Creating Metallic Color Sequences for an Architectural Wall

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Abstract

A metallic paint scheme for an architectural wall is created using computer aided color appearance design techniques. New computer graphic hardware that allows real-time rendering of complex reflectance functions is employed to produce photo-realistic images of the metallic paint applied to the surface of the wall. An interpolation scheme is developed that permits one and two dimensional metallic shade sequences to be determined between individual bricks in a single row of the wall and between the complete rows of bricks that compose the wall. Paint formulation software, originally developed for auto refinish applications, is used to determine the paint mixtures necessary to realize the metallic colors in the design. A prototype of the wall is constructed and exhibited in a museum gallery.
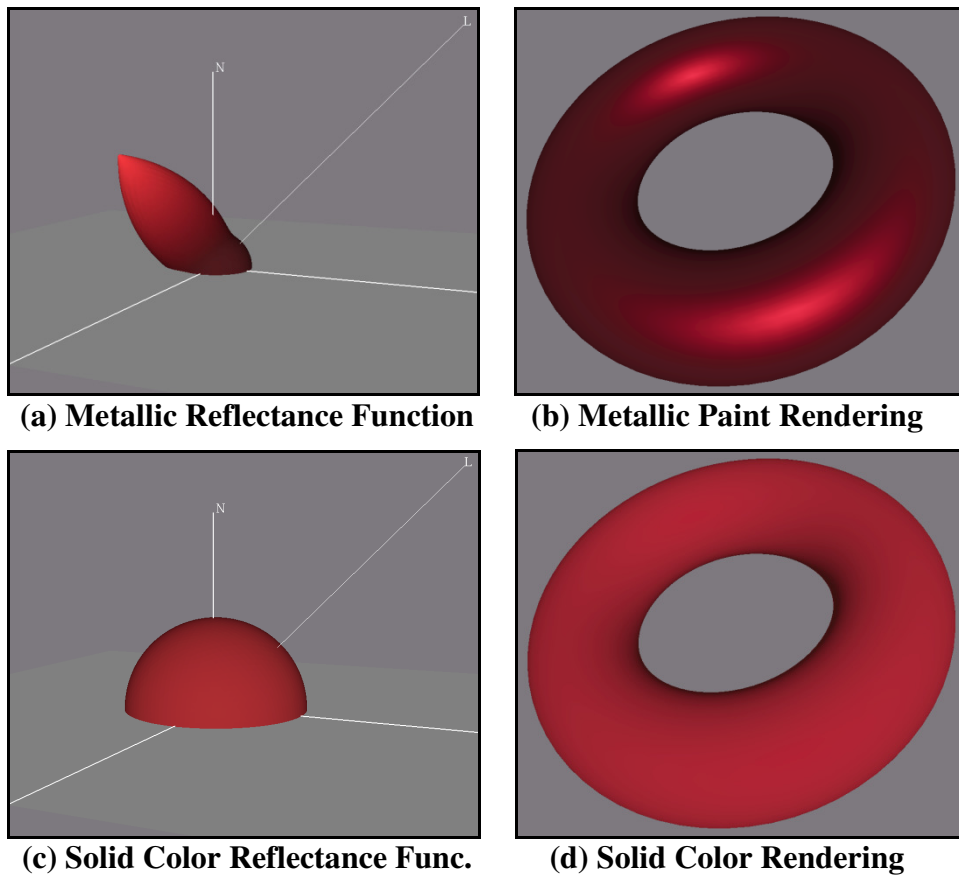
1 Introduction

Most architectural coatings in use today are solid colors, meaning they are expressible by a single color measurement. However, as the coating industry advances they are offering unique 'special effect' paints. In particular we see the emergence of metallic paints available in many different hues and shades. These paints have reflective properties similar to raw or treated metal surfaces and differ from a solid color in that multiple color measurements must be made to characterize their appearance (see Figure 1). Most architects and designers are familiar with solid colored coatings. They use them in isolation to cover large surfaces or in combination to create interesting designs or patterns. Perhaps the simplest of these patterns is the use of sequences of colors, gradients in lightness or saturation that produce a uniform changing quality. It is these color sequences that are the focus of this paper and how they may be extended to newer metallic coatings.

Creating a sequence of related solid colors is a natural, straight-forward task. We have an intuition about it and when that intuition fails we can appeal to well defined mathematical techniques such as interpolation to help. However, creating a sequence of related metallic colors is a more difficult task. Our intuition on the matter may be non-existent or misleading. Even expressing a metallic color is difficult as their qualities go beyond a

single triple. They cannot be constructed from three primaries alone. Consequently, they are typically used as accent colors. They form borders or trims in facades or appear only when the raw material itself is a metal.

This paper will explore the technical side of expressing a metallic color by appealing to well established techniques in the coating and appearance industries. Using this representation we will discuss in detail the task of creating a sequence of metallic colors by using the technique of interpolation and by extending it to a multi-dimensional domain for these complex surface coatings. The paper concludes by discussing how an interpolation tool was used to design a complex color scheme for a prototype architectural wall.

| (a) Metallic Reflectance Function | (b) Metallic Paint Rendering |
| (c) Solid Color Reflectance Func. | (d) Solid Color Rendering |

Figure 1. Metallic paint (top) vs. solid color (bottom). The solid color reflects light evenly in all directions 1(c) while the metallic paint has a preferential reflection function around the specular (or mirror) direction 1(a). In addition, the solid color reflects the same color light in all directions while the color of the metallic paint changes with reflection angle.

**(a) Intended site of Cloak House**
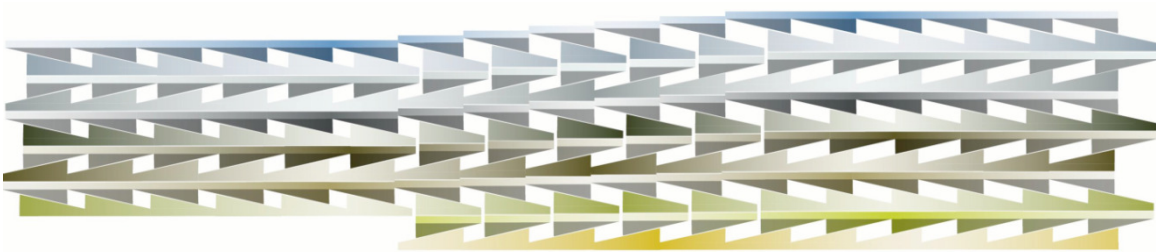
(b) Illustration of Cloak Wall

Figure 2. The Cloak Wall - The key colors in the color scheme come directly from this photograph of the intended site.

## 2 Representing Metallic Colors

There is an accepted standard for describing a metallic color in the appearance and coating industries (Alman (1987); Rodrigues and Steenhoek (1996); Rodrigues (1995, 1990)). The description uses the CIE standard *L*a*b** color space. CIE *L*a*b** uses a perceptually uniform organization, originally developed by Albert Munsell (Munsell (1912)), but substitutes rectangular dimensions for the circular hue dimensions. It approximates the perceptual uniformity of Munsell's work while also providing desirable mathematical characteristics and relationships with other color standards (such as CIE *XYZ* color space). A variant of *L*a*b** color space is CIE *LCH* color space where the *a** and *b** dimensions are transformed into *C* and *H* (chroma and hue) the same way Cartesian *XY* coordinates are turned into the polar coordinates *r* and *theta*. The *LCH* variant will be particularly important when interpolation is applied to colors later in the paper.
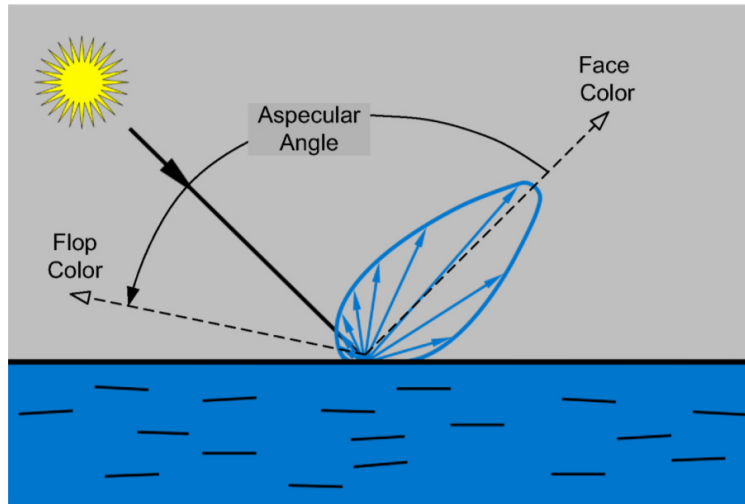
Figure 3. Metallic Reflection Angles - The face color occurs at the specular reflection angle. All other angles are aspecular angles with the flop color being very skew to the sample.

In *LCH* space a solid color has a single lightness, hue and chroma. However, a metallic color requires more than a single *LCH* value. Its *LCH* value changes depending on the viewing angle. This extra dimensionality, namely viewing angle, causes the color to be a curve through the color space rather than a single point. In the appearance industry metallic colors are casually characterized by two extreme viewing angles called face and flop (see Figure 3). Viewing a metallic sample in hand straight on produces the face color. Letting the sample drop away to a very skew angle shows the flop color. Each of these extremes is a single point in *LCH* space along the curve of the metallic color. Experts have found that these two measurements combined with three more measurements between the face and flop (five total) are sufficient to characterize the entire metallic curve. The five points are fit to a smoothly curving second degree polynomial using a least-squares fitting algorithm.

More precisely, the *L*a*b** value of the metallic coating is measured at five specific angles with respect to specular (the ideal reflectance angle): 15°, 25°, 45°, 75° and 110°. These angles are referred to as the aspecular angles. The entire color curve is built by fitting each of the *L**, *a** and *b** dimensions from these measurements to a second degree, parabolic curve in a least squares sense. It is important that each curve be monotonically increasing or decreasing. If left alone, a naive fitting would curve back on itself as the viewing angle is extrapolated. To achieve this result the curve's inflection point is found (the minimum of an upward facing curve or maximum of a downward facing curve) and the curve is clamped to this value as the angle increases. For more details on applying these measurement standards to computer graphics see (Westlund and Meyer (2001)).
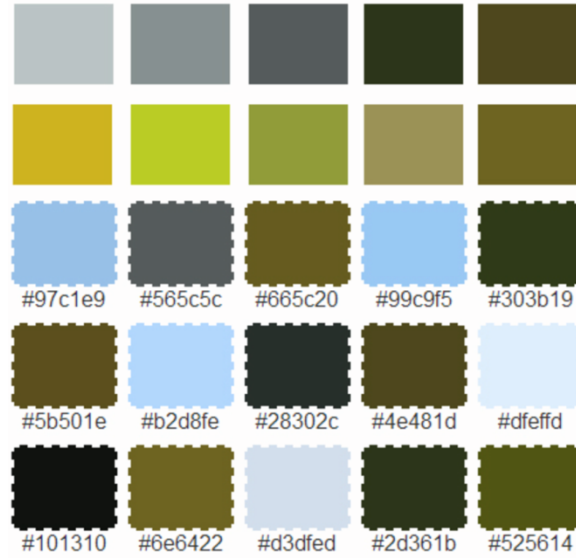
Figure 4. Palette extracted from the site photograph. Created with an online tool (Watson 2008).

3   The Cloak Wall

The Cloak Wall is an example of a direct application of the techniques described in this paper. Swackhammer et al. (Swackhamer and Satterfield (2006)) developed the cloak wall as a modular, energy-efficient and affordable housing project. While many other types of building materials and elements have been considered throughout the lifespan of the project the current form of the project is shown in Figure 2(b). The exterior is composed of modular bricks with many desirable properties each constructed of sheet metal. The colors used on the wall should come directly from the site where the Cloak House would eventually be built (see Figure 2(a)) helping it to blend in with its surroundings and even disappear (or *cloak*). The colors from this site were analyzed with an online tool (Watson 2008) to produce a palette of solid colors (see Figure 4). This became the basis of the color scheme and was used to design key metallic colors. It was decided that these key colors would be sequenced across the rows of the wall interpolating through a common neutral color similar to Figure 2(b).

3.1 Sequences of Metallic Colors

The mathematical process of interpolation is useful for creating sequences of solid colors. With two colors, A and B, described in the same color space, we can produce a sequence of colors of size *n* by creating a line between A and B and sampling that line at *n* evenly spaced points. This is called linear interpolation. If we work in a perceptually uniform space (such as CIE *L*a*b**) then those even spacings along the line will be perceptually even as well. If, for example, A is a very dark forest green and B is a very light lime green the line between them with change mainly in the lightness dimension. Sampling

this line at even intervals will give us a color sequence that slowly changes in lightness from the dark green to the lighter green.

This same process can be used for metallic colors but it must first be extended to deal with the extra dimensionality of the viewing angle. As stated before, each metallic color is described by five *L*a*b** values corresponding to the five aspecular angles. If we treat each of these five values as a single color then we can interpolate it as we would a solid color. By connecting each of these five values with a line and sampling those five lines at *n* regular intervals we get a sequence of *n + 2* sets of triples each of which describes its own metallic color. These sequences can range from lightness gradients (similar to the example given for green colors) to trips around the entire rainbow of hues and everything in between.

Interpolation of both solid and metallic colors is done in *L*a*b** space so that the evenly spaced samples will produce perceptually uniform steps. Alternatively the values can be transformed from *L*a*b** space to *LCH* so that interpolation occurs along the hue and chroma dimensions. Linear interpolation can still be performed in this space but care must be employed with the hue dimension which is circular. Interpolation can move either clockwise or counterclockwise and the choice of direction will make a dramatic difference in the sequence produced. No single choice will be appropriate all the time so it should be left to the user to decide in which direction to proceed when interpolating in LCH space.

3.2   Metallic Sequence Tool

A tool was developed to help with interpolation of metallic colors across the Cloak Wall (see Figure 5). The tool presents a grid of checkboxes, one for each brick in the wall. To create a sequence, the user assigns colors to the key bricks that form the ends of the sequence. These colors can be selected from a catalog of existing colors or they can be custom designed using an interface described in (Meyer and Shimizu (2005)). The user then checks off these bricks in the interface and clicks 'interpolate' to fill in the color sequence. The user has the option to select the abstract *a** and *b** dimensions for interpolation or the more natural hue and chroma dimensions. They can also specify the type of interpolation to be used by choosing from linear and cosine interpolation. Cosine interpolation spaces the sequenced colors unevenly using a cosine function. If they are interpolating in *LCH* color space they can also reverse the direction around the hue circuit to produce a different sequence of colors. The Cloak Wall is roughly arranged in a row-column organization. Interpolation can occur in one dimension along a row; interpolation can also occur in between rows along columns effectively making this a bilinear interpolation scheme. Only rows and columns with two or more key colors checked off are interpolated; the rest are left alone.
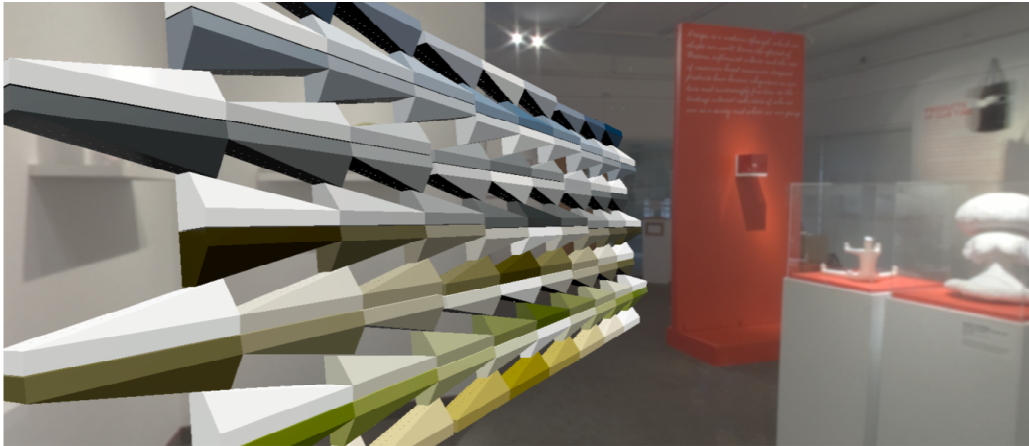
3.3 Rendering the Cloak Wall

Throughout the color selection process, the architect worked with a real-time rendering of the painted wall alongside the interpolation interface. This system performs all calculations in real-time by employing modern hardware shader technology permitting per-pixel calculation of the metallic reflection model. The angular dependence of this model necessitates per-pixel calculations as the color of the primary underlying pigment must be re-calculated at each point on the surface. Recent developments in computer graphics hardware have opened up this portion of the hardware rendering pipeline to allow a small program (called a shader) to be executed for each fragment/pixel on the surface of the object being rendered. The shader used for this program calculates the lighting and viewing angles along with the surface normal at each pixel and uses them to compute the color according to the curves fitted to the $L*$, $a*$ and $b*$ dimensions. This color modulates the lighting calculation to give the surface a metallic appearance.

The latest version of this rendering engine uses environment maps instead of point light sources to compute the metallic model. This provides a superior effect when the surface has a high-gloss finish, however it was not as useful for our task as no clear-coat was applied to the bricks giving the coatings a matte finish. Regardless, it was known that a small portion of the wall would be exhibited in the Goldstein Museum of Design in St. Paul, Minnesota. To fully exploit the flexibility of the environment map rendering engine and visualize the wall in this gallery, we created environment maps of the Goldstein (see Figure 6). These environment maps were used for rendering and visualization throughout the design task along with several other 'stock' lighting situations with their own desirable characteristics.
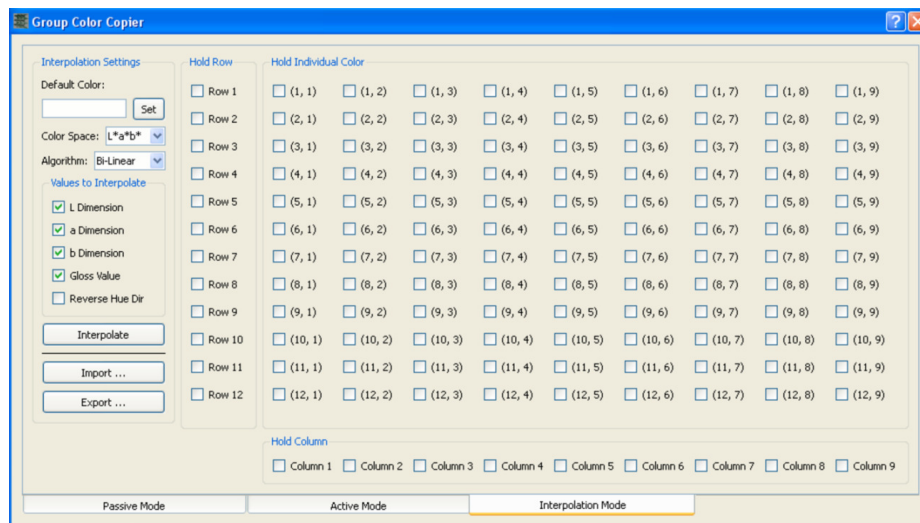
Figure 5. User interface for the interpolation tool. Individual bricks or entire rows and columns can be set as key colors for interpolation.

Figure 6. Rendering of the final design of the Cloak Wall. There are more columns and rows in this design then were used in the final exhibit due to space constraints.

3.4 Exhibiting the Cloak Wall

A unique opportunity became available to exhibit the cloak wall at a local design museum. For this a sub-section of the full prototyped wall pictured in Figure 7 was carefully finalized and the measurements were sent to DuPont. DuPont has developed a computerized system to match paints based on these measurements. Normally it is used in auto body shops for automotive paint repairs. In our case it was used to formulate new colors. DuPont calculated the formulations as well as the predicted measurements of the coatings which were as close to the requested measurements as possible but never equal. The predicted measurements were loaded back into our rendering system and problem areas were identified. In these cases work was done to change the colors and bring them closer to existing DuPont paints. A database of DuPont's SpectraMaster color library as well as a visualization system comparing designed colors to known colors was utilized in this step. Once the predicted measurements of the formulated coatings were found to be acceptable the paints were mixed and applied using standard automotive paint techniques. The final wall installed in its exhibit can be seen in Figure 8.

4   Conclusions

Computer aided tools will play an increasingly important role in the design and selection of surface finishes for architectural applications. Architects have been able to use computer graphics to manipulate the shape and form of their buildings for over forty years. Within the last twenty years advanced computer graphic illumination algorithms have made it possible to consider the effect of natural and artificial lighting on the appearance and functionality of a building. The work presented in this paper demonstrates how recent developments in computer graphics hardware permit the reflectance properties of complex architectural coatings to be displayed *and* manipulated in real time. This capability allowed one and two dimensional sequences of metallic

colors to be designed for use on a prototype architectural wall. The realistic display, iterative adjustment, and automatic formulation of these metallic paint colors demonstrates the basic steps necessary to achieve computer aided color appearance design in an architectural application.

Acknowledgments

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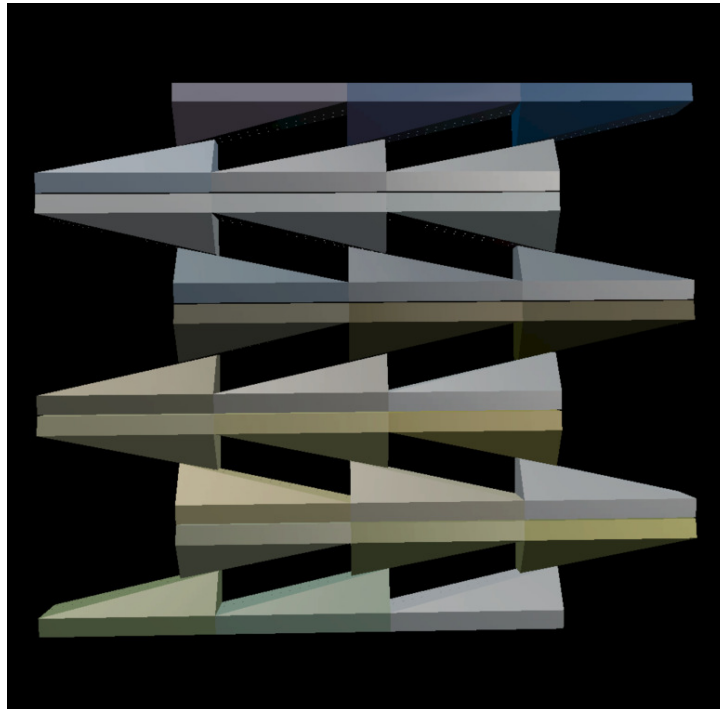
Figure 7. Subsection of the Cloak Wall for the Goldstein Museum showing the predicted appearance of the formulated coatings.

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Figure 8. Prototype of the Cloak Wall exhibited in the Goldstein Museum of Design