved in one liter of water. The solution was applied twice a day over an eleven-day period. A fine spray was used to apply the solution evenly and to avoid having large amounts of solution flow into indentations in the surface.

Acquisition of Appearance History: Appearance data was captured prior to each new application of the solution. Initially, the copper was shiny, and the shape of the object resulted in highlights and shadows in the captured images. To obtain maps of the surface independent of lighting, i.e., "unlit textures" (or albedo maps), the appearance data was captured by scanning the shape of the object with a laser scanner, and by acquiring a series of images with the mold illuminated with lights in five different positions. The laser scanner used was a ShapeGrabber (//www.shapegrabber.com) with an SG1002 scan head. The camera was the same Olympus model used for the paint crackling acquisition. It was calibrated in terms of the scanner coordinates, so that the captured image could be applied to the geometry as a texture. The lights were small, 150-watt halogen bulbs mounted on a frame around the scanner and camera. The light positions were also calibrated in terms of the scanner coordinates. (Figure 2 shows an image of the experimental setup.)

Using the shape and light positions, an unlit, diffuse texture map, with the effects of the five initial lighting conditions removed, was computed using essentially the same methodology as described in [28]. (Other setups and algorithms for measuring geometry and BRDF could equally be used with our approach.) Since the copper mold needed to be moved off the scanning table for each application of the solution, the shape was scanned each time. All of the textures could then be projected into the same view by using the iterative-closest-point algorithm [2] to geometrically register the shape data associated with the textures. With registered textures we could track the time evolution of the copper surface appearance pixel by pixel.

Measuring Accessibility: Although there are many factors that can potentially affect the process of patination, and hence the appearance of a surface, we have noted that the concave parts of the copper mold surface shown in the top row of Figure 4, namely the spokes and other indentations, have markedly different appearance. This is possibly explained by differences in the amount of patination due to the variability in the amount of solution that gets deposited on the surface. The solution was applied by spraying from about two feet above the surface, trying to apply it uniformly and without allowing the formation of small puddles. The created solution mist drifted mostly downwards, but small air currents could also cause small sideways motions. This has the effect of depositing more material on the exposed, convex parts of the surface than on the regions

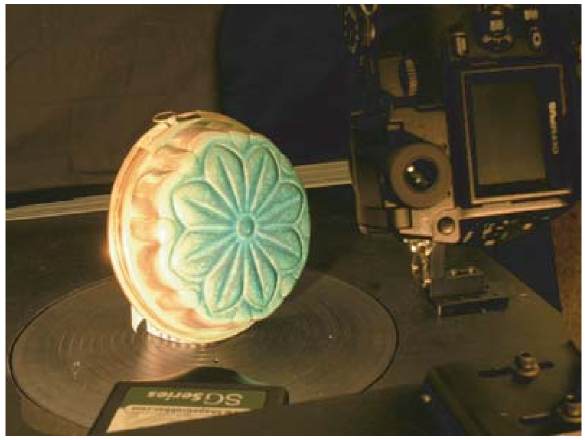

Figure 2: Photograph of our experimental setup showing the acquisition of a copper mold.

inside the radial spokes and other crevices. We observed that much of the reaction happens while the object surface is still wet/damp, but it also continues after evaporation. The residual salts, which are more abundant on the convex parts of the surface, attract some atmospheric moisture, and the two react with the copper surface. The variation in the amount of reaction from one part of the surface to another, which is indirectly related to the object geometry, leads to differences in the appearance of the surface.

The amount of solution deposited on the surface can be related to the notion of accessibility [25]. This, in turn, is related to how much a point on the surface can be affected by outside events. Miller has characterized accessibility as "how easily a surface may be touched by a spherical probe." Namely, a numerical map can be built on the surface noting the radius of the maximum sphere that can touch a point without intersecting any other parts of the surface. This leads to small accessibility values for concave parts of the surface, where less solution has been deposited, and large values for more exposed parts. Unfortunately, this measure can explode to infinity for convex (or even planar) parts of the surface and could lead to numerical problems when used as a control parameter. A more appropriate measure of accessibility is to use something related to the inverse of the radius of the maximum sphere that can touch the surface. Such a measure has been defined as the proportion of rays emanating from a point on the surface that can intersect other parts of the surface.

This definition of accessibility is related (up to a normalization) to the mean curvature of the object surface, which can be readily estimated from the measured 3-D shape. The ease and speed of estimation of the mean curvature compares quite favorably with algorithms that estimate accessibility using the slow, and with potentially noisy results, method that shoots multiple rays from each point on the surface. We measure the mean curvature of a surface by first capturing the object shape using the ShapeGrabber range scanner. From the shape, we can determine the $x-$ and $y-$derivatives of the surface, which we assume to be a height function. After smoothing the derivatives with a Gaussian mask, not larger than the smallest feature that a user desires to preserve in the accessibility map, we use the standard formula for calculating the mean curvature. To create an approximation to the accessibility map, for use as a control parameter, we normalize the mean curvatures to be between 0 and 1, with the concave parts having high values. The captured images (all taken with the same camera view) were registered to the geometry, so that the generated accessibility map was registered to the captured images recording the material history.

4 Texture Transfer

The focus of our work is not to create a new texture transfer algorithm; rather, the proposed approach is meant to enhance the applicability of the area of texture synthesis and transfer. To transfer our observed data, though, we need to adapt existing techniques with regard to the parameters used to test for similarity between the source and destination locations, and for coherence in the generated texture. In considering the source and destination, we want to transfer from source areas that have a similar control parameter—thickness in the case of the paint, and accessibility in the case of the patination.

The technique we used is derived from the texture synthesis techniques by Efros and Leung [10], and Efros and Freeman [9]. Like the former, we synthesize one pixel at a time on a 3-D geometry, taking into account the foreshortening. We combined that algorithm with the texture transfer technique by Efros and Freeman, where both spatial coherence and similarity of parameters need to be satisfied. Using our systematically acquired data, we have extended the concept of texture transfer to the realistic synthesis of novel object appearances, which can be controlled with plausible and intuitive parameters. Furthermore, we have created novel time-varying textures with satisfactory temporal consistency.

Our algorithm consists of two stages. In order to synthesize a pixel value, we first place a 100×100 search window centered around a region of the source image where, within some tolerance, the control parameter value—be it paint thickness or accessibility—is similar to the one in the destination image. This satisfies to a large extent the requirement mentioned above that texture should be transfered from areas with similar control parameter values. We also loosely constrain the center of this search window to be near the weighted average center positions used to determine the pixel values of the current pixel's known neighbors. This helps to some extent in preserving the spatial coherence in the synthesized image and is related to the approach in [1]. In the second step, we perform a search within the 100×100 window to find the pixel value, while satisfying, as much as possible in a least-squares sense, both the spatial coherence and the similarity of the control parameters. Their relative significance is controlled in a similar fashion as in Efros and Freeman's work.

The texture transfer is performed once for all time frames, i.e., each pixel in the texture-map is defined for all times. During synthesis, we keep the (x, y) positions in the source image from which each pixel value in the destination image has been transfered. These are then used to synthesize new images of the texture at different time instances in its history using a simple and fast lookup.

5 Results

Our results for the paint crackling and patination experiments, which were performed on non-convex objects, are shown in Figures 3 and 4. In each figure, we show examples of the captured input materials and examples of transferring the captured data to a new shape.

In Figure 3, the top row shows the thickness map of the paint sample we obtained and three images of the captured time series of the crackling paint. We chose to concentrate on the thickness of the paint layer because we believe this is an intuitive control parameter that can be easily incorporated into computer graphics applications. One can envision a user applying paint with a "spray" tool of varying thickness on a 3D object. The thickness of the applied paint could be a function of how long the user stayed over a particular spot while "spraying," or it could be a function of the angle of the surface normal with respect to the direction of "spraying." We have tested both scenarios. The surface appearance is then synthesized across time using as source data

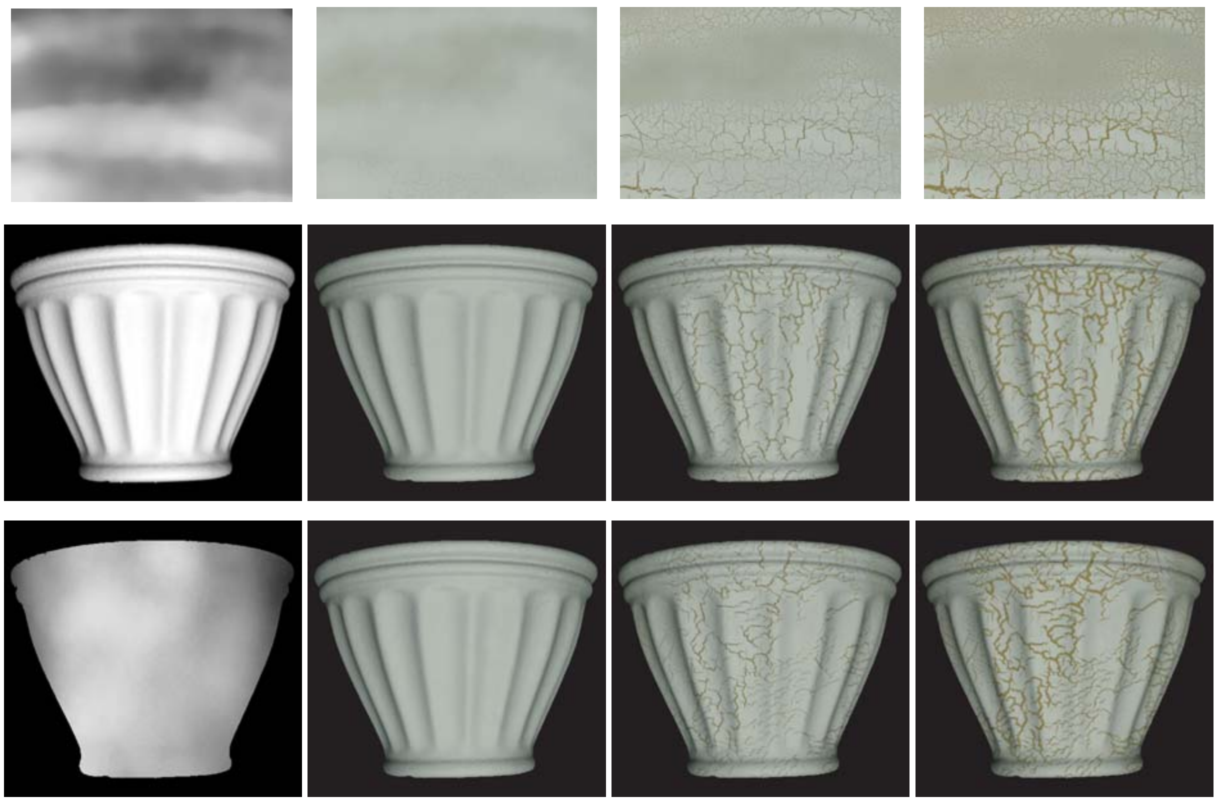

Figure 3: Paint crackling results: Top row: the captured thickness map and three images from the captured time series. Second row: the thickness map for the synthetic object, and synthesized images for the same three time steps as shown in the top row. Bottom row: a different thickness map for the synthetic object, and synthesized images for the same three time steps as shown in the top row.

Figure 4: Patination results: Top row: captured data (relit) for five points in the temporal sequence. Bottom row: material from captured data applied to a new object and relit in the same way. *(Note that black holes in the base of the new object are holes in the scanned geometry, not holes in the texture.)*

the captured appearance history of a sample of crackling paint, which has been specifically prepared to have spatially varying thickness.

The next two rows in Figure 3 show new thickness maps applied digitally to a new shape. In the middle row, the paint thickness map is proportional to the cosine of the angle of the surface normal with respect to the viewing direction. In the bottom row, the paint thickness is proportional to the time of spraying. The images for the synthesized appearance are shown for the same time steps as in the first row. All of the images are shown with the diffuse component only. In the animation (see Objectwithsynthesizedmaterialhistory.avi), the temporal evolution of the synthesized object in the second row, is shown with an estimated specular component for the gold paint under layer. Comparing the rows shows that the essential appearance of the captured data is apparent in the synthetic objects. However, the actual synthesized crackle patterns are unique due to the shape of the new object, and different applied paint-thickness maps. Note in particular that large cracks form where the paint is relatively thick, e.g. the central part of the new object in the middle row and towards the left in the bottom-row case. Conversely, small cracks appear where the paint is relatively thin. The animation demonstrates that the evolution of the crackling in time is coherent for the synthetic object.

In Figure 4, the top row shows close-up images of the captured copper mold (also shown in Figure 2) at a selection of five points in the eleven days of data. The images of the captured model are shown here relit in a novel way, with an estimated spatially varying specular component. The appearance data has been transfered onto a new shape (a seahorse), shown in the second row. The transfer from the copper mold to the seahorse was from source areas that have a similar control parameter, in this case accessibility. On the new object, the same estimated specular components and the same lighting conditions are used. Changes from the original copper to the blue-green patina develop irregularly over the surface of the seahorse, as in the captured data, but are evolving consistently through time. Note, for example, that the concavities on the side of the seahorse share the same essential appearance as the concavities of the copper mold, but they evolve in a unique way due to the particular shape of the seahorse resulting to a different accessibility map. Since the patination is the result of discrete treatments—twice each day—the images for this case do not form a smooth animated sequence.

6 Conclusions

We have introduced a framework for capturing and transferring changes in material appearance over time. We capture the changes in the appearance, but also identify and measure key parameters that control these variations. By using captured data and parameters, we have synthesized images of new objects that change in a manner similar to the observed objects, but with spatial and time variations that are unique to the new synthetic objects.

The two distinct cases we described—paint crackling and patination—are representative examples of the approach to appearance synthesis presented in this paper. Preliminary experiments suggest that the framework will be applicable to wide range of effects. For example, our approach can handle drying, where plausible control parameters are accessibility, distance from the boundary of a wet patch, or angle of the surface normal with the direction of gravity. Other possible phenomena are: dust, where the control parameters could be accessibility and direction of the surface normal with respect to gravity; frost on windows where the appearance of the build-up is controlled by the distance from the window frame; fading due to UV radiation exposure where the control parameter could be the angle of the surface normal to the direction of the radiation; and bacteria propagation, which could again be related to accessibility and direction of lighting.

Capturing parameterized time histories of materials will allow a user to control the variation of material appearance indirectly through the design of the object shape, or directly by specifying parameters on the object surface that control the material history. Future work includes developing a large library of material histories, which could be applied in isolation or in novel combinations. Such a resource would likely suggest ways of classifying materials for use in computer graphics applications. Because our material histories are not tied to a particular modeling or simulation technique, they can easily be incorporated into an image synthesis pipeline and should therefore find broad applicability. Capturing and exploring other parameters would provide additional interactive controls.

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