PREDICTING AND FIXING GEOMETRIC COLOR MISMATCHES

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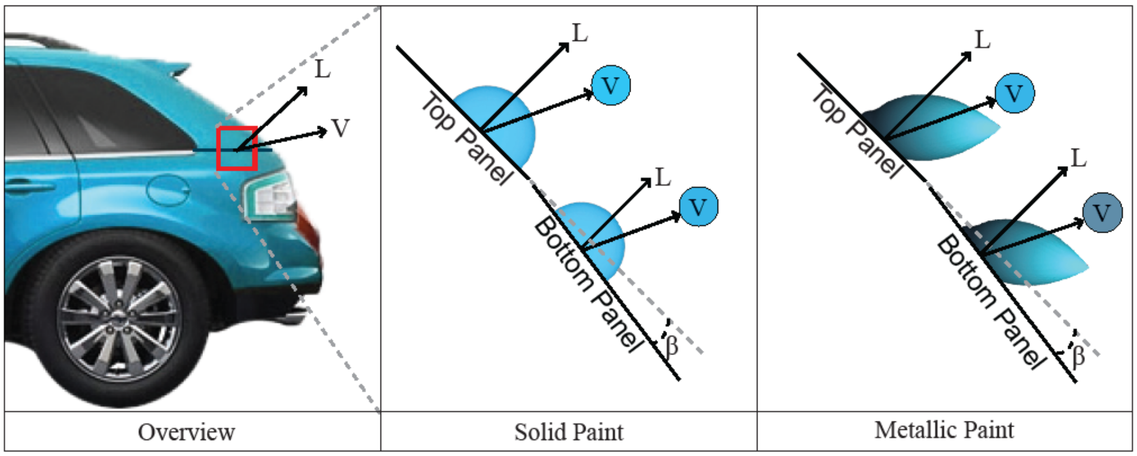

Figure 1: Color difference occurs between misaligned body panels. Because color and intensity vary with reflection angle for metallic and pearlescent paints, the effect is stronger for these goniochromatic colors (right) than for solid colors (center).

ABSTRACT

Color mismatches that result from geometric misalignment are studied. Differences in color can result when adjacent parts of an object are coated with the same paint but are not aligned to create a continuous geometric surface. The color difference that results due to shading can be accentuated by the use of metallic and pearlescent paints with goniochromatic properties. A metric is developed for determining when the color difference is large enough for the misalignment to become apparent. A technique is also presented for selecting a paint that matches the adjacent part and creates the illusion of geometric continuity even though the two parts are misaligned.

Keywords: color measurement, color difference, goniochromatic, computer graphics

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INTRODUCTION

Industrial designers often use metallic paints to enhance the appearance of curvature in products. Most notably in the automobile industry[1], but also other consumer markets including personal electronics, household appliances, and architectural finishes[2]. However, a metallic paint's exaggeration of curvature can induce unexpected color matching problems. Since the color of the reflected light changes with the angle of reflectance, an objectionable color mismatch is sometimes noticed at a joint where two panels meet at a slight angle. Even though the two panels are painted identical colors, a mismatch is still seen (see Figure 1). The color mismatch comes from a difference in lighting and viewing geometry. This problem is more noticeable on certain colors and on certain cars. Solid colored paints exhibit the issue, but to a much lesser degree, because light reflects uniformly across viewing angles. Metallic paints are called goniochromatic because the appearance varies with lighting and viewing angle. This document refers to the color difference due to geometric misalignment as a *goniogeometric color mismatch*.

This paper proposes a new metric, the *goniogeometric index*, for ranking and predicting the magnitude of goniogeometric color mismatches on particular paints or particular geometric designs. It also introduces a new technique, inverse *trompe l'oeil*, for fixing goniogeometric color mismatches.

BACKGROUND

A variety of color difference metrics and color indices have been proposed and are used by industry to objectively determine when material pairs will exhibit noticeable mismatches in color appearance. However, most of these color difference metrics and indices have ignored the spatial aspects of color appearance and thus have been limited to the analysis of solid color.

Many materials are unlike solid colors and have the property, called goniochromism, where the appearance changes with viewing angle. To fully characterize these gonioapparent materials, a specialized instrument called a goniospectrophotometer takes multiple color measurements at various lighting and observation angles.

In computer graphics, material reflectance is represented by a Bidirectional Reflectance Distribution Function (BRDF). A BRDF is a function which describes the ratio of incoming light to outgoing light for every possible incoming and outgoing light direction. This is the most general way of specifying surface reflection. Pictures of objects illuminated by a point light can be generated by using a shader to evaluate a parametric form of the BRDF.

GONIOGEOMETRIC INDEX

As described in the introduction, a goniogeometric color mismatch is a color mismatch between two objects, with identical reflectance, that are geometrically misaligned. Although the color and reflectance of the objects are identical, the color difference comes from the objects being lit and viewed from slightly different angles thereby causing the viewer to see dissimilar portions of the material's reflectance lobes. The issue of goniogeometric mismatch is a subtle problem facing designers today. When a manufactured product exhibits goniogeometric mismatches, people may notice a problem but incorrectly diagnose it.

We will illustrate the issue using a car bumper that exhibits a goniogeometric mismatch relative to the adjacent front-end panels of the car. A quality assurance technician may assume that the color mismatch problem is from the paints not being formulated correctly and order the car to be repainted-especially if the bumper and front end were manufactured on separate days or in separate factories. A customer evaluating the car for purchase may be suspicious that the car was in an accident and repainted incorrectly. A color scientist may hypothesize that the two parts exhibit goniometamarism[3], but measurements with a multi-angle spectrophotometer could miss the problem altogether.

Formulation

In order to characterize goniogeometric color mismatches, this paper proposes a simple metric, titled the *goniogeometric index*, for ranking and approximately predicting the magnitude of this issue for a particular paint or a specific geometric design. Instead of a difference in ΔE that the CIE Lab color difference metric measures, the goniogeometric index measures, in degrees, the minimal angle of geometric misalignment needed to create a certain level of ΔE difference. That level would typically be a just noticeable difference or one JND.

Imagine two panels of the material in question joined at an adjustable angle β degrees. Given the specific material, with reflectance function f, illuminated under a particular lighting Ω and viewing geometry $\vec{\Psi}$, the goniogeometric index is the minimal angle of geometric misalignment β_{min} needed to create a certain amount of color difference.

To assist with the evaluation of the reflectance functions we reframe how the BRDF is calculated. Geometrically rotating an object by β degrees is equivalent to keeping the object fixed and rotating the lighting and viewing geometry by β, denoted by Ω_β and $\vec{\Psi}_\beta$.

In order to keep this metric as useful as possible, we propose the metric in a generic way that can be applied in a number of specific situations. Note that lighting Ω_β could either be a specific lighting angle or a global lighting environment. The viewing geometry $\vec{\Psi}_\beta$ could be any viewing angle or angles. The reflectance function of the material, f, can be any BRDF. The variable denoting the color difference threshold, ε, is measured in CIE ΔEs, but can be more or less than one JND depending on the application of the metric.

The color difference between color of the object at the original and rotated geometries is a ΔE difference and is computed with a ΔE function. The equation below shows the generic formula for the goniogeometric index. The large vertical bar denotes a mathematical constraint on the minimum value of β, namely the goniogeometric index is computed by minimizing β subject to the constraint on the right hand side of the equation.

$$\beta_{\min} = \min \beta \;\Big|\; \Delta E\left(c(f,\Omega,\vec{\Psi}); c(f,\Omega_\beta,\vec{\Psi}_\beta)\right) \;\geq\; \varepsilon$$

In this expression, $c(f,\Omega,\vec{\Psi})$ is a function that determines the color for each panel given the BRDF, the lighting, and the viewing circumstances. For the simple case where there is a single viewing direction $\vec{V}$ and a single light source in direction $\vec{L}$ with intensity I, the value of c is determined as follows:

$$c(f,\vec{L},\vec{V}) = I \;\; f(\vec{L},\vec{V}) \;\; \vec{L} \bullet \vec{V}$$

where $\vec{L} \bullet \vec{V}$ is Lambert's cosine law.

Application to solid paints

Before we move on to complex materials, we first apply the goniogeometric index to solid paints. In the case of solid paints, the assumption is that light reflects uniformly in all directions. The only change in color is the shading due to the lighting angle. This change in reflectance is very gradual and is approximated by Lambert's cosine law. It does not matter what angle you look at the material from-you observe the same color. For a simple lighting and viewing circumstance

$$I \;\; f(\vec{L},\vec{V}) = \overline{C}_{\text{diffuse}}$$

in the above expression for c. Because there are no inter-reflections, the product of the light source intensity and the BRDF yields a constant CIE Lab value after tristimulus integration is performed.

(Note that this research discounts the color of the specular highlight because the highlights do not need to line up across a seam in order for the color of the material to match. We think that this is a reasonable assumption and doing so simplifies the calculations.)

To apply the goniogeometric index on a solid paint, assume an industrial designer is creating a product that is painted a solid color. The manufacturing specification dictates that the exterior shell is manufactured as two panels that meet together at a seam. Because of the manufacturing process, the seam is not exactly flush, but has a minor angle, and we want to set a manufacturing tolerance for the design. The ideal would be that the panels meet perfectly flush, but we want to know how misaligned they can be before a difference is noticeable – we want to compute the goniogeometric index.

Application to metallic paints

In this section, we apply the goniogeometric index to metallic automotive paints. In the case of materials that have non-trivial reflectance, computing the goniogeometric index is more complex than for solids. The appearance of a metallic varies with both lighting *and* viewing angle. To compute the goniogeometric index we need the formula for reflectance, and we need to specify lighting and viewing geometries as well as the threshold of color difference.

Ignoring gloss, the product of the intensity I and the reflectance f of a metallic automotive paint is approximated using the parametric form of the metallic reflection model found in our previous work[4,5,6], which is based on the work of Alman[7] and Rodrigues[8]. The color of the metallic is represented by a few variables that correspond to the face($\overline{C}_{\text{face}}$), flop($\overline{C}_{\text{flop}}$), and travel($\theta_{\text{flop}}$) of the color. In terms of the previous expression for c:

$$I\ f(\vec{L},\vec{V}) = g(\vec{L},\vec{V},\overline{C}_{\text{face}},\overline{C}_{\text{flop}},\theta_{\text{flop}})$$

g evaluates a second order polynomial that goes from $\overline{C}_{\text{face}}$ at 0 aspecular angle to $\overline{C}_{\text{flop}}$ at θ_{flop} aspecular angle. g returns $\overline{C}_{\text{flop}}$ for aspecular angles greater than θ_{flop}. Just like the diffuse calculation, because there are no inter-reflections, the function g yields a CIE Lab value.

(Note that this research currently only considers in-plane reflections from metallic paints.) The situation that this formula is emulating is as follows. The point light illuminates two panels that are painted identically but geometrically misaligned. We want to know how far the panels can be out of alignment before a color difference of one JND (2.3 ΔEs) is observed.

Figure 2 illustrates how the goniogeometric index can be determined graphically for a metallic paint. Each curve shows how the color difference between two painted panels varies as a function of the viewing direction, $\vec{V}$, from which the panels are observed, the lighting direction, $\vec{L}$, from which the panels are illuminated, and the amount of misalignment, β, between the panels. In this case, to find β graphically, one selects the curve which is below the acceptable color difference threshold for some range of possible viewing and lighting directions. The misalignment angle β associated with this curve is the goniogeometric index.

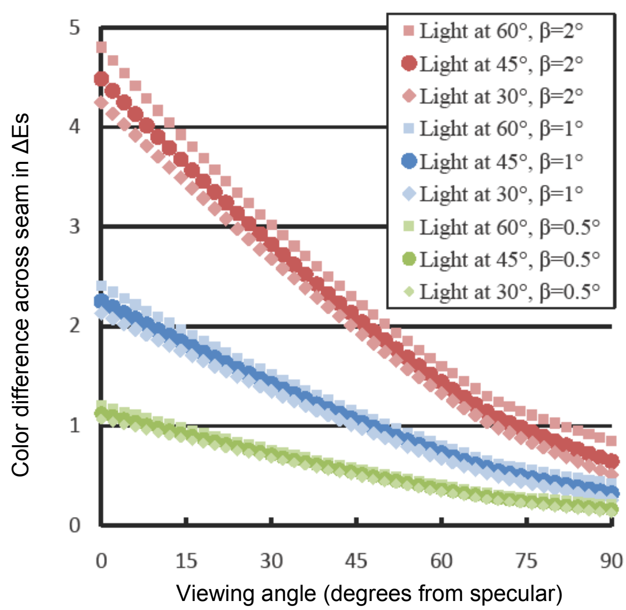

Figure 2: Variation of color difference between panels as a function of viewing position, light source position, and geometric misalignment.

INVERSE TROMPE L'OEIL

Trompe l'oeil designs make flat architectural interior elements look like complex three dimensional shapes. French for "to trick the eye", trompe l'oeil designs[9] actually go back to the Romans who decorated walls with simulated columns and open windows. Although some designs create striking three dimensional deceptions intended to capture viewer's attention, other trompe l'oeil designs are so good that they may be overlooked as the real thing.

In the same way that traditional trompe l'oeil creates the illusion of curvature on a geometrically flat object, this section proposes *inverse trompe l'oeil* to suggest flatness across a geometrically creased object. This idea is offered as a potential solution to certain cases of the geometric color matching problem in which two panels are joined together at an angle and create an apparent color difference. Two panels that come together at an angle can be painted slightly different colors to account for the change in reflectance due to lighting or viewing geometry. How exactly should the color be tweaked to reduce the color difference across the seam?

We seek to minimize the difference in color reflected from the surface by posing this question as a mathematical minimization problem. Although it is impossible to completely eliminate color difference from all lighting and viewing angles, we can minimize color differences over a limited set of lighting angles and a limited range of viewing angles.

Diffuse paints

In Figure 3, a scene is constructed as a test bed for illustrating different optimization heuristics for applying inverse trompe l'oeil to solid colors. The figure shows a grid of colored panels. The top and bottom halves of each panel are geometrically misaligned by 3 degrees. A simple point source lights the panels at 0°, 15.5°, 29.1°, 39.8°, 45.0°, 52.0° from normal (top to bottom rows).

The leftmost column shows the control case where the top and bottom sections of each panel are painted the same color. The color difference across the seam of each panel is a result of shading differences due to misalignment of the panel halves.

The remaining columns are painted using the idea of inverse tromp l'oeil. In the second column, we compute a new color for the bottom half of the panels, using an optimization routine that minimizes the ΔEs color difference across the seam at a 45° lighting angle. Employing parametric forms of the BRDF to calculate the ΔEs color difference, we use the solver functionality in Microsoft Excel[10] to determine the parameters of the reflection model. In the case of a solid color, the reflectance is uniform across viewing angles and only changes with lighting angle. Therefore, the system is able to find a perfect match at 45.0°, but the quality of the match fades off as the lighting angle moves away from 45.0°. The match is quite poor at 0°, about 2 ΔEs.

In the third column, the optimization heuristic solves for the RMS error of the color difference across all of the seams in the column combined. In effect this reduces the color differences across the seams while avoiding any excessively poor matches. In this case the worst error is about 1 ΔEs.

In the final column, we create a separate paint for the bottom half of each panel by solving for each row independently. The solver found six inverse tromp l'oeil colors that effectively eliminate the appearance of the geometric misalignment.

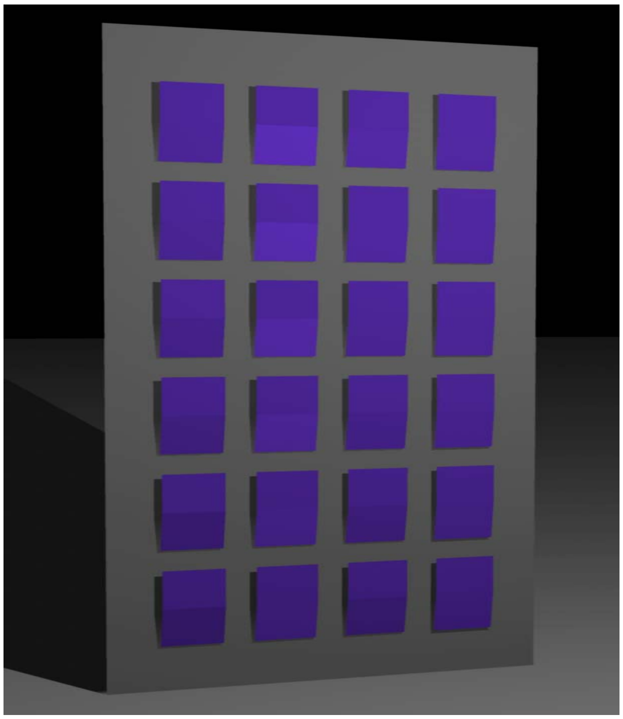

Figure 3: Determining a solid color for the bottom half of each panel that matches the top half of the panel even though the two halves are misaligned by 3 degrees. Each row represents a different light source direction and each column a different solution technique. See text for details.

Metallic paints

In this section we apply the idea of inverse trompe l'oeil to a metallic paint reflection model. Because the reflectance of metallic paints varies with lighting and viewing angle, there are more constraints on the solution. However, because the metallic reflection model has more parameters, it can be fit at more angles.

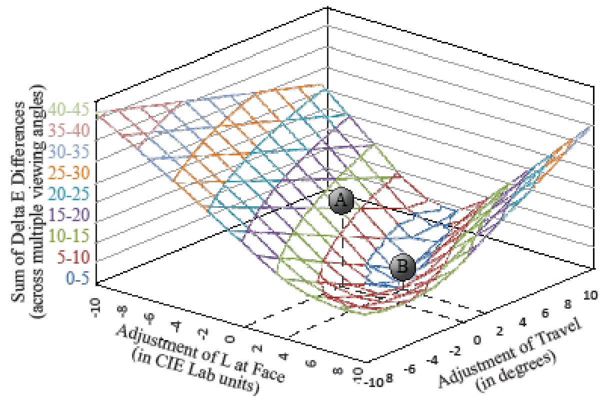

Figure 4: Finding a silver color that matches another silver color even though the two paints are on panels that are misaligned by 3 degrees. Color difference A results when the paints are identical, and the decreased color difference B occurs when there are dissimilarities between the face color and the travel for the two paints.

Consider the simple example of a silver paint with a black flop color (basic metallic reflection). In this case, because there is no chromatic travel, the face color CIE Lab L value and the amount of L travel are the only free parameters available to solve the inverse trompe l'oeil problem. Figure 4 shows how color difference varies with face L and L travel for a 2 degree geometric misalignment problem. The minimum delta E is easily found to occur when face L increases by 3.4 units and travel increases by 2.0 degrees.

A more complicated goniogeometric color mismatch problem is shown in Figure 5. Although the car on the left of the figure is painted with a single metallic paint, a goniogeometric color mismatch is visible across the seam between the bumper and fender. The car's bumper is not flush to the fender and exhibits a goniogeometric color mismatch. (In order to clearly illustrate goniogeometric color matching issues, this example uses an exaggerated misalignment of 8° to create a color difference that will be more visible.) The image on the right is geometrically the same as the left image, but the bumper is painted a separate color from the fender. The color of the bumper was chosen using inverse trompe l'oeil to create a visual match across a seam that would normally have a goniogeometric color mismatch. An optimization algorithm was used to find values that produced the minimum color difference.

A comparison of the original BRDF on the fender to the BRDF computed for the bumper is shown in Figure 6. The computed BRDF is brighter (to account for the difference in lighting angle). The difference is far more substantial in the “face” region than the “flop” region to account for the difference in aspecular viewing angle across the seam. The face color is brighter and more chromatic while the travel occurs over a slightly larger range of aspecular angles. The system calculated the optimal tangent point of the computed BRDF θ_{flop} to be approximately 8° more than the original BRDF in this example.

Figure 5: Bumper and fender misaligned by 8 degrees. Identical metallic paints cause a color mismatch (left) while painting the bumper a different color, determined using the inverse trompe l’oeil technique, eliminates the problem (right).

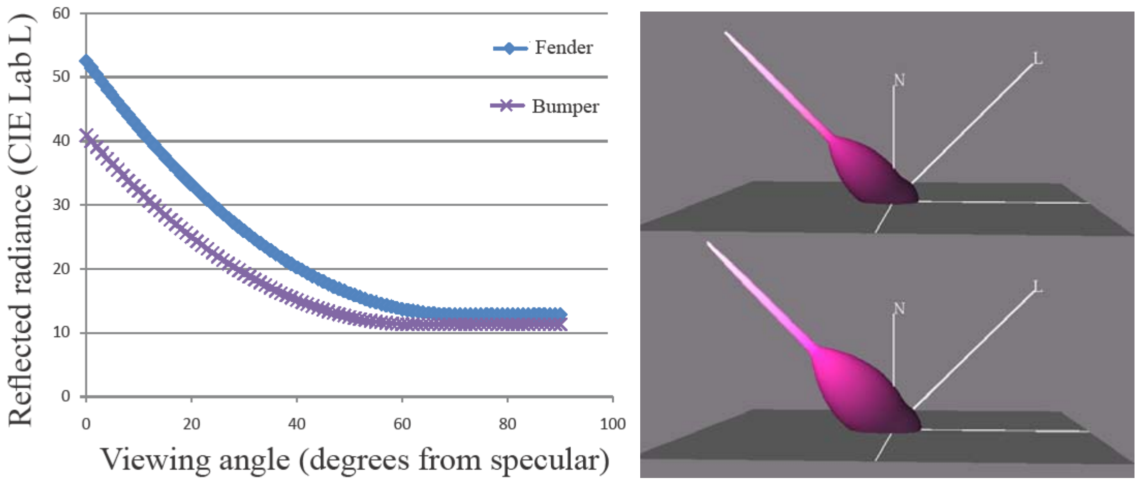

Figure 6: (left) Goniogeometric mismatch between the misaligned fender and the bumper in Figure 5 when they are both painted the same color. (right) Comparison between the BRDF for the original paint (top) and the BRDF for paint found using the inverse trompe l'oeil technique (bottom).

CONCLUSION

We conclude this document with a list of styling guidelines that, if followed, will help designers reduce the effect of color mismatches stemming from geometric misalignment of surfaces. 1) Choose high travel paints only when you can ensure that seams in flush panels come together precisely parallel. 2) Choose solids or low travel paints when seams are not flush. 3) Avoid placing seams in orientations that will be commonly viewed at low aspecular angles. 4) Set geometric manufacturing tolerances based on the types of paint being used and select paint based on the precision of the seams on the object. 5) Choose seams that limit the range of viewing angles, this reduces artifacts and opens the door for inverse trompe l'oeil type corrections.

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