Digital Image Analysis for Colorimetric Surface Inspection of Paint Coatings Stressed by Materials Testing

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Abstract

A method that allows an objective description of microscopic surface changes of paint coatings was developed for the quality assurance of paint and cleaning agent´s producers. Colorimetric and morphological features can be quantified by the method of digital color image analysis. The first step to apply this technique requires a systematic investigation of the color transformation properties with respect to the selected input/output devices used for digital imaging (flatbed scanner, CRT display). Next step is to develop a color management system. Therefore mathematical models of the color transformation processes were optimized and embedded in commercial color image analysis software. For an industrial application, such system allows the objective characterization and description of decorative quality of paint coatings after weathering. An extended version of this system is implemented successfully for quality control and certification of car washing stations and affiliated cleaning agents.

Introduction

Today, the quality of painted surfaces is evaluated mainly by visual inspection. However, quality assurance according to ISO 9001 requires suitable methods for relevant measurements of colorimetric and morphological properties. An efficient method to describe color related surface structures objectively is color image analysis, because conventional digital input devices for examination of surfaces can be used. For an industrial application, such a image analysis system was developed. This system allows the objective characterization and description of decorative quality of paint coatings after weathering. An extended version of this system is implemented successfully for quality control and certification of car washing stations and affiliated cleaning agents.

This color image analysis system described here is a low cost solution and meets economic needs of the SMEs, because only commercial software products and conventional digital input/output devices are used. Two problems arise: Firstly, the input/output devices (flatbed scanner, CRT display) require colorimetric calibration using a device independent color space, which allows an exchange of colorimetric data between them. Secondly, the spectral sensitivities of the detecting system are far off needed spectral sensitivities of correct colorimetric analysis. This may result in a more or less extended metameric effect. The solution of these problems is described.

Colorimetric Calibration of Scanners

Two flatbed scanners were investigated. They have optical resolutions of 2000 dpi x 1000 dpi (Linotype-Hell Saphir Ultra) and 1200 dpi x 2400 dpi (Quato x-finity pro 42) respectively.

The spectral sensitivities of the scanner detectors deviate from the color matching functions and, hence, cannot be used for direct color measurement. Moreover, the spectral radiance functions of the fluorescent lamps used for lighting deviate from standard illuminant D65 and may produce metameric effects[1] in samples under test. To cope with these problems colorimetric calibration should consider the spectral characteristics of these samples.[2] As the investigated automotive paint coatings were pigmented with modern lead-free pigments at hiding thickness a similarly pigmented atlas of a color order system could serve as reference. Therefore the RAL-Design color atlas,[3] consisting of 1687 color samples more or less uniformly distributed in CIELAB color space, was used as reference colors for calibration.

The spectral reflectance values of all samples of the RAL-Design atlas were measured with a Zeiss DMC25 spectrometer (45/0 geometry) followed by the calculation of tristimulus values (standard colorimetric observer CIE 1931, standard illuminant D65). Then all samples were presented to both scanners, and the digital output RGB-values were measured.

A relation between RGB-values and tristimulus values X, Y, Z was established. Based on different published analytical models[4-6] several polynomials up to third degree with variable numbers of coefficients and mixed terms for each tristimulus value were used. In general the results were improved by an increasing number of mixed terms. From these results polynomials with 14 and more coefficients (see Table 1) were systematically analyzed with carefully directed variation of mixed terms such as $\{1, x, xy, xyz, x^2, x^2y, x^2y^2, x^2yz, \ldots, x^3\}$ (1 means constant term, x means R, G, or B, xy means mixed term such as RG, or GB, etc.). The coefficients were evaluated using regression analysis over the 1687 reference colors for the relation between digital output RGB-values and measured tristimulus values X, Y, Z.

The 1687 samples of the calibration procedure were used to predict the model tristimulus values. Comparing them with the original tristimulus values, CIELAB color differences, averaged and standard deviations were computed. 21 BAM test colors, which were not used in the calibration procedure, were analyzed in the same manner, to provide an independent test of precision.

Results for different mathematical models under test are shown in Table 2 for the Linotype Hell Saphir Ultra scanner and in Table 3 for the Quato x-finity pro 42 scanner. Given are the averaged color differences $\Delta E^*_{ab,1687}$, standard deviations $\sigma_{ab,1687}$ and maximum color differences $\Delta E^*_{ab,max}$ of the calibration set (1687 samples), and the averaged color differences $\Delta E^*_{ab,21}$ of the test color set (21 samples) in each case. Table 2 shows for the Linotype-Hell Saphir Ultra flatbed scanner that the model with 3 × 18 coefficients is a good compromise between a small averaged color difference, a tolerable maximum color difference and a small number of coefficients. For the Quato x-finity pro 42 scanner the model with 3 x 19 coefficients including the mixed term *xyz* is selected for the same reason (see Table 3).

Table 1. Analytical models tested for scanner calibration.

Coefficient Matrix	Polynomial Types
3 × 14	$1,x,xy,xyz,x^2,x^3$
3 × 18	x,xy,x^2,x^2y,x^3
3 × 19[a]	x,xy,x^2,x^2y,x^3,xyz
3 × 19[b]	$1,x,xy,x^2,x^2y,x^3$
3 × 20	$1,x,xy,xyz,x^2,x^2y,x^3$
3 × 23	$x,xy,xyz,x^2,x^2y,x^2y^2,x^2y^2z^2,x^3$
3 × 24	$1,x,xy,xyz,x^2,x^2y,x^2y^2,x^2y^2z^2,x^3$
3 × 29	$x,xy,xyz,x^2,x^2y,x^2y^2,x^2yz,x^2y^2z,x^2y^2z^2,x^3$
3 × 30	$1,x,xy,xyz,x^2,x^2y,x^2y^2,x^2yz,x^2y^2z,x^2y^2z^2,x^3$

Table 2. Precision for recalculation of tristimulus values using different analytical models for the Linotype-Hell Saphir Ultra scanner.

Coefficient Matrix	$\Delta E^*_{ab,1687}$	$\sigma_{ab,1687}$	$\Delta E^*_{ab,max}$	$\Delta E^*_{ab,21}$
3 × 14	2.0	2.4	16.7	4.7
3 × 18	2.6	2.0	15.1	3.2
3 × 20	2.6	1.9	15.0	3.7
3 × 23	2.6	1.9	15.1	3.2
3 × 24	2.6	1.9	15.0	4.0
3 × 29	2.5	1.9	15.3	3.2
3 × 30	2.6	1.9	15.1	4.1

Table 3. Precision for recalculation of tristimulus values using different analytical models for the Quato x-finity pro 42 scanner.

Coefficient Matrix	$\Delta E^*_{ab,1687}$	$\sigma_{ab,1687}$	$\Delta E^*_{ab,max}$	$\Delta E^*_{ab,21}$
3 × 14	4.4	5.5	85.0	4.6
3 × 18	3.0	2.4	17.6	3.6
3 × 19[a]	3.0	2.3	15.8	3.5
3 × 19[b]	3.0	2.4	17.7	3.4
3 × 20	3.0	2.3	15.8	3.4
3 × 23	2.9	2.3	17.0	3.4
3 × 24	2.9	2.4	16.9	3.5

Color Image Analysis System

The commercially available color image analysis software Image-Pro Plus (4.0 and 4.1 respectively) of Media Cybernetics was installed on two personal computers with Microsoft Windows 98. The previously obtained analytical models of the flatbed scanners were inserted via a plug-in written in Microsoft Visual C++ 6.0. This color management system allows colorimetric analysis of digitized images of samples in a standardized color space (CIELAB or XYZ). Suitable mathematical models of CRT displays[7] for accurate color image reproduction were inserted in this color management system additionally. The quality of color reproduction of two analytical calibrated CRT displays was investigated by applying a test color method as is it known for television technique.[8] It has been shown that a color reproduction of 21 defined test colors (14 chromatic CIE test colors and 7 achromatic test colors of different lightness) with an averaged color difference down to 1.4 CIELAB units is possible.[9]

After calibration of the flatbed scanner not only shifts of colors in the image but also changes of color differences can arise due to metamerism. To learn more about such negative effects 56 weathered samples of the practical application of this image analysis system were chosen for colorimetric microanalysis. On each sample a small patch was selected for a colorimetric measurement using a Zeiss microscope spectrometer with a measuring field of 0.5 mm x 0.5 mm at 45/0 measuring geometry. In near vicinity (up to 2 mm apart) a second measurement was taken from the background under identical conditions and the CIELAB color difference between both was calculated. For the same positions the color difference was calculated from the image in CIELAB space using the averaged CIELAB values of the pixels over the area of the 0.5 mm x 0.5 mm field.

The averaged uncertainty of the imaged color differences for 56 pairs was rather small at 1.2 CIELAB units. However, the type of damages on the coatings largely influences the accuracy of individual color differences.

Applications

Quality Evaluation of Surface Defects on Weathered Paint Coatings

Method

Paint producers perform weathering test of paint coatings to examine the resistance against climatic influences. Paint coatings on aluminum change their morphological and colorimetric properties by natural weathering of several years. These consist of large colorimetric shifts (chalking, fading) and inhomogeneous optical fine structures on the surfaces (patches, clouds).

Visual Estimation of Damages on the Coatings

To describe the quality of the decorative appearance objectively, first, significant attributes and magnitude categories of the damages of the coatings have to be deduced in such a way that they are highly correlated with the quality judgments of experts. Therefore, a set of ten experts was asked for inspection and quality judgments of 150 selected weathered coatings. Ten employees of BAM performed the task viewing a sample in a color-matching booth with approximate D65 illumination under 45/0 geometry and a viewing distance of 50 cm. They had to perform judgments of patchiness and cloudiness according to DIN 53230[10] and ISO 4628[11] using a categorical scale from 0 to 5 that classifies magnitude of size, amount and discernibility. At the end a total judgment should be given using the same scale.

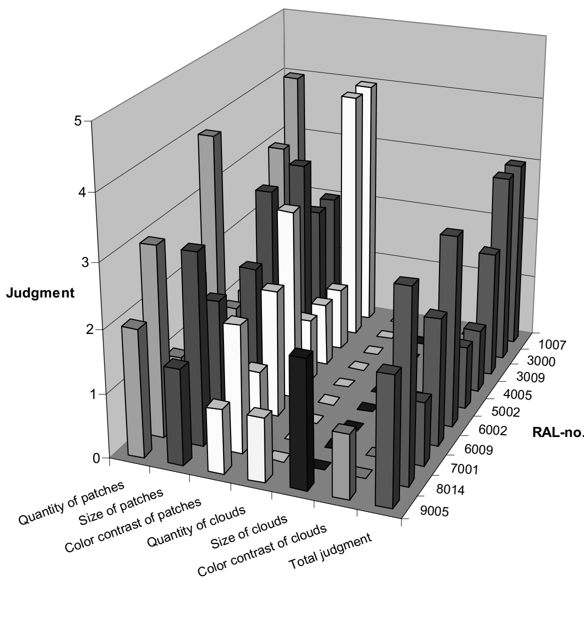

Figure 1. Results of visual judgment of 10 weathered paint samples after 5 years of weathering.

The results were statistically analyzed. Figure 1 shows an example for 10 samples of the coating system F that had been weathered for 5 years. The coatings are clearly stained, and three of them show slight cloudiness. The different colors of the samples are indicated by their number from the RAL 840 HR color register. They ranged from RAL 1007 (chrome-yellow), RAL 3000 (fire-red) to RAL 8014 (sepia-brown) and RAL 9005 (deep black). Judgments indicate the median scale values of all observers. The first impression is a clear differentiation of judgments over the series of different RAL colors. They are used to obtain appropriate attributes that may classify objective evaluation of the damages on the coatings by color image analysis.

Description of Staining

The weathered samples were scanned with a resolution of 250 dpi which allows analysis of structure down to 0.1 mm. Patches are separated from the homogeneous background in approximately uniform DIN99 color space[12] by applying histogram-based segmentation. Attributes of the damages of the coatings proved to be significant as follows:

- area of patches
- DIN99 color values of patches
- DIN99 color values of the background
- DIN99 color difference between patch and background
- number of patches in the area of interest (AOI)

An example of one coating is given in Figure 2. The left part shows an image of the tested surface with edge lengths of 13 cm and 9 cm. The large light and small dark patches are clearly visible. The right part shows a diagram presenting the color differences of the patches against the homogeneous background ($L^*_{99} = 56$, $a^*_{99} = 23$, $b^*_{99} = 6$) as function of patch sizes. Color differences extend between 4 and 13 DIN99 units at patch sizes up to 1.1 mm^2. 2.4 ‰ of the tested area of the coating was covered with patches.

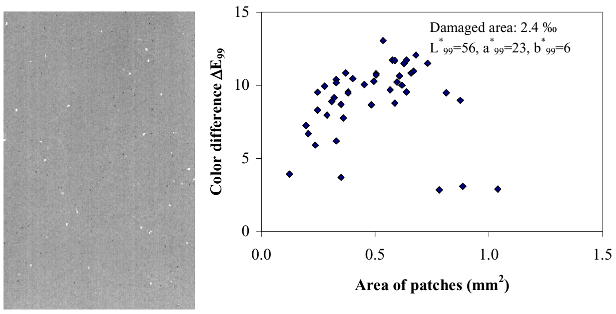

Figure 2. The left panel shows an image of patches on a weathered paint sample (RAL 3000) after 5 years of weathering. The right panel shows color differences between patches and homogeneous background versus size of patches of that sample. 2.4 ‰ of measured area are damaged by patches.

Classification of Staining

To classify the magnitude of staining a relation between visual judgments of three categories of defects (quantity, size and color contrast of patches) and the features measured by image analysis was established. For approximation of the three required analytical classifiers the following polynomial was used in each case:

$$f(\Delta E^{*}_{99,SP}, F_{SP}, n_F) = a \cdot (\Delta E^{*}_{99,SP})^{b} (F_{SP})^{c} (n_F)^{d} \quad (1)$$

The averaged color difference between patches and background $\Delta E^{*}_{99,SP}$, averaged area of patches F_{SP} and number of patches n_F of each sample are related to the corresponding visual judgment f of each category of defects by one coefficient a and three exponents b through d. The four constants were computed by general least square fit for the measured values and corresponding visual judgments of 150 chose samples. The performance of classification of all three defect categories is greater than 81%.

Results

The developed image analysis system allows the objective classification of staining of paint coatings after weathering in relation to judgments by experts. Furthermore, four significant texture attributes according to Haralick[13] were investigated for description of cloudiness. A sufficient correlation between visual judgments of cloudiness and attributes was not found.

Evaluation of Cleaning Efficiency of Car Washing Stations

Method

Cleaning tests on car surfaces, soiled in a defined way, were used for estimation of cleaning efficiency of car washing stations. Therefore, flexible magnetic foils with a thickness of 1 mm were varnished with automotive paint coatings. These parts were cut in stripes with a size of 160 mm x 60 mm. Later a field of 80 mm x 60 mm on each test stripe (sample) was coated with a defined pollution mixture of 0.02 mm thickness, similar to ÖNORM B 5106.[14] The content of used pollution mixture for simulation of car surfaces with a little oil coverage is shown in Table 4. Afterwards, the stripes were dried in an oven for 24 hours.

On different places on the car surface (trunk lid, hood, back doors) one of four samples was fixed. Then the prepared car was driven to the standard position according to instructions of the washing stations manufacturer. After standard washing procedure and drying process the test samples were picked up for evaluating.

Table 4. Content of used pollution mixture.

37 % white spirit	25 % quartz powder
15 % kaolin	15 % calcite powder
3 % activated carbon	3 % wool grease
2 % Vaseline	

Image Analysis

The four cleaned samples of each car were fixed side by side onto a special steel panel. As reference the panel includes 21 color patches made from paints on paper board (14 chromatic colors, 7 achromatic colors at approximately equal stepping, source: BAM). The output RGB-values of reference color patches were needed to control the reproducibility of radiant characteristics of the fluorescent lamp during repeated scans.

The panel including the four samples was scanned with a resolution of 250 dpi (Linotype-Hell Saphir Ultra) or 300 dpi (Quato x-finity pro 42) which allows analysis of structure down to 0.1 mm. Patches of remaining pollution were separated from the homogeneous background in CIELAB space by applying histogram-based segmentation. Significant attributes of the remaining pollution and color shifts of the coated stripes were the following measures:

- CIELAB values of the original material, never treated by soiling and cleaning (original area)
- CIELAB values of the first soiled and then cleaned area (measuring area)
- CIELAB values of the never soiled but cleaned reference area (reference area)
- CIELAB color difference between reference area and measuring area
- CIELAB color difference between original area and measuring area
- percentage area of remaining pollution inside the measuring area

Figure 3 shows an image of the mechanically cleaned surface onto a back door with edge lengths of 160 mm and 60 mm. The left, white bordered, rectangle is the first soiled and then cleaned measuring area. It contains 6.8% remaining pollution caused by wrong pressures of brushes. The right rectangle is the never soiled but cleaned reference area. Color difference between these areas is 1 CIELAB unit. Currently, washing stations with results of averages percentage area of remaining pollution of four samples less then 15% are certified for good cleaning efficiency. Color differences served for decisions at exceptional cases.

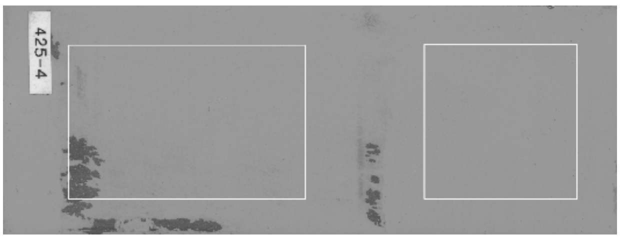

Figure 3. Image of a cleaned sample from a back door.

Results

Until now 58 car washing stations were tested, and 39 of them received an certificate. On 8 stations an optimization of the process parameters was necessary. After a second test the quality standards were obtained and a certificate could be received. The evaluation on nine stations is not jet completed.

The first results and the ones expected for the future are collected in a sample catalogue. This catalogue includes a database with images of samples with different degrees of remaining pollution, affiliated measurements and visual judgments of experts.

Based on this sample catalogue an improved color image analysis system for quality management of cleaning agents producers will be developed. This system should describe objectively the quality of the decorative appearance caused by distribution of remaining pollution and microscopic scratches. The metric parameters must be deduced for highest possible agreement with visual judgments of experts. The sample catalogue is necessary for investigating this correlation to classify the cleaning efficiency.

Moreover, the application of information technology provides additional advantages: modern electronic storage allows archiving imaged data for a long time at low cost and few losses. The data are easily transferable to other places in the world, e. g. via internet, and avoid unwanted changes on coated samples due to handling, storage, and long term fading. Hence, decentralized documentation and evaluation of coatings may be organized.

Conclusion

The inhomogeneous surface changes on paint coated samples after material tests were imaged in an approximately uniform color space with conventional input/output devices. To reproduce color differences on the samples as precisely as possible an extended color calibration was used. Color image analysis provides metric attributes of the surface changes, which can be used for quality assurance of paint and cleaning agent producers. These consist of a combination of color differences and geometric forms, which can be classified in relation to judgments of experts.

The described color image analysis system can be an important basic module for development of an improved quality assurance of painted surfaces according to ISO 9001.

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Biography

Carsten Steckert received his German Dipl.-Ing. degree in Physics in 1997 and a Dr.-Ing. degree in 2003 from the Technical University at Berlin. Since 1997 he has worked in the Laboratory S.13 ”Optical Measurement and Testing Methods; Reference Materials” at Federal Institute for Materials Research and Testing (BAM) in Berlin. His work has primarily focused on colorimetry, fluorescence measurements and digital color image analysis.