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Evaluating gonio-appearance in advanced printing materials with quality control procedures and instrumentation used for automotive coatings

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Abstract

The future and current digital economy and society is based on the perceptual choice by the consumer of many real objects (cards, cosmetics, toys, etc.), but increasingly from digital simulations with a great photorealism. Due to the existence on the market of new and sophisticated gonio-apparent pigments, with aesthetic and physic-chemical aspects changing according to the illumination and observation directions, nowadays, it is a current great challenge the simulation on digital media (displays, virtual reality, printing technologies), of objects, with different shape and size, with the maximum perceptual realism. Regarding printing technologies, above all multi-channel and 3D printing technologies, needs to be checked the actual and future capacities to be used in the automotive sector in order to get more colored plastic pieces (add-on parts for the car body) with the same or better aesthetic and physic-chemical features.

In this contribution, we will provide a general overview of a recent funded Spanish project called ADIREVGAO (Advanced DIgital REproduction of Visual Gonio-Appearance of Objects) for three years. One of the main goals of this project is to go into detail about the reproduction capabilities of the gonio-appearance on several printing technologies, above all on multi-channel inkjet and 3D printing (additive manufacturing, FDM technology).

Only the interplay of concepts and terminology (gonio-appearance, measurement geometries, etc.), in addition to available commercial instruments, color & texture quality control by models, and the characterization techniques, and guidelines for testing gonio-apparent 3D printed materials, will be shown in this work.

Introduction

Visual gonio-appearance of materials [1-3], or variation of visual appearance according to different combinations of illumination and observations directions, can be understood as an interplay of structural, physical, chemical, optical and visual variables taking into account top-down and bottom-up approaches (Figure 1). Different special-effect pigments (metallic, pearlescent, even diffractive) are extensively used nowadays in automotive coatings, but applying high-demanding and specific color and texture quality control procedures [4]. For this, some commercial multi-angle color measuring instruments and color differences and tolerances by AUDI2000 color difference formula [5] are commonly used. In addition, variable texture according to illumination & observation geometry as sparkle or glint (directional) and graininess or coarseness (diffuse illumination), or even gloss, are also measured and used for visual quality controls [6, 7].

In parallel, there are applications due to multi-channel inkjet technology. Even, there are several inkjet toners based on metallic pigments (Grace, Schlenk, Eckart, Roland, etc.), and even substrates with gonio-apparent finishing (Grace, Marrutt, etc.). On the other hand, 3D printing technologies (as laser sintering, FDM, etc.), or generically additive manufacturing, is at this moment a promising and disruptive multi-technology potential for many current or future applications [8-10]. Interesting prospective for the automotive sector using 3D printing technologies [11,12], based on many types of materials and hybrid technologies (photonics based on laser, microwaves, etc.), are also emerging in the last years.

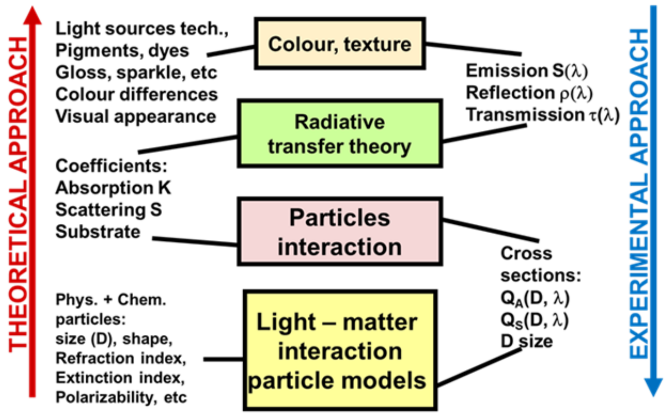


Figure 1*. Top-down vs. bottom-up approaches for understanding the interplay of physical and chemical variables on the visual appearance of materials. Applicable to multi-channel inkjet and 3D printing technologies.*

But, for both advanced printing technologies, there are nowadays some challenges to be overpassed as the limitation of the materials available in market, visual appearance of surface finishing [13-15], use of gonio-apparent pigments and their performance on physic-chemical features, etc., even comparing with current conventional coatings technologies for plastics and objects [16].

Fundamentals

The following sub-sections are shown to give an overview of current status of science and technology implemented in many coloration industries using gonio-apparent pigments, with special relevance in the automotive sector, where the color & texture (included surface gloss) quality controls are more restricted (that is, with very low tolerances) than those applied on other industries (coatings, plastics, printing inks, cosmetics, textile, etc.). Therefore, our main goal in this work is to show how we can extend or implement the current visual and optical metrology used in automotive coatings, with highly-demanding requirements in quality controls, to be applied on advanced printing materials, where increasingly the visual quality of the printed objects, both plane or curved, for any shape complexity, can be key to acquire and maintain competitive advantages in front of other competitor technologies.

Goniochromatism

Color is based on the light-matter-eye(brain) interaction, and the basic color attributes (lightness, colorfulness and hue) are extensively applied on any object, both with natural, handmade or artificial / digital origin. But, the basic optical properties of materials related to color, as spectral reflectance or transmittance, are shown a special behavior for gonio-apparent colors. Isotropic or solid colors show a constant spectral reflectance or profile regardless the measurement geometry (illumination direction vs. viewing direction). On contrast, the anisotropic or gonio-apparent colors show variable colorimetry according to the measurement geometry. We can easily distinguish between metallic and interference / diffractive colors, where the former show a visible lightness flop (i.e., variable lightness with constant colorfulness and hue), and the latter show a visible color flop (variable colorfulness and hue, and lower variable lightness). Then, any gonio-apparent color, according to CIE colorimetry, is not graphically encoded as an isolated point for all measurement geometries in any CIE chromatic diagram (Figure 2), as a solid color would be.
Due to structural variables (shape and size pigment particles, etc.) [4], these gonio-apparent pigments are like-flake arranged as best as possible parallel to the coating surface, so any variation in chemical additives, presence of other conventional pigments in the color recipe, application processes, etc., final visual appearance of the colored material (Figure 1) can be strongly influenced.
Nowadays, there some commercial color-measuring instruments able to characterize goniochromatism, and following some recommendations from international standards for optical set-up and selection of measurement geometries. However, these measurement geometries, usually six for metallic colors [21], and eight for interference colors [22], are not enough to know and manage the complete color gamut or palette corresponding to any gonio-apparent specimen [23]. This is caused by the hybrid color mixing, additive in near aspecular geometries and substractive far aspecular geometries, present in gonio-apparent colors, clearly more attractive for interference and diffractive colors. So, in many cases, partial colors, or specific measurement geometries, corresponding to the own color gamut of the gonio-apparent specimen, are outside the classical color limits or Rösch-MacAdam color solid [24]. For this reason, many international optical metrology institutes have developed complete multi-gonio-spectrophotometers, able to obtain the spectral BRDF (*Bidirectional Reflectance Distribution Function*) of any gonio-apparent specimen, usually modeled in simplified versions, though sometimes computationally complex, in computer graphics and rendering [25-27]. However, recently there are new evidences, based on optical principles, proposing a limited number of measurement geometries for estimating efficiently the sBRDF of any gonio-apparent specimen [28-30].

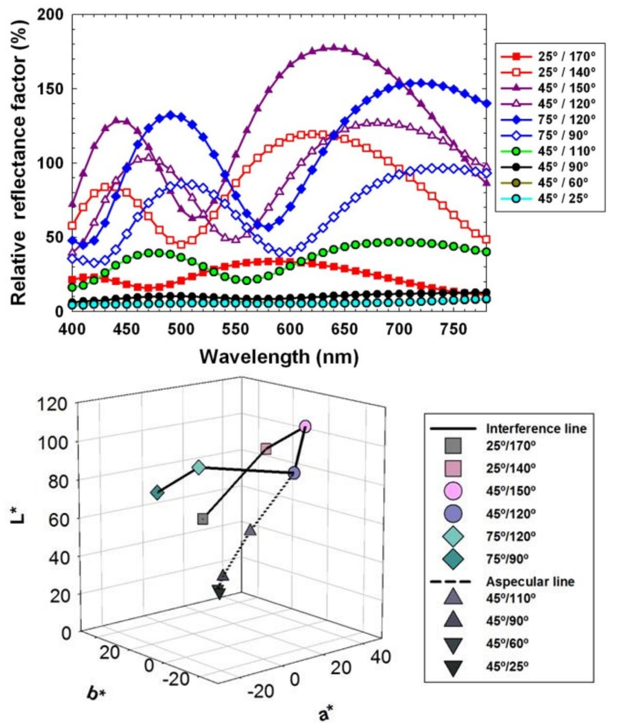


***Figure 2**. Example of pearlescent panel (Merck Colorstream ArticFire). Top: spectral reflectances using the multi-angle spectrophotometer Datacolor MFX-10. Bottom: corresponding limited gamut, or color travel, in CIELAB space.*

In printing, the gonio-apparent colors are used in many applications, but the goniochromatic pigments are difficult to manage efficiently in printing inks [31, 32], so it is more usual to include this color behavior in substrates (paper, etc.). But, this multi-challenge is partly covered with a current multi-national scientific collaboration from Europe by the project Colour Printing 7.0: Next Generation Multi-Channel Printing (CP7.0). So, many new scientific interactions and interesting results could be derived about goniochromatism for printing technologies, even in 3D printing, for the next decades.

Gloss

This is a visual attribute clearly related to the surface properties of the specimen and the measurement geometry. But, although the glossmeters are conventionally used in many industrial applications, even in printing [33] and automotive [34, 35], the recent evidences [36, 37] show that this visual attribute should be modeled by a multivariate function, and the current reference instrument, with other complementary surface attributes (DOI, haze, etc.), should improve its visual and instrumental correlation. This can be interesting even for previous studies about the gloss variation in plastics in front of several chemical and/or physical tests, as in ABS [38], typically used nowadays in some 3D printing technologies [39].

Texture: sparkle vs. graininess

Visual texture is nowadays other challenging topic in inter and multi-disciplinary sciences [40-42]. In the automotive sector, the visual textures in automotive coatings key to be combined for a visual harmony approach [43] of the car boy are sparkle (glitter) and graininess (diffuse coarseness). Both are measured by imaging techniques, and currently there is an only one reference instrument: BYK-mac-i®, by BYK-Gardner (Figure 3). Recently, there are some advances [44-46] in imaging techniques and alternative algorithms for the sparkle measurement, but till now for graininess. Sparkle grade value (S_g) is derived from two partial instrumental values (Figure 4), sparkle area (S_a) and sparkle intensity (S_i), extracted to the histogram analysis of the captured image in directional illumination, although multiplied for three measurement geometries, and keeping the monochrome digital camera in a perpendicular position to the specimen surface. On contrast, and using only diffuse illumination, and keeping the same position and direction to the same monochrome digital camera, the graininess value is directly obtained from a patented imaging algorithm.

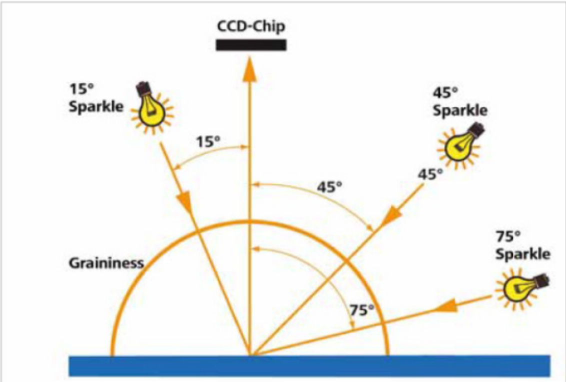


Figure 3. *Optical set-up of the BYK-mac-i instrument for the sparkle and graininess measurement.*

Visual appearance of these texture attributes, both in detection [47, 48], scaling and discrimination, is just starting to provide new interesting findings [7] to test the performance of the reference instrument used in the automotive industry [6]. However, the current trend is to focus firstly on sparkle instead of graininess, when in daily lighting conditions, there is a mixed combination of both visual texture appearances.

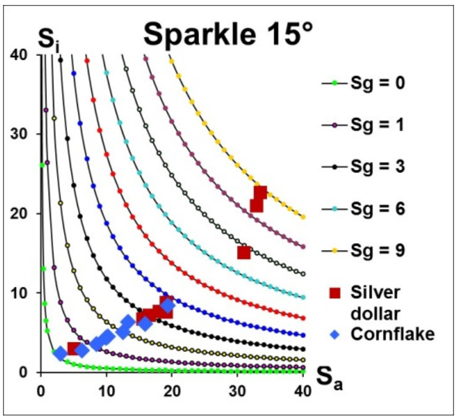


Figure 4. *Sparkle values, by BYK-mac-i, by the measurement geometry 45as45 or 15°, corresponding to some effect coatings based on metallic flakes with two different types and sizes (see below for additional information about the visual experiment, and its findings, using this panel set).*

So, in printing technologies, many opportunities can be developed this new visual texture instrument, even future ones, to manage efficiently the visual quality of printed materials [32], and not only for gloss.

Visual and instrumental correlation

In visual appearance of materials, the current and future challenge is the improvement of the visual and instrumental of future and current commercial color- or texture-measuring instruments. This involves to design and run psychophysical experiments for detection, scaling and discrimination tasks of color and texture appearance. And, to carry out this, it is necessary to use a calibrated lighting booth or cabinet [49]. A conventional diffuse lighting booth for color matching is not useful for gonio-appearance. So, only directional lighting booth is valid for this (Figure 5), both for goniochromatism and texture appearance assessments, even assisted by a tele-spectroradiometer located in the same position and direction as the human observer [5].

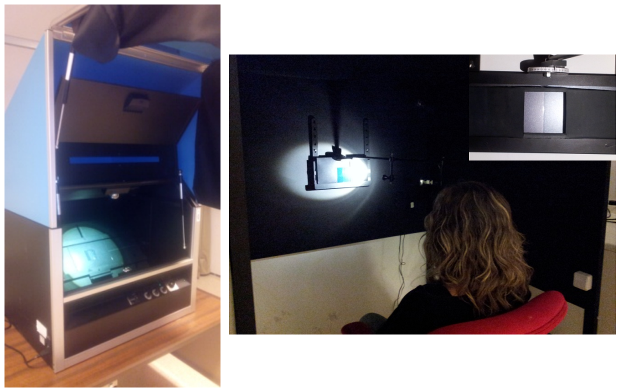


Figure 5. *Left: Byko-spectra effect cabinet®. Right: Alternative optical set-up of the directional lighting booth, with free measurement geometries, for the sparkle appearance assessments, both for detection, scaling and discrimination.*

Color differences for gonio-apparent specimens can be done in these special lighting booths, but following or implementing non yet official guidelines conventionally used in other coloration industries for color quality controls. For instance, the standard CIE ΔE2000 is not valid for gonio-apparent colors [50], and since many years the ΔE AUDI2000 is the most used color difference formula in the automotive sector, even applying color tolerances for final color harmony approval.

In visual texture, there is only a sparkle discrimination formula, with corresponding tolerances, proposed by BYK-Gardner. But, this, joint to gloss difference, and graininess difference, should be tested in current and future instruments. One easy way is to generate printed (plane) samples and putting them into the directional lighting booth for testing the instrumental texture value (i.e., sparkle) by a magnitude estimation method, and comparing the visual sparkle value in front of the instrumental value.

On other hand, and coming back to the top-down and bottom-up of the light-matter-eye(brain) interaction (Figure 1), and thinking again in printing technology, even in 3D technologies, is to know the interplay of qualitative and quantitative variables involved in this multi-scale approach applying the statistical design of experiments (DoE) [51, 52].

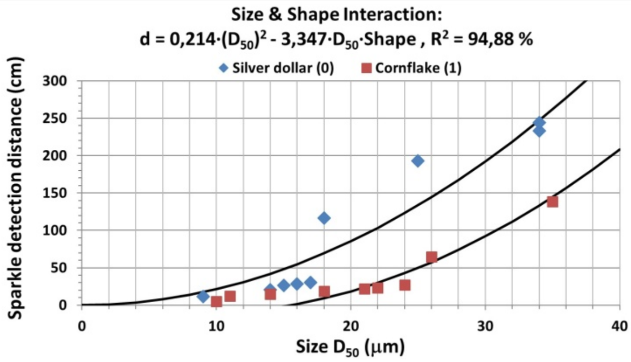


Figure 6. Empirical relationship of the sparkle detection distance (d) according to two structural variables of the metallic pigments.

Using an alternative directional lighting booth for sparkle assessments (Figure 5, right), in a recent work we applied a DoE design for testing the influence of the pigment size and shape (silverdollar vs. cornflake) in metallic coatings (Figure 4). The preliminary 2^2 factorial design, for 2 variables with 2 levels, demonstrated that big size is more important than shape, being in addition better silverdollar than cornflake. Including more samples, up to 18, with increasing sizes (D50 in µm), we could parametrize the size & shape interaction (Figure 6). And, even taking into account the instrumental sparkle grade (S_g), we could find a non-linear prediction model of sparkle detection distance (Figure 7), with better prediction performance for cornflake than silverdollar metallic flakes.

Therefore, this statistical multivariate techniques (DoE, and multidimensional regression methods), combined with new advanced color and visual texture instruments, can be useful for advanced printed materials.

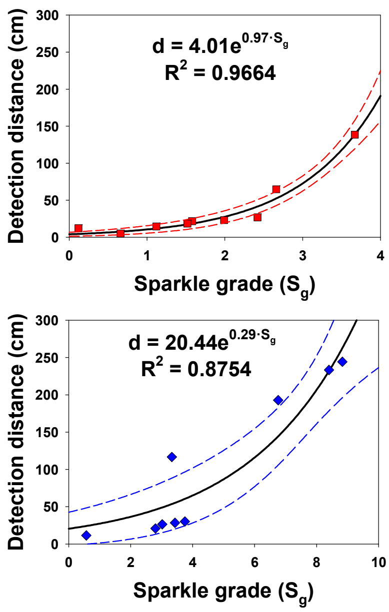


Figure 7. Empirical relationship of the sparkle detection distance (d) according to instrumental sparkle value (S_g) for two types of metallic flakes (red symbols: cornflake; blue: silverdollar) commonly used to obtain metallic finishes in coatings, plastics and printed materials.

Methods and work plan

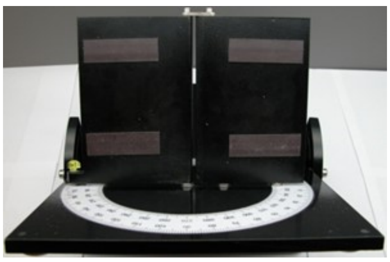
As said before, one of the three main goals of the Spanish recently funded project called "ADIREVGAO", which is an acronym for "Advanced Digital Reproduction of Visual Gonio-Appearance of Objects", is to go into detail about the reproduction capabilities of the gonio-appearance on several printing technologies, aboe all on multi-channel inkjet [31, 32, 52] and 3D printing, mainly in FDM technology [17, 20, 39].

To carry out that, a spectral and colorimetric characterization will be done for a multi-primary inkjet printer and a 3D (FDM) printer in order to evaluate the colour gamut by combining conventional and gonio-apparent pigments and to be compared with original color gamuts associated with the same special-effect pigments used on automotive paints and plastics, etc.

The color and texture (sparkle/glint and graininess/coarseness) parameters will be measured by a commercial reference multi-angle instrument in the automotive sector (BYK-mac-i), and graphically encoded by CIE-L*a*b* color space and other industrial graphs for sparkle (or glint) and graininess (or coarseness). And the conventional color and texture quality procedures applied on the automotive sector will be based on an excellent visual and instrumental correlation models as AUDI2000 color difference formula [5, 6].

In addition, other multivariate math techniques to be applied for next years for both printing technologies will be the PCA (principal component analysis) [53] and statistical design of experiments (DoE) [52]. The former can be applied as alternative physico-chemical modelling as Yule-Nielsen-Neugebauer [54] or Kubelka-Munk for color characterization of primary-inks, and even for color formulation, or gonio-fluorescence [55, 56]. And the latter to know the relevance and interplay among quantitative and qualitative variables (paper type, pigment type and size, etc.) in the characterization.

A separated proposal is worth to discuss here with regard to the curvature of the advanced printed samples, and its influence on the visual appearance. Current directional or diffuse lighting booths are basically designed for comparing plane specimens. The topographic data for any 3D printed sample is clearly available from its digital file [8, 26, 42]. But, it can be initially complicated to tackle this 3D spatial data into a realistic lighting conditions, as being parts of the car body or of the its dashboard or other car interior area, for understanding and managing the interplay of variables influencing on the visual appearance of 3D printed specimens. So, using for instance the gonio-device shown in Figure 8, and for identical plane specimens, it is possible to study the color and visual texture variation of curvature, both for concave and convex borders, and its corresponding color and texture tolerances when the border condition cannot be perceived as normal shading due to smooth curvature.



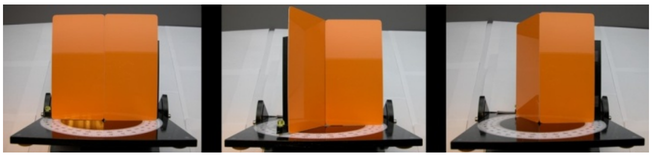


***Figure 8**. Gonio-device (top) available in our lab to study the influence of curvature in gonio-apparent specimens. Bottom, left: identical color pair; center: same color pair with concave border; right: same pair with convex border. Use as reference for visual assessments the upper side of both identical specimens.*

Therefore, this new artefact, combined with new advanced color and visual texture instruments, and multivariate statistical techniques, can be useful for advanced 3D printed materials.

Conclusions

This works shows a general overview of current standard methods, by using commercial advanced color and texture-measuring instruments, with additional new techniques and analysis, commonly implemented for the improvement to the visual and instrumental correlation of the gonio-appearance of automotive coatings. But, these basic principles, methods, and artefacts, can be applied on advanced printed materials.

So, in printing technologies, many opportunities can be developed at short and medium term measuring and testing gonio-appearance with the reference commercial instruments, even future ones, to manage efficiently the visual quality of advanced printed materials, both for color, even gonio-fluorescence, gloss, sparkle and graininess appearances in many measurement geometries.

Only with this empirical approach (top-down, Figure 1), we can understand and manage the complex interplay of qualitative and quantitative variables, from nano/micro to optical/macro scales, involved in the final appearance of advanced gonio-apparent printed products.

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Bárbara Micó obtained her masters in textile and materials engineering at the Technical University of Valencia and University of Alicante (Spain) in 2008 and 2012, respectively. She finished her PhD within the group of Prof. Martínez-Verdú (University of Alicante, Spain, 2015) with the focus on the optimization of the synthesis of natural nanostructured hybrid pigments for biopolymers by statistical design of experiments. She continues her work with Prof. Martínez-Verdú as post-doctorate staff member at the University of Alicante covering applied public and private R&D projects related to visual appearance of materials, colored nanomaterials and 3D printed bio-materials.