

A Computer Aided Color Appearance Design System for Metallic Car Paint

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Abstract. A computer aided design system for determining the color appearance of metallic automotive coatings has been developed. A sketch based bidirectional reflectance distribution function design interface allows simple concept art to be used to style new metallic car colors. The final design is specified using industrial measurement standards for metallic color appearance, and paint formulations are determined by employing an automotive refinish system. A virtual collection of existing automotive paints, specified using the measurement standard, is provided, and tools for searching this database, for both design and manufacturing purposes, are described. The system is assessed by using it in industrial and educational design studios. © 2015 Society for Imaging Science and Technology.

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INTRODUCTION

In this article, a complete computer aided design (CAD) system for color appearance is presented. The application domain is metallic automotive finishes which, because they modify both the spatial and spectral distribution of the reflected light, meet the requirements for being described as a color appearance problem.¹ To visualize and modify the color appearance of the paint, a sketch based interactive computer graphic design tool is presented. Once the desired color appearance has been achieved, the specification is stored using a special digital file format. A digital database of existing automotive finishes is provided in which each color is represented using the same color appearance specification employed throughout the system. Final prototypes of the paint can be produced by submitting the color appearance specification to an automotive refinish paint formulation system.

Three existing technical accomplishments make this CAD system for color appearance possible.

- **Metallic color appearance measurement standards**—The color appearance industry has adopted a set of conventions for measuring metallic paint and for describing its appearance.^{2,3} These measurement conventions form the basis for the digital representation that is used in this work to both exchange and store color appearance information. The metallic color appearance terminology embraced by the industry is used to

develop interfaces for color appearance design tools that are intuitive and easy to use.

- **Computer graphic pixel shading hardware**—The popularity of computer games has spurred the development of pixel shading hardware that can be used to compute the color of every picture element in a display at interactive rates. This technological advance is what makes it possible to develop the interactive color appearance design program that is at the heart of this work.
- **Computerized automotive refinish systems**—The automotive refinish industry has developed computer programs that can be used to predict paint mixtures that match a measurement made in terms of the metallic color appearance measurement standards. These programs are used in this work to fabricate paints that have color appearances created using the interactive computer graphic color appearance design tool.

This article describes all of the elements that are part of this computer aided color appearance design system. After discussing related work in the areas of automotive paint simulation and color appearance prototyping, the reflection model employed in the research is introduced. This reflection model is based on the measurement standards that have been defined for work with metallic and pearlescent paints, and it makes use of the terminology that has been adopted for describing metallic paint. A design interface is then presented that allows simple concept sketch artwork to be used a seed for defining new automotive color appearances. Next, a database that can be used to store the color is introduced, along with search techniques that are tailored for use with metallic colors. Finally, the automotive refinish system that is used to make the paints is introduced, along with tools for seeding the paint formulation process. The article ends by describing the feedback that was obtained by deploying the system in automotive design studios. Figure 1 shows a paint that was produced with the workflow described.

RELATED WORK

The use of slides and projectors to design new solid colors that, given the desired spectral curve, could be matched using pigment mixing technology was first proposed in Ref. 4. The system was developed before the use of interactive color computer graphics was possible, but it did make use

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Figure 1. The paint finish for an automotive design student's truck was selected with the computer graphic tools described in this document.

of computers to perform the color matching calculations. Interactive computer graphic programs have been written that allow the creation of arbitrary bidirectional reflectance distribution functions (BRDFs),^{5–8} but these applications were not directly tied to fabrication systems that could produce prototypes. Recent efforts in the field of computer graphics have attempted to fabricate material appearances that match a given BRDF,^{9–12} but this work does not include intuitive interfaces that can be used to design the BRDF, nor does it involve coatings or surface finishes that are commonly used in industry.

There have been several attempts to characterize the surface reflectance of automotive paint and to use the result to produce a computer graphic picture. In one of the earliest efforts, measurements were made of the BRDF, and this data was used to create a realistic image.¹³ Gondek et al.¹⁴ also used BRDF data to simulate the appearance of pearlescent paint, but in this case the reflectance information was obtained by modeling the titanium coated mica plates within the paint and by using ray tracing techniques to simulate how light interacts with these structures. The reflectance properties of car paint have also been acquired from digital images and then used to make synthetic images.¹⁵ A detailed reflectance model that accounts for all of the constituent materials within the paint has been developed,¹⁶ and inversion techniques have been explored that permit this model to be fit to an existing BRDF.¹⁷ In a different approach that forms the basis for the work reported in this article, the authors of Ref. 18 built a low parameter reflectance model based on industry standards for measuring gloss and metallic surface finishes.

The automotive industry standardized the measurement of the overall appearance of metallic automotive paint using three to five angles measured with reference to the specular direction. Experiments show that a plot of these color measurements versus this *aspecular angle* can almost always be fit with a “clamped” second-order polynomial.^{19–22} While the original measurements that led to this conclusion were made using traditional metallic paint that contains aluminum

flakes, the standards that were established have also been successfully applied to many paints that include interference pigments (although specific measurement standards are also now available for these paints²³).

Considering only the L value from International Commission on Illumination (CIE) Lab color measurements (similar equations can be written for a and b), this second-order equation is

$$L(\theta) = L_a\theta^2 + L_b\theta + L_c.$$

This equation is clamped to be constant at the minimum of the parabola. The shape of the L function approximates the shape of the directional reflectance. The a and b functions model the “face” to “flop” color travel that is exhibited by automotive paints.

In previous work, this polynomial was employed to create a computer graphics reflection model that was used as the basis for some color appearance design tools. The BRDF Designer^{24,25} provides an interface for adjusting a plot of this polynomial by editing the data points that define the curve at three or five aspecular angles, or by controlling the endpoints of the curve. Color styling tools were also built to manipulate the reflection model in a way that mimics the workflow of traditional color stylists.²⁶ A rendering engine called the BRDF Viewer was created to display the output of the color appearance design tools by using photographically acquired lighting. Details of the algorithms used by the BRDF Viewer for the realtime rendering of interactively designed BRDFs are given in Ref. 27.

SKETCH BASED COLOR STYLING

Artists and designers often communicate initial vision for a final product through the use of “concept art”. Concept art may take many forms—from hand-drawn renderings to modifying existing images that provide visual insight into the designer’s ideas on form, color, texture, mood, and so on. The software described in this section provides a sketch based BRDF design interface that effectively utilizes the contributions of the concept artist in the final design. Color appearance is designed by directly painting it onto an image of an object. Again, the parameters of the reflection model that need to be modeled by the sketch based interface are face, flop, and travel. These are modeled by using standard fitting routines to find the parameters of the reflection model that match the concept artist’s design. There are three main steps to the system. First, a setup step prepares the initial image upon which the designer will base their concept art. Next, the artist creates concept art over the initial image using an image editing program such as Adobe Photoshop[®]. Finally, a BRDF fitting system finds the parameters to the reflection model that best approximates the concept art.

The artist starts by positioning a three-dimensional (3D) object and a simple point light in a scene. A preprocessing step saves a rendering as the initial image that the designer will use as a basis for their concept art. In addition to the screenshot, it renders the scene using a special shader that encodes lighting and viewing geometry on a per pixel

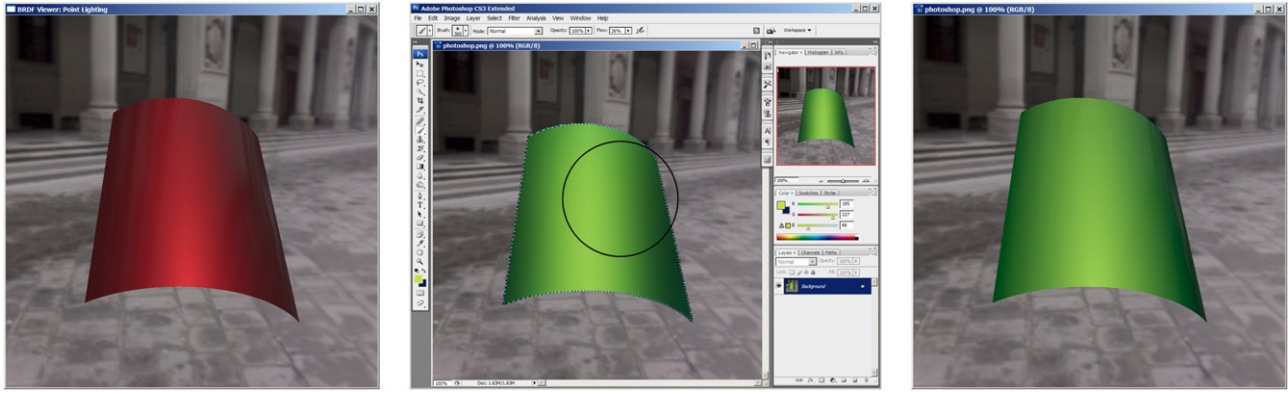


Figure 2. The initial image (left) was loaded into Photoshop and masked with the quick select tool. Photoshop's foreground/background colors were selected to be new starting face/flop colors. The gradient paint bucket tool was used to approximate the color's travel. The burn tool was used to darken the flop color. An overall hue rotation pushed the new color to green. The face color was brightened using the paint brush set to a yellow with low flow to create the final goal image (middle). The least squares fitting routine fit the BRDF rendered on a 3D surface (right).

basis. The shader computes the aspecular angle between the reflected light and view vectors (θ) as well as the cosine between the light and surface normal (ϕ). This is the minimum information needed to completely index the metallic reflection model. The Aspecular angle, θ , is encoded in the red channel, ϕ is encoded in the green channel, and the blue channel is simply used for foreground background segmentation by encoding a value of 100% for material to be designed and 0% for the background, interior, and nonmetallic trim.

Next, the initial image is loaded into Photoshop. The user modifies the image using any of the tools that Photoshop has to offer. Because of the choice of the fitting routine used in the next step, it is important that they paint the color in a manner that is consistent with the scene and lighting geometry. The user may use Photoshop's magic wand to mask the automobile and adjust the color of the car using Photoshop's rich set of color correction tools. They may also use Photoshop's burn and dodge tool to adjust the brightness of the face and flop color or the rate of travel. The artist may also repaint the object completely from scratch, using the gradient paint bucket, airbrush, and other painting tools. Once the user is satisfied with the changes that have been made, the image is saved and the modifications are sent to the fitting routine.

The final step uses least squares to fit the parametric form of the metallic reflection model to the artist's drawing. The parametric form of the metallic reflection model is written for the R or red component below.

$$\theta_i^2 \phi_i R_a + \theta_i \phi_i R_b + \phi_i R_c = R_i.$$

The subscript i is the index of the i th of n changed foreground pixels. θ_i and ϕ_i are the aspecular angle and Lambertian term of the i th changed pixel. This term is never needed for design, but is present here because the parametric form is used in an inverse rendering context. $R_a, R_b, R_c, G_a, G_b, G_c, B_a, B_b,$ and B_c are the nine parameters for the red (R), green (G), and blue (B) quadratic equations (three for each equation).

A matrix is constructed that represents the mapping between the BRDF and the image of the artist's design. Every pixel in the foreground of the image that was modified by the artist is inserted into the matrix. White pixels, near white pixels, and pixels with low aspecular angles are removed to discount for gloss, since we are not solving for it. An inverse gamma correction function is applied to take the colors from the nonlinear RGB values for display to linear RGB values for calculation. The matrix is shown below.

$$\begin{bmatrix} \theta_1^2 \phi_1 & \theta_1 \phi_1 & \phi_1 \\ \theta_2^2 \phi_2 & \theta_2 \phi_2 & \phi_2 \\ \vdots & \vdots & \vdots \\ \theta_n^2 \phi_n & \theta_n \phi_n & \phi_n \end{bmatrix} \begin{bmatrix} R_a & G_a & B_a \\ R_b & G_b & B_b \\ R_c & G_c & B_c \end{bmatrix} = \begin{bmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots \\ R_n & G_n & B_n \end{bmatrix}.$$

Because the parametric form of the BRDF is a clamped quadratic polynomial rather than a U-shaped parabola, θ_i needs to be clamped to be less than θ_{clamp} when constructing the matrix. Since θ_{clamp} is unknown at the time the matrix is constructed, multiple values of θ_{clamp} are tested, and the solution with the least error is used.

Although this matrix equality is over constrained, $R_a, R_b, R_c, G_a, G_b, G_c, B_a, B_b,$ and B_c for the red green and blue channels can be solved for using least squares fitting. We are guaranteed to find the parameters of the metallic reflection model. Least squares minimizes the error of approximating the artistically designed BRDF in the concept art as the coefficients to quadratic equations for red, green, and blue. The least squares fitting is robust enough to find a solution even if the artist did not perfectly draw the material, although an image that was not drawn accurately will have poor correspondence with the BRDF found by least squares.

The solution needs to be converted from RGB to *Lab* color in order to load the color back into the design system. The RGB parametric form is simply evaluated at $15^\circ, 45^\circ,$ and 110° and the RGB values are converted to *Lab* values. For work with pearlescent paints and other effect colors, the fit should probably be done in *Lab* space.

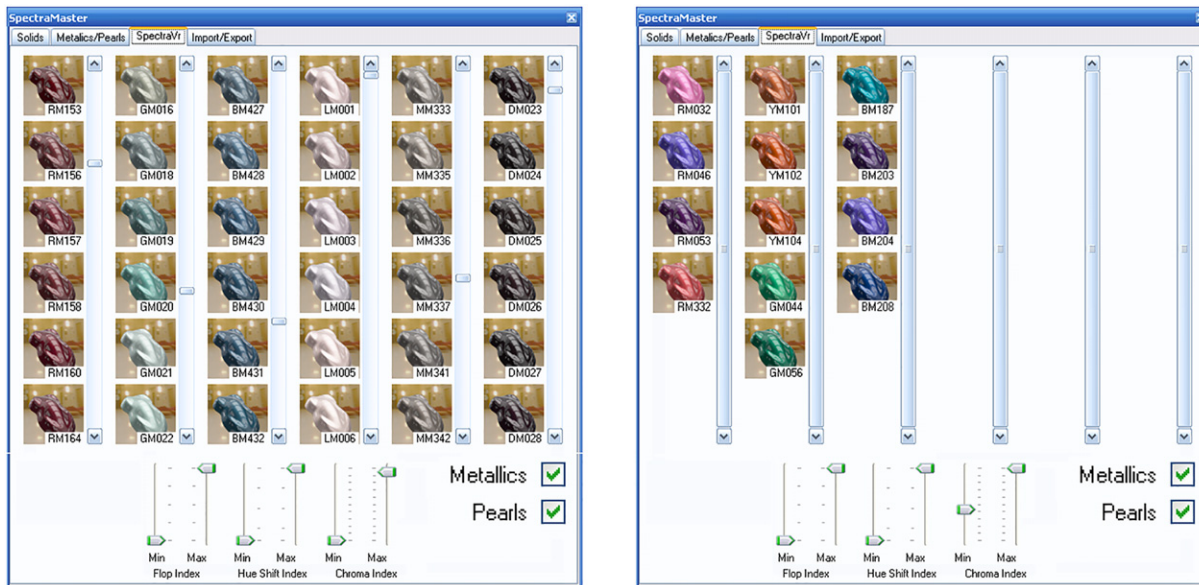


Figure 3. The Virtual SpectraMaster Color Library shown as a thumbnail preview, rendered with environment map based lighting, along with the paint code. The entire collection of over 3000 metallic and pearlescent paints is shown on the left. Sliders allow the user to filter the selection of colors to, for example, colors with high chroma travel (right).

In Figure 2, the original image (left) was selected as a mask and then repainted in Photoshop to create the goal image (middle). The artist used the gradient paint bucket, as well as dodge, burn, and an overall hue rotation, with the paint brush set to low flow. A rendering of the fit BRDF is shown on the right.

DIGITAL REPRESENTATION AND DATABASE

Once the design is complete, a CAD system stores the result in a digital format that can be added to a database, searched to find prior outcomes, and recalled for subsequent modification. An extensible markup language (XML) formatted file is used to store the definition of a new metallic paint and to pass information between the applications that are part of our color appearance CAD system. Starting with the SpectraMaster[®] color system developed by DuPont Performance Coatings, a virtual color collection was created. Novel tools were also developed for searching the reflectance functions stored in this compilation.

XML File Format

We define an XML file that specifies all solid and metallic colors inside of the BRDF design system. It is used for importing colors from measurement tools, exporting colors to paint formulation systems, and for the interprocess communication of automotive color within the BRDF Design Suite. The color styling tools, presented above, are able to read and write the color definition files. The BRDF Viewer rendering engine reads the color definition file for visualization.

The XML file ties all of the software tools together by providing a common format that all tools can read and/or write. Color appearance is specified with standard D65

illumination at 45° from normal. The color sample is defined in the XML file using the automotive industry's standard of 3 or 5 CIE *Lab* tristimulus values as well as the aspecular angles of each value. The XML file also contains a single number for standard gloss.

Since the XML file format uses the automotive industry's standard method of specifying solid and metallic colors, paints can be quickly and accurately measured using commercially available multi-angle spectrophotometer and imported into the BRDF Design Suite. We also use this XML file format to specify electronically designed colors to be formulated.

Virtual SpectraMaster Color Library

The physical SpectraMaster book includes about 3000 solid colors and about 3000 metallic and pearlescent colors. This collection of colors is enormous because it needs to match the vast majority of the automotive colors that are on the road today. If an automobile gets scratched and needs a paint touch up, the refinish catalog needs to have a color that will be a close match regardless of make, model, or year. The book is a companion to DuPont's ColorNet paint formulation system and is used by body shop technicians as a visual reference for refinish colors.

The Virtual SpectraMaster Color Library is an application that is driven from the database of SpectraMaster colors. Every color in the collection has a name and CIE *Lab* tristimulus values (obtained by DuPont using a three-angle spectrophotometer). The application allows you to browse colors by name or by thumbnail preview. The preview is a computer graphic rendering of the paint on a 3D surface for quick evaluation, as shown in Figure 3. When a color

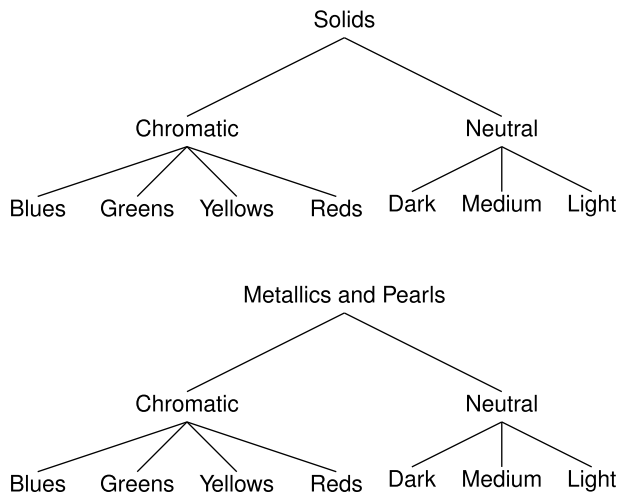


Figure 4. The Virtual SpectraMaster Color Library follows the intuitive hierarchical organization the physical book uses to categorize 6000 solids, metallics, and pearls.

is selected, it is loaded into the software suite for analysis, modification, and visualization.

The Virtual SpectraMaster Color Library follows the intuitive hierarchical organization the physical book uses. The colors are divided into two main sets: solids and metallics/pearls. Metallics and pearls are grouped together, because it is not apparent if a paint is a metallic or a pearl just by looking at it. Each set is further divided into chromatic colors and neutral colors. The chromatic colors are divided by hue into blue, green, yellow, and red sets. The neutral colors are divided by value into light, medium, and dark sets; see Figure 4. This scheme facilitates finding and matching colors.

The software includes three check boxes to limit the selection of colors to solids, metallics, and/or pearls. The software also provides sliders to set upper and lower bounds on three metrics specific to metallic colors: Flop Index, Hue Shift Index, and Chroma Index. The three metrics can be used individually or together to narrow the selection of colors in the database. Each metric corresponds to a change in color appearance (brightness, hue, or chroma) due to metallic travel.

The Flop Index gives a measurement of the magnitude of travel for a metallic color.^{19,28} It is a metric computed from the L dimension (luminance) of the three standard aspecular Lab measurements of a paint. The equation for the Flop Index is given as

$$\text{Flop Index} = \frac{2.69(L_{15} - L_{110})^{1.11}}{(L_{45})^{0.86}}.$$

Solid colors have a Flop Index of 0 because L_{15} and L_{110} for solids are identical. All metallics have a Flop Index above zero. The average Flop Index in the database is 11.38. Over 96% of colors have a Flop Index between 0 and 20. The graph in Figure 5 illustrates the distribution of flop indices for the solids, metallics, and pearls in the database. Most colors with

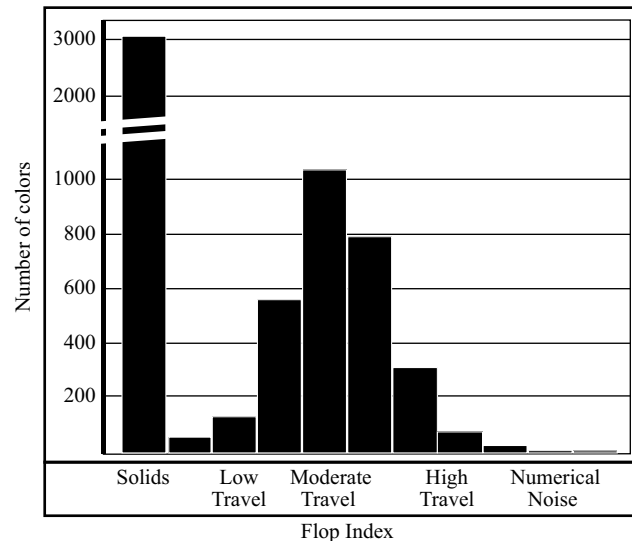


Figure 5. The distribution of flop indices for the solids, metallics, and pearls in the SpectraMaster database. Solid colors have a Flop Index of 0. Ignoring solids, the average Flop Index in the database is 11.38. Over 96% of colors have a Flop Index between 0 and 20.

Flop Index beyond 25 are the result of numerical instability of the formula for very dark colors.

Taking this into account, the Flop Index can be used to limit the colors by magnitude of travel in luminance. For example, bounds on the Flop Index sliders could be set to be between 3 and 10 to get colors with moderate luminance travel. If the bounds are set to be between 17 and 25, the selection will only include colors with more extreme travel.

Since the Flop Index is computed exclusively on the luminance dimension of the BRDF, it cannot distinguish colors that have high or low travel in chroma or hue. In this document we present two new metrics to rank colors by color travel and hue travel. Ignoring the brightness (L component) of the Lab aspecular measurements, only the a and b values of the color at face and flop are considered in the calculating the Chroma Index and the Hue Shift Index. Both of these formulas compute in units of $Lab \Delta E$.

If a paint has color travel, the Chroma Index provides a measurement of the paint's change in saturation across viewing angles. To compute it, the Chroma Index is simply the absolute difference of the chroma of the color measured at 15° and the chroma of the color measured at 110° . This is an index of the change in saturation that is not affected by the change in brightness or hue with respect to reflection angle. The equation is shown as

$$\text{Chroma Index} = \left| \sqrt{a_{15}^2 + b_{15}^2} - \sqrt{a_{110}^2 + b_{110}^2} \right|.$$

Another dimension that a metallic paint can travel in is hue. The Hue Shift Index provides search control over hue shifting colors. If a paint has a color shifting effect pigment, the hue at the face will be different than the hue at the flop. The formula for the geometric distance from a point to a line is used to compute the Hue Shift Index. To compute the Hue

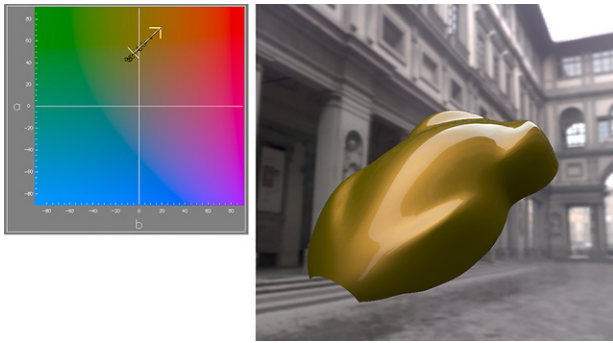


Figure 6. This shows YM144 that has a fairly high Hue Shift Index of 12.6 ΔE . The start and end of the ab plot have different hues.

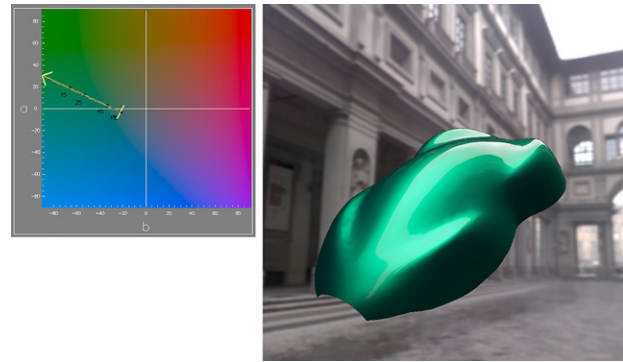


Figure 8. This shows GM044 that has a Chroma Index of 46 ΔE .

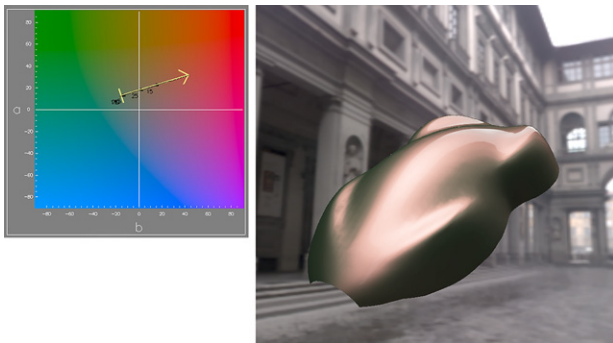


Figure 7. This shows GM027 that has an extreme Hue Shift Index of 19.8 ΔE , as illustrated by the off-radial projection on the ab plot.

Shift Index, measure the distance between the ab_{110} color to the nearest point on a line projected from the origin through the ab_{15} color. Although this works well for many hue shifting pigments, this metric will fail on extreme colors that rotate nearly 110° around the hue circuit, such as interference based paints and situations where the face color is achromatic. The equation for the Hue Shift Index is shown below.

$$\text{Hue Shift Index} = \frac{|a_{110} * b_{15} - a_{15} * b_{110}|}{\sqrt{a_{15}^2 + b_{15}^2}}$$

The upper and lower bounds on the metrics can be used to explore the SpectraMaster library. To find hue shifting colors we limit the search to colors with a high Hue Shift Index. Figure 6 shows a color coded YM144 that was found to have a fairly high Hue Shift Index of 12.6 ΔE . Figure 7 shows the color coded GM027 that has an extreme Hue Shift Index of 19.8 ΔE . To find colors with a lot of color travel, we limit the search to have a high Chroma Index. Figure 8 shows a color that is coded GM044 that has a Chroma Index of 46. The search metrics can be combined. When searching for colors with high Flop Index but a low color travel we found BM304, which has a moderately high Flop Index of 16.6 but a low Chroma Index of 5.6 ΔE , as shown in Figure 9.

PROTOTYPING AND MANUFACTURE

To turn the digital representation for a design into a prototype or an actual product, a CAD system must have access

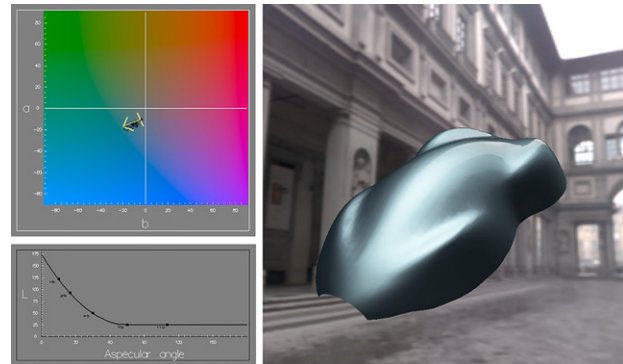


Figure 9. This shows BM304 that has a higher Flop Index of 16.6 but a low Chroma Index of 5.6 ΔE . The travel in brightness is seen in the L plot, while the lack of chroma travel is seen the ab plot.

to rapid prototyping technology. The ColorNet[®] software developed by DuPont Performance Coatings was used by our color appearance CAD system to determine paint formulations for the reflectance specifications created using the design interfaces described above.

ColorNet

ColorNet is DuPont's software for formulating automotive paint in their refinish business. Typically this program is used to find formulas for paints that do not exist in the SpectraMaster database. For example, if the original color of a car has faded, the paint code specified by the vehicle's make and model would not be a good match. In this case, the paint technician will supply ColorNet with measured aspecular Lab values of the paint as well as the paint code for a near match of the color as a starting point for the reformulation. ColorNet will tweak the formulation of the start color until it finds a paint formula that will be a close match to the scanned aspecular Lab measurements.

We utilize ColorNet to create formulas for paints designed using the color appearance CAD software. The aspecular Lab values (the parameters from the reflection model) are required as well as a paint code to be used as a formulation starting point. The BRDF Design Suite outputs the aspecular Lab values as an XML file to be imported into ColorNet. Since the color may be designed from scratch, we

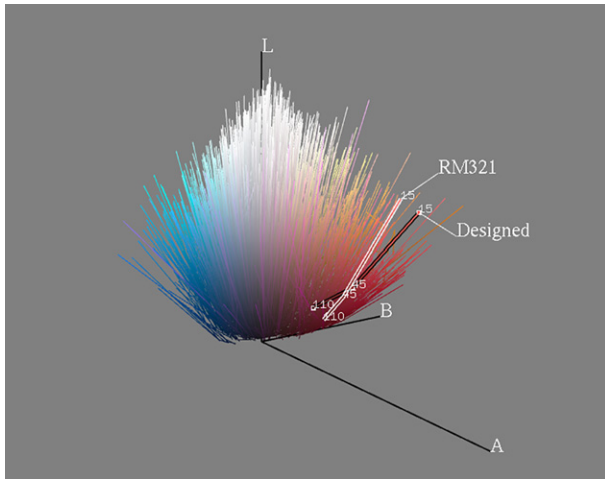


Figure 10. ColorSnap shows a designed metallic red relative to the nearest metallic color in the SpectraMaster database.

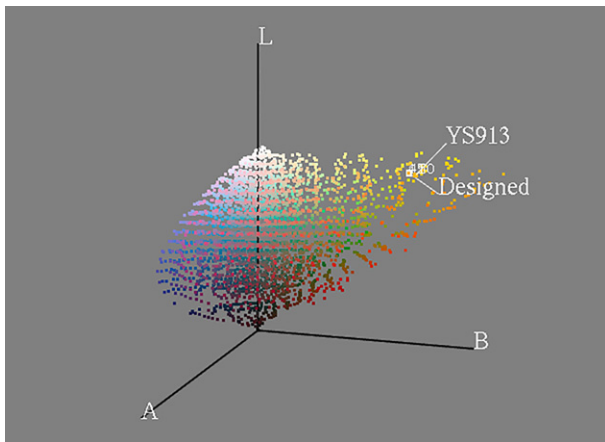


Figure 11. ColorSnap shows a bright diffuse yellow color design relative to the nearest solid color in the SpectraMaster database.

need to find the paint code for a close match. ColorSnap, described in the ColorSnap section, finds the paint code of the closest color.

ColorSnap

In order for ColorNet to formulate a paint designed from scratch, it needs the paint code of a similar paint to use as a starting point. We designed ColorSnap to solve this problem. ColorSnap finds the closest color in the SpectraMaster database to a designed color. It visualizes the designed color relative to the entire SpectraMaster database in a 3D graph.

Colors are plotted in *Lab* space. The nearest color is determined by finding the color in the database with the smallest total ΔE color difference at the three standard aspecular angles. Even though 6000 colors are searched, the result is found in real time. This is because of the simplicity of the reflectance model representation. Figure 10 shows a screen shot of ColorSnap in action. A designed metallic red is shown relative to the nearest metallic color in the SpectraMaster database. A bright yellow diffuse color's

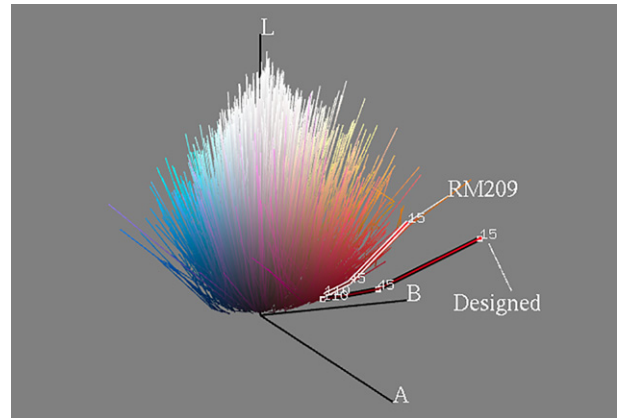


Figure 12. ColorSnap's visualization exposes a problematic color design. The designed color is too deep in saturation and shows up hanging far outside the range of colors in the collection. The nearest match, RM209, is the correct hue, but it is not chromatic enough.

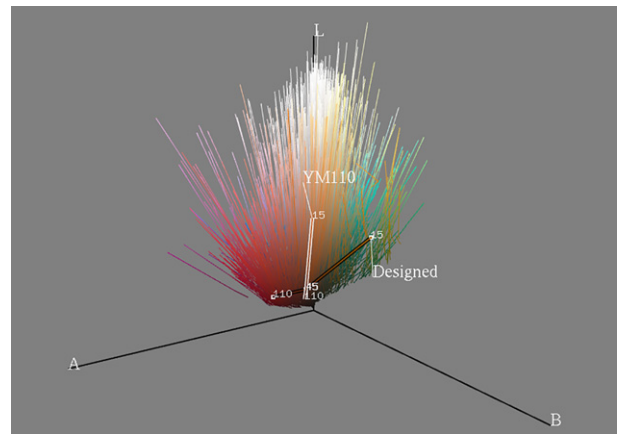


Figure 13. The designed color has an unusual off-radial travel. The closest match does not capture the hue shifting nature of the design.

design is shown relative to the nearest solid color in the SpectraMaster database (Figure 11).

In Figure 12, ColorSnap's visualization exposes a problematic color design. The designed color is too deep in saturation and shows up plotting far outside the range of colors in the collection. The nearest match, RM209, is the correct hue, but it is not chromatic enough. The designed color in Figure 13 has an unusual off-radial travel. The closest match does not capture the design's hue shifting nature. A paint chemist needs to be consulted to determine if this color can be manufactured with available technology.

The BRDF Viewer can render multiple colors on a single object. This is useful for comparing a designed color to the closest match in the database or a predicted match from ColorNet. In Figure 14 (left), ColorSnap's visualization reveals that a designed color has a brighter face and a darker flop than the nearest match. A rendering is used to evaluate the difference between the designed color compared to the closest match, RM331 (right image). Given RM331 as a starting point, ColorNet will attempt to formulate a better match for the designed color.

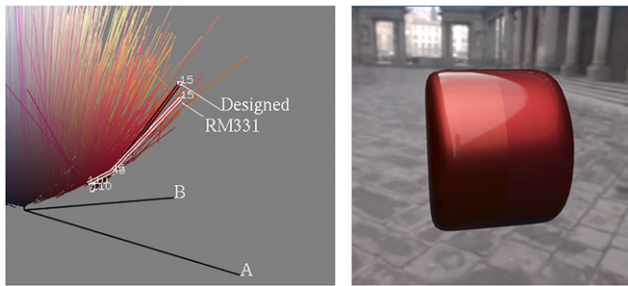


Figure 14. ColorSnap's visualization reveals that the designed color has a brighter face and a darker flop than the nearest match (left image). The rendering shows the designed color on the left side of the cylinder and the closest match, RM331, on the right side of the cylinder (right image).

RESULTS

Informal tests were performed by using the system in two different design environments. The experiment with the College for Creative Studies involved creating colors for an entire classroom of students studying automotive design. The experiment at Ford's automotive design center was done using only the paint systems found on their site.

Ford Product Development Center

Two tests were performed using members of the professional automotive design staff at the Ford Motor Company in Dearborn, Michigan. An initial experiment, done at the headquarters of DuPont Performance Coatings in Troy, Michigan, involved the creation of three new paint colors. The hue of an existing blue metallic paint was shifted toward green, the lightness of another blue metallic paint was increased, and gold highlights were added to the travel of a red metallic paint. These paints were formulated, mixed, sprayed, and evaluated at DuPont's labs. The satisfactory results of this experiment have been previously documented in Ref. 25.

In a more recent test, a new paint color was designed right on Ford's premises. The travel of an existing blue metallic paint (Figure 15) was decreased. DuPont used their software to determine the paint formula necessary to achieve the design intent, but the paint was mixed and sprayed at Ford. The whole process, performed during a meeting of Ford's color and trim group, took less than an hour. The outcome was judged to be adequate for initial design work by the design professionals who participated.

College for Creative Studies

The software was used by the students in a one-term Junior level transportation design class at the college for creative studies (CCS) in Detroit, Michigan. CCS is one of the premier automotive design schools in the world, and the design project undertaken in each course is sponsored by a major automotive manufacturer. In this particular class, Toyota asked the students to create a next-generation vehicle for their Scion brand. The students were responsible for the complete development of their design, from concept art that defines the initial shape and form of the vehicle, through



Figure 15. Ford design center color test.

tape drawings that are used to refine the lines of the car, to a final one-quarter-scale clay model that is finished using automotive paint. The students in the class were given the option of selecting their paint color using our software tools or by working with traditional paint chips.

The students primarily employed our software to visualize the small physical color samples in the SpectraMaster Book (see Virtual SpectraMaster Color Library section) on a 3D form. Many of the students who started the color selection process from scratch found it useful to first browse through the real SpectraMaster Book to identify a range of interesting colors. They were then able to refine their selection by working with the Virtual SpectraMaster Color Library (see Virtual SpectraMaster Color Library section) to pick specific colors and by using the BRDF Viewer rendering engine to observe the color on a 3D form. Fig. 1 shows a color that was selected by using this process.

Some of the students had very specific ideas about the colors that they wanted to use for their designs, and a few of them had artwork or pictures that illustrated the desired color appearance. The software did not contain the artistic color styling tools described in this document or²⁶ at the time that the experiments were performed at CCS. This made it necessary to visually match the colors in the students' pictures with the available colors in the Virtual SpectraMaster Color Library.

A few students attempted to create custom colors by using the basic BRDF Design interface described in Ref. 24. In most cases this was accomplished by making a small adjustment to an existing color in the SpectraMaster Color Library. The desired CIE *Lab* values at specific reflectance angles were output by the BRDF Designer program and were passed to the DuPont ColorNet software (see ColorNet section). It was not possible to determine a paint formula for each of the designed colors.

CONCLUSIONS

In this study, digital color design tools were connected with paint formulation systems to create a rapid color prototyping system for metallic automotive paints. The Virtual SpectraMaster Color Library provides both a traditional interface for browsing the colors and advanced filtering capabilities. Another tool, called ColorSnap, visualizes designed colors relative to the rest of the SpectraMaster database and finds starting points for the paint formulation system. Finally, an experiment showed the rapid color prototyping in action in a real design environment.

Rapid color prototyping enables us to create new solutions to problems faced by the color appearance industry. One issue confronted by color stylists is that the current breed of color appearance CAD tools are too technical. These tools are unable to leverage the unique creative skills of many color stylists who have been trained in the traditional creative fields such as fashion design, industrial design, or the traditional arts. The traditional creative processes employed by color stylists in the industry today has inspired the artistic electronic design tool described in the sketch based color styling section. The surface finishes designed with this innovative tool can be rapidly prototyped using the system described in this section.

In its current form, our system has a couple of limitations. When this research was initiated, a standard had been written for measuring only metallic automotive paints.³ Even though interference pigments were not included, they were still evaluated using the metallic standard, and we have also successfully applied our system to many pearlescent paints. Future CAD systems for automotive color styling should incorporate the recent standard for characterizing paints with interference properties.²³ Our system is also limited in that it cannot automatically predict when a design can be manufactured. Forecasting this at interactive rates remains an open research question. Finally, we only consider the base metallic layer paint layer in this work, and we ignore design issues, such as gloss and orange peel, related to overlying clearcoat.

The future may include color appearance CAD systems for all types of material design, including plastics, glass, textiles, wood stains, and other nanotech surface finishes. In order to be truly useful, these color appearance CAD systems will have measurement, visualization, analysis, design, and rapid color prototyping tools. Color, texture, and appearance will be manipulated at macro, meso, and microscopic detail levels. Finally, rapid color prototyping will be integrated into 3D printers to create physical objects, complete with surface finish, from electronic designs. The future of color finishes in industrial design is very bright.

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