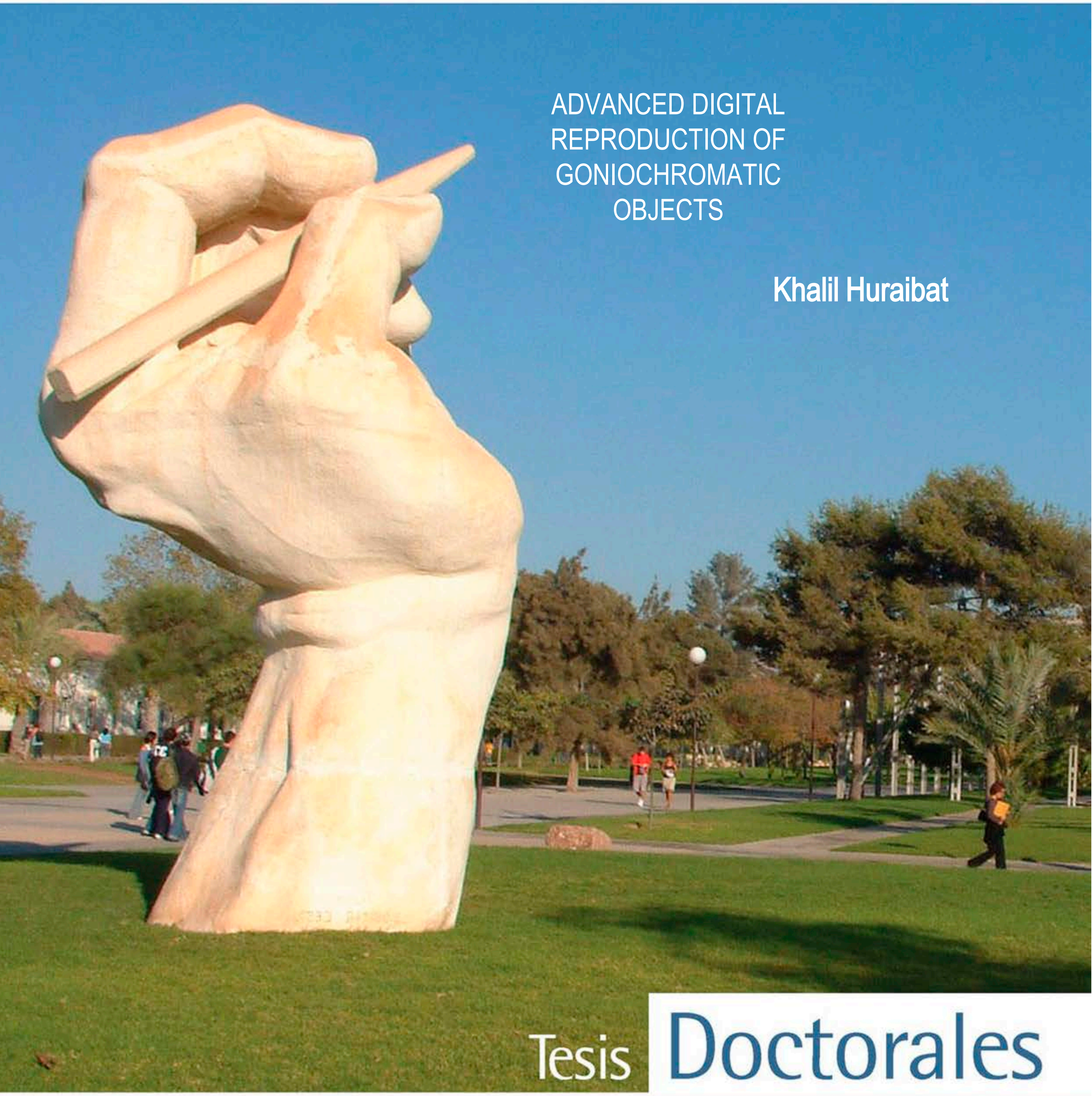

ADVANCED DIGITAL REPRODUCTION OF GONIOCHROMATIC OBJECTS

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This doctoral dissertation is presented to obtain the
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Dra. Esther Perales Romero, Profesora Asociada del Departamento de Óptica, Farmacología y Anatomía de la Universidad de Alicante, y el Dr. **Eric Jacob Jan Kirchner**, Doctor por la Universidad Libre de Ámsterdam (Vrije Universiteit Amsterdam),

CERTIFICAN:

Que la presente memoria “Advanced digital reproduction of goniochromatic objects”, presentada por **KHALIL I. Y. HURAIBAT**, ha sido realizada bajo la dirección de Esther Perales Romero y codirigida por Eric Jacob Jan Kirchner, en el Instituto Universitario de Física Aplicada a las Ciencias y Tecnologías de la Universidad de Alicante, y constituye su tesis para optar al grado de Doctor.

Y para que así conste, presentan la referida tesis, firmando el presente certificado.

Alicante, 28 de Marzo de 2022

Fdo: Dra. Esther Perales Romero

Fdo: Dr. Eric Jacob Jan Kirchner

DEDICATED

To

My parents: **Ismael** and **Fatima**
Thank you for giving me endless love, unconditional support, and invaluable educational opportunities. I am deeply indebted.

My small family: **Razan** (*my wife*) and **Elia** (*my daughter*)
Razan, thank you for being such a great partner on this trip. Thank you for being there for me, you have been the main engine of this success.
Elia, thanks to Allah for having you. You are mean of my everything. Never cease to be so wonderful as you are now.

My sisters and brothers: **Madleen, Yousef, Ali, Baraa, Mahmud, and Ibrahim**
Thank you all for caring about me. I am a lucky guy because I have supportive brothers and sisters like you, love you all.

لأمّي غاليتي

لأبي المثل الأعلى

لأحبّائي إخوتي وأخواتي

لرفيقة الدرب زوجتي ولزهرتي إيليا

لعائلتي الكبيرة

إليكم جميعاً أهديكم نتاج السنوات الماضية ملخصاً في هذه الأطروحة

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CONTENTS

ABSTRACT

The *digital reproduction* of materials has developed greatly over the past decades. The improved interactive rendering technology available nowadays enables broad digital visualization applications like gaming, cinema and film production, advertising, and online shopping. These recent advances in digital technologies are also playing an important role in the improvement of some industrial processes such as computer-aided design and manufacturing, virtual prototyping, and scientific visualization and simulation. Currently, many rendering software packages provide impressive images and often even claim photorealism. However, producing realistic appearance images is very challenging taking into account the high sensitivity of the human visual system. The *visual appearance* of products is still an important aspect to take into account even for the digital simulation of materials, since the appearance of these simulated products on the screen is still a critical parameter in the purchase decision of customers.

During the last years different efforts have been carried out by industrial manufacturers in different applications, such as textile, cosmetic, automotive, etc., to provide attractive visual effects and new visual impressions of their products using, for instance, innovative *effect pigments*, also called *goniochromatic pigments*. The digital rendering of these pigments is a very active hot topic since this type of coatings changes considerably its visual attributes such as color and texture with the illumination/viewing geometry. Achieving accurate simulation of these materials demands an extra effort due to the physical complexity of their surfaces. Special BRDFs (bidirectional reflectance distribution functions) reflectance models are needed to characterize their visual appearance. This complex appearance is produced due to the presence of special effect pigments containing metallic, interference, or pearlescent pigments, which are responsible for the strong dependence of the color of these coatings on viewing and illumination directions. These pigments also exhibit visually complex texture effects such as *sparkle* and *graininess*. Under bright direct illumination conditions, such as sunlight, the flakes create a sparkling effect, while under diffuse illumination such as a cloudy sky, effect coatings create a salt and pepper appearance or a light/dark irregular pattern, which is usually referred to as graininess or coarseness.

Two main issues limit the digital reproduction of effect pigments. The first issue is related to the current display technologies. The quality of the displays is an essential component toward accurate color reproduction of materials. Previous studies have evaluated the validity of available display technologies for the visualization and digital reproduction of effect pigments, which are usually not enough for the reproduction of such a wide variety of colors due to their limited color gamut. The second limitation is more related to the current rendering software. The color accuracy of their images is often not sufficient for the reproduction of colors and effects produced by these materials. The available rendering software provides impressive images that serve the needs for applications such as the cinema and games industries, but when it comes to more critical applications such as automotive design, the color accuracy of their rendered images is not accurate enough, especially for such complex materials such as effect pigments.

The first issue is addressed in this thesis by, evaluating the performance of the new Quantum dots (QDs) display technology for the reproduction of effect pigments. For further improving the display capability, a new solution is given by developing a multi-primary display model based on the QDs technology (addressed in the first research article of this thesis in *Chapter 1*). The proposed multi-primary display model provides an expanded color gamut, which guarantees a better reproduction of effect pigments. In a first step, the emission spectral radiance curves of the three RGB channels of a commercial QD display were fitted to a four-parameter function. From this modeling, it is possible to gain new theoretical color primaries by selecting new spectral peaks (cyan, yellow, magenta, and/or additional RGB primaries) and imposing colorimetric conditions for the resulting white of this proposed theoretical multi-primary display. Proper characterization to assess the performance of the display was conducted to know if the basic "gain-offset-gamma" (GOG) model can be used for direct and inverse color reproduction (from RGB to CIE-XYZ, and vice versa). The GOG model was found to well characterize this display. The spatial uniformity of the display was also evaluated in luminance and color chromaticity terms. Finally, with the primaries modeling and color characterization based on the GOG model, a 5-primary model (RGBYC) was tested. The evaluation of this theoretical RGBYC display model confirms the gamut enlargement, which can also improve goniochromatic color reproduction.

In the second place, and focusing on the second issue, a big portion of the work of this thesis was dedicated to the development of a new 3D rendering tool for improved and accurate visualization of the complete appearance of effect coatings, including metallic effects, sparkle, and iridescence (addressed in the second and third research articles of this thesis in *Chapter 2* and *Chapter 3*). This task was carried on by firstly building a specific rendering framework for this purpose, using a multi-spectral and physically based rendering approach, and secondly, by validating the performance of this rendering framework through psychophysical tests.

Spectral reflectance measurements and sparkle indices from a commercially available multi-angle spectrophotometer (BYK-mac i) were used together with a physically based approach, such as flake-based reflectance models, to efficiently implement the appearance reproduction from a small number of bidirectional measurement geometries. With this rendering framework, a virtual representation of a set of effect coating samples is reproduced on an iPad display, by simulating how these samples would be viewed inside a Byko-spectra effect light booth. Therefore, for this purpose, an accurate virtual representation of the Byko light booth was built using a physically based representation of global illumination. The rendering framework also accounts for the colorimetric specifications of the rendering display (iPad5) by applying the recent device-specific MDCIM model. The appearance fidelity of the rendering was validated through psychophysical methods. For this task, observers were asked to evaluate the most important visual attributes that directly affect the appearance of effect coatings, i.e., color, the angular dependence of color (color flop), and visual texture (sparkle and graininess). Observers were asked to directly compare the rendered samples with the real samples inside the Byko-spectra effect light booth. The visual validation was performed in three different steps. In the first study, the accuracy of rendering the color of solid samples is evaluated. In a second step, the accuracy of rendering the color flop of effect coatings is validated by conducting two separate visual tests, by using flat and curved samples respectively. In the third and last step, the digital reproduction of both color and texture of metallic samples is tested, by including texture effects in the rendering by using a sparkle visualization model. The parameters of the sparkle visualization model were optimized based on sparkle measurement data from the BYK-mac i instrument using a matrix-adjustment model.

Results from the visual evaluations prove the high color accuracy of the developed rendering tool. In the first test, the visual acceptability of the rendering was 80%. This percentage is much better than what was found in a previous investigation using the default sRGB color encoding space. Results of the second study show an improved accuracy when curved samples were used (acceptability of 93% vs 80%). The final visual test shows high visual acceptability of the rendering at 90%.

In conclusion, this thesis provides a method for accurate digital simulation of effect coatings, by developing a multispectral and physically based rendering approach on a simple iPad tablet computer. The research developed in this thesis comes with many advances in the scientific and industrial levels, with a great contribution to the development of innovative tools for digitization of materials, as needed in today’s society.

RESUMEN

La reproducción digital de materiales ha evolucionado mucho en las últimas décadas. La mejora de la tecnología de renderizado interactiva disponible hoy en día permite amplias aplicaciones de visualización digital, como, por ejemplo: los videojuegos, la producción de cine y películas, la publicidad y las compras por internet. Estos recientes avances en las tecnologías digitales también están desempeñando un papel importante en la mejora de algunos procesos industriales, como el diseño, la fabricación asistida por ordenador, la creación de prototipos virtuales, y la visualización y simulación científica. En la actualidad, muchos paquetes de software de renderizado proporcionan imágenes impresionantes e incluso afirman que son fotorrealistas. Sin embargo, producir imágenes de apariencia realista es todo un reto teniendo en cuenta la gran sensibilidad del sistema visual humano. La apariencia visual de los productos sigue siendo un aspecto importante a tener en cuenta incluso para la simulación digital de materiales, ya que la apariencia de estos productos simulados en la pantalla sigue siendo fundamental, por ejemplo, en la decisión de compra de los clientes.

Por otro lado, durante los últimos años, los fabricantes de diferentes sectores industriales, como el textil, la cosmética, la automoción, etc., han intensificado sus esfuerzos para proporcionar efectos visuales atractivos y nuevas impresiones visuales de sus productos utilizando, por ejemplo, innovadores pigmentos de efecto, también llamados goniocromáticos. La representación digital de estos pigmentos es un tema candente y muy activo, ya que este tipo de recubrimientos cambia considerablemente sus atributos visuales, como el color y la textura, con el cambio de las geometrías de iluminación/observación.

Lograr una simulación precisa de estos materiales exige un esfuerzo adicional debido a la complejidad física de sus superficies. Se necesitan modelos especiales de reflectancia BRDF (funciones de distribución de reflectancia bidireccional) para caracterizar su apariencia visual. Esta apariencia compleja se debe a la presencia de pigmentos de efecto especiales que contienen pigmentos metálicos, de interferencia o perlados, y que son los responsables de la fuerte dependencia del color de estos recubrimientos de las direcciones de observación e iluminación. Estos pigmentos también presentan efectos de textura visualmente complejos, como el *sparkle* (brillo) y el *graininess* (granulosidad). Bajo condiciones de iluminación directa como la luz del sol, las láminas de pigmento crean un efecto de destello (*sparkle)*, mientras que bajo una iluminación difusa como la de un cielo nublado, los recubrimientos de efecto crean una apariencia típica del conocido efecto “sal y pimienta” o un patrón irregular de claro/oscuro, que se suele denominar *graininess* o *coarseness*.

Actualmente, existen dos problemáticas principales que limitan la reproducción digital de los pigmentos de efecto. La primera está relacionada con las tecnologías de visualización (pantallas) actuales. La calidad de estas pantallas es un componente esencial para conseguir una reproducción precisa del color de los materiales. En estudios anteriores se ha evaluado la validez de las tecnologías de pantallas disponibles para la visualización y reproducción digital de los pigmentos de efecto, las cuales no eran suficientes para la reproducción de una variedad tan amplia de colores, debido principalmente a su limitada gama cromática. La segunda limitación está más relacionada con los programas/software de renderizado actuales. La precisión cromática de sus imágenes no suele ser suficiente para la reproducción de los colores y efectos producidos por los pigmentos de efecto. Los programas de renderizado disponibles proporcionan imágenes impresionantes que satisfacen las necesidades de algunas aplicaciones, como el cine y los videojuegos, pero cuando se trata de aplicaciones más críticas como el diseño de automóviles, la precisión del color de sus imágenes reproducidas no es suficientemente precisa, especialmente para materiales tan complejos como son los pigmentos de efecto.

Por ello, esta tesis doctoral aborda estas dos cuestiones por separado. La primera cuestión se abordó evaluando, en primer lugar, el rendimiento de la nueva tecnología de pantallas *Quantum Dots* (*QDs*) para la reproducción de los pigmentos de efecto. Para mejorar aún más la capacidad de reproducción de colores, se ha trabajado en una nueva propuesta mediante el desarrollo de un modelo teórico de pantalla multiprimario basado en la tecnología *QDs* (abordado en el primer artículo científico de esta tesis en *Chapter 1*). Para ello y en un primer paso, se ha realizado un ajuste matemático para modular las curvas de radiación espectral de los tres canales *RGB* de una pantalla *QDs* comercial, los cuales se ajustaron a una función matemática de cuatro parámetros. Con este modelado, fue posible obtener nuevos primarios teóricos seleccionando nuevos picos espectrales, como, por ejemplo, cian (*C*), amarillo (*Y*), magenta (*M*), y/o primarios *RGB* adicionales). Mediante este modelado también se han impuesto algunas condiciones colorimétricas para el blanco resultante de este modelo teórico propuesto de pantalla multicanal. Cabe destacar también que se llevó a cabo una caracterización adecuada para evaluar el rendimiento de la pantalla con el fin de saber si el modelo básico *gain-offset-gamma* (*GOG*) podía utilizarse para la reproducción directa e inversa del color (de *RGB* a *CIE-XYZ*, y viceversa). Se ha demostrado que el modelo *GOG* caracteriza bien este tipo de pantallas. También se evaluó la uniformidad espacial de la pantalla en términos de luminancia y cromaticidad del color. Por último, con el modelado de primarios y la caracterización del color basados en el modelo *GOG*, se generó un modelo de 5 primarios *(RGBYC*). La evaluación de este modelo teórico (*RGBYC*) de pantalla confirma una ampliación considerable de la gama, que garantiza mejorar la reproducción de los colores goniocromáticos.

En segundo lugar, y centrándonos en la segunda problemática, una gran parte del trabajo de esta tesis doctoral se dedicó al desarrollo de una nueva herramienta de renderizado 3D para una reproducción mejorada, fiable y precisa de la apariencia total de los pigmentos de efecto, incluyendo los efectos metálicos, el *sparkle* y la iridiscencia (problemática abordada en el segundo y el tercer artículo de esta tesis en *Chapter 2* y *chapter 3*). Esta tarea se llevó a cabo, en primer lugar, construyendo un marco de renderizado específico para este fin, y utilizando un método de renderizado multiespectral y basado en medidas físicas, y, en segundo lugar, en una fase de validación, se evaluó el rendimiento de este marco de renderizado mediante pruebas psicofísicas.

Para el renderizado se utilizaron medidas físicas de reflectancia espectral e índices de *sparkle* obtenidas con un espectrofotómetro multiángulo disponible en el mercado (*BYK-mac i*), junto con modelos fisicos de reflectancia como el *flake-based reflectance model*. De este modo, fue posible implementar de forma eficiente la reproducción de la apariencia de las superficies con recubrimientos de efecto a partir de un pequeño número de geometrías de medidas bidireccionales. Con este marco de renderización, se han generado simulaciones virtuales de una serie de muestras de pigmentos de efecto en la pantalla del iPad, simulando cómo se verían estas muestras dentro de la cabina de iluminación *Byko-spectra effect*. Para este fin, se construyó una representación virtual precisa de la cabina *Byko-spectra effect* utilizando una representación de la iluminación global basada en medidas físicas. También se han tenido en cuenta las especificaciones colorimétricas de la pantalla de renderizado (iPad5) aplicando el reciente modelo específico MDCIM de calibración de este dispositivo. La validación de la fiabilidad de este modelo de renderizado fue validada mediante pruebas psicofísicas. A los observadores se les pidió que evaluaran los atributos visuales más importantes de la apariencia de los revestimientos de efecto, que consisten en el color, la dependencia angular del color (*flop*) y la textura visual *(sparkle* y *graininess*). A los observadores se les pidió que compararan directamente las muestras renderizadas dentro de la cabina virtual con las muestras reales dentro de la cabina (*Byko-spectra effect*) física. Este proceso de validación visual del marco de renderizado se realizó en tres pasos diferentes. En un primer estudio, se evaluó la fidelidad de la representación del color de las muestras de colores sólidos uniformes. A continuación, y en un segundo paso, se evaluó la fidelidad de la representación del color de muestras con revestimientos de efecto (muestras metálicas) mediante la realización de dos pruebas visuales separadas y utilizando muestras planas y curvadas respectivamente. En el tercer y último paso, se evaluó de manera conjunta la reproducción digital del color como de la textura de las muestras metálicas, incluyendo la textura en el renderizado mediante un modelo teórico para la representación del *sparkle*. Con este modelo de *sparkle* se consiguió optimizar los parámetros del modelo de renderizado basándose en los datos de medición del *sparkle* del instrumento *BYK-mac i* utilizando un modelo de ajuste matricial.

Los resultados de las evaluaciones visuales demuestran la gran fidelidad cromática de la herramienta de renderizado desarrollada. En la primera prueba, la aceptabilidad visual del renderizado fue del 80%. Estos resultados son mucho mejores que los encontrados en una investigación anterior al utilizar el espacio de codificación de color *sRGB* por defecto. En el segundo estudio, los resultados muestran una mayor fidelidad cuando se utilizan muestras curvadas (aceptabilidad del 93% frente al 80%). Los resultados de las pruebas visuales de apariencia total en el experimento final confirman la alta fidelidad o rendimiento del renderizado con una aceptabilidad visual del 90%.

En conclusión, esta tesis doctoral proporciona una nueva herramienta de renderizado digital capaz de proporcionar una simulación precisa y de alta fidelidad de los pigmentos de efecto, utilizando una simple pantalla de tableta (iPad), mediante el desarrollo de un modelo de renderizado multiespectral y basado en medidas física en un simple procesador de una tableta iPad. La investigación desarrollada en esta tesis doctoral proporciona muchos avances a nivel científico e industrial, con una gran contribución al desarrollo de herramientas innovadoras para una necesidad tan esencial en la sociedad actual como es la digitalización de materiales.

GENERAL INTRODUCTION

This chapter provides an overview of the appearance and digital reproduction of materials. Firstly, a general view of the visual appearance of objects and their importance in daily life is given (*section 1*). This chapter also includes a brief description of how the total appearance of objects is perceived and interpreted by the human visual system. Particular attention is given to the gonio-appearance of materials, especially effect pigments, which are classified into two main groups: metallic and special effect pigments (*section 2*). The last part of this section (*subsection 2.3*) focuses on the physical and visual characterization of these coatings. It addresses the different visual attributes of effect pigments and their evaluation based on the characteristics, texture, and applications of these pigments. The characterization, behavior, instrumentation, and psychophysical methods implemented on the visual perception of these characteristic pigments are also discussed in this subsection.

Details on physics-based rendering approaches for goniochromatic materials are also pointed out in this chapter (*section 3*). Special attention is given to the visualization of goniochromatic objects and the use of improved display technologies to better reproduce the complex appearance of such objects (*section 4*).

The contents here are aimed at all kinds of audiences and not only at professionals who work with effect pigments. The fundamentals and applications presented here will surely help to provide basic knowledge to newcomers to this field, or to anyone curious about any of the technical terms related to effect pigments. Experts in the domain can also delve into some specific topics and improve their skills and knowledge.

1. *Visual Appearance of Materials*

Before addressing appearance, it is essential to go through the definition of vision to understand the visual perception process, and how objects are seen by human eyes.

The human eye is the most important organ of sense since up to 80% of impressions perceived by the human body are provided by vision. To well understand the process of vision, it must have clear that the human visual system does not consist simply of the eyes, as these, together with the brain form the basis of the visual system and work as a team to make sense of the surrounding world. The process of vision (Figure 1) can be simplified into three different elements: a light source, an object, and a human observer. These three factors define, in general terms, the color and appearance of objects (Choudhury, 2014).

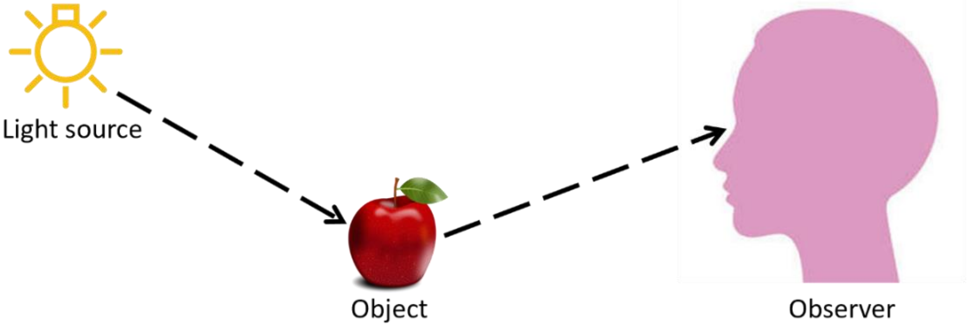

Figure 1: The vision process. Light-matter interaction and the human observer.

When an object is illuminated by a light source, the incident light hitting the object's surface undergoes a series of physical modifications. The nature of these modifications depends directly on the object's surface and, more precisely, on its physical and chemical construction. Absorption, scattering, and many other physical and optical behaviors are all possible results of the light-matter interaction (Choudhury, 2014). This interaction leads to a partial or total reflection/refraction of the light, and once it reaches the observer's eyes, especially the visible range of the lighting spectrum, i.e., the wavelength of about 400-700 nm, the light enters the eye through the cornea; then, it passes through the pupil, before being finally converged and focused upon the retina by the eye lens. The photoreceptors (light-sensing pigment cells of the retina) transform this light energy into electrical signals. This information is sent via the optic nerve in the form of a nerve impulse, to be gathered and modulated in different areas of the brain in a complex way until it reaches the visual cortex. There, the visual cortex ultimately processes the overall image of the surroundings (Klein, 2010; Choudhury, 2014).

A noteworthy aspect is the extreme complexity of visual information processing in humans, which is not yet fully understood. Based on the aforementioned stages of the visual process, a complete definition of visual perception could be "the ability to perceive and interpret the surrounding environment by processing the collected information from the visible light" (Klein, 2010). The American Society for Testing and Materials-ASTM defines visual perception as "the visual experience resulting from stimulation of the retina and the resulting activity of associated neural systems" (ASTM, 2009). Visual perception allows the observer to interpret the appearance of an object. The term *appearance* in this thesis means the visual sensation by which attributes of an object such as size, shape, color, texture, gloss, transparency, opacity, etc., are perceived (Pointer, 2006). The appearance of an object can be useful to determine its age, whether it is an original piece or not, the extent to which the object is a fake, etc.

The following subsections will focus on the importance of the appearance of objects and the characterization of the main attributes (color, texture, gloss, transparency) of visual appearance.

1.1. The Importance of Products Appearance

Usually, people examine the objects around them and judge their qualities with bare eyes, without caring about the optical process that allows them to visually judge their surroundings (Sharma & Bala, 2017; Lozano, 2015). Objects are made from a huge variety of materials. The visual appearance of objects is the most important aspect to assess their quality and materials, and directly affects the customer's choice (Sharma & Bala, 2017; Lozano, 2015; Eugène, 2008). There is a widespread belief that first impressions count. It has been proven that the first 10 seconds perception impression are crucial and create a lasting visual impression of the aspect and quality of an observed object (Kettler et al, 2016). From that springs the extreme importance industrial manufacturers give to the quantification of the appearance of their products, seeking to ensure its reproducibility and uniformity (Sharma & Bala, 2017; Lozano, 2015; Eugène, 2008).

The psychological component of perception is essential, and it receives great attention in the design and production of commercial products. Buyers tend to connect a product's appearance to other aspects. A good-looking product usually leads to a positive judgment of its performance, purpose, and durability.

Buyers often use appearance consistency to evaluate a product's appeal and quality. Consumers expect products to always look the same and if a difference in appearance is perceived, products are judged as inferior, old, or even defective, while a consistent appearance increases consumer confidence and the chances of the product being judged positively. Appearance properties are also essential in the designing and development of new materials as they form the basis for understanding the behavior and temporal properties of such materials (Hutchings & Ronnier Luo, 2012).

Color is the most critical appearance attribute. To guarantee the appearance consistency of their products, manufacturers adopt precise color specifications (objective and technical methods) to evaluate their products. These assessing methods are derived from the principles of colorimetry; this concept, which refers basically to the measurement of color (Fairchild, 2013), was first described by Wyszecki (1973), who defined colorimetry as "the methods of assessing the appearance of color stimuli presented to the observer in complicated surroundings as they may occur in everyday life". Nevertheless, color is not the only factor to be considered, and the term *total appearance* is mainly used to combine the different factors of the overall appearance of objects (see the following *subsection 1.2*), which is still a hot topic, especially with the constant innovation of new materials with very complex structures and visual effects, such as "effect coatings". Obviously, and as Klein (2010) pointed out, "aside from the constant efforts to develop the theoretical concepts of appearance, the visual sensation of the observer will always be the final authority on all efforts in the color industry".

1.2. The Total Visual Appearance

Total (or overall) appearance is a combination of the chromatic and the geometrical attributes of an object in the environment in which the object is being observed. The chromatic attributes are given by the color and its properties (hue, lightness, and chroma or saturation). The geometrical attributes are more related to the object's surface structure (like gloss, translucency, texture, and shape) (Eugène, 2008). The psychophysical response of the human visual system, and also the psychological characters (like education, culture, and traditions), all affect the physical parameters of the observed object (Eugène, 2008; Viénot, 2006). Choudhury (2014) describes the creation of appearance response in four different steps as follows:

Step 1: a structure is created from the molecules and geometry of elementary substances, where the appearance image of an object is influenced by its:

- optical properties, such as reflectance, transmittance, etc.
- visual properties, such as shape and surface structure.
- temporal aspects that change with time, like movement.

Step 2: a stimulus is the result of the interaction of the structure with the environment and its components, like illumination.

Step 3: this stimulus is then modified into the appearance responses by the visual path process on the observer's eyes and the cortex (the retina, optical nerve, and all the related neural connections in the brain).

Step 4: the appearance response, together with the observer's mood and temperamental factors, builds the final impression of the observer about the object, which can be translated into different quality judgments and preferences depending on the observer.

The way these parameters interact to build a complete perceptual scene is complex. Therefore, further research efforts were essential to defining a complete and uniform description of total visual appearance. The term total appearance was introduced by Hutchings (2011) and others, like Lozano (2006). Hutchings's research was initially focused on food. He discussed its color and other distinct properties like smell, taste, and mouth consistency. Later, Hutchings established the concept of total appearance and its philosophy, which in his judgment should incorporate all the perceptual elements of a scene, including color and texture. According to Hutchings, total appearance then is the interpretation that an individual gives to a product or situation, involving all the visually perceived information concerning the product, the situation, and the environment (Hutchings, 1995a, 1995b, 2011). This total appearance philosophy was extended to the design environment in a later work by Hutchings and Ronnier Luo (2012), and it was restricted to the perceived properties of materials, i.e., the visual structure of materials, including size, shape, and surface structure, roughness, colors and color pattern, gloss and gloss pattern, translucency, and translucency pattern.

In the early 21st century, the physical and psychophysical properties of total appearance came under active consideration. Many other investigations focusing on total appearance including texture were carried out by the International Commission on Illumination (CIE, French acronym for Commission Internationale de l'Éclairage) (Viénot, 2006) and the American Society for Testing and Materials (ASTM International). The Japan Paint Inspection and Testing Association studied the micro-appearance of paints (Arai & Baba, 2005). A research project focusing on the measurement of appearance was run by the National Physical Laboratory (NPL) in the UK (Pointer, 2003). The NPL built a sub-framework by specifying what aspects of visual appearance could or might be measured at that time to lay the basis for a future framework to determine total appearance. Simultaneously, the National Institute of Standards and Technology (NIST) performed similar research on advanced methods and modeling of the total appearance of coatings (McKnight & Martin, 1998; McKnight, 2002). More recently, methods to visually evaluate and quantify the total appearance of effect coatings were developed by Huang et al. (2010) and Dekker et al. (2011).

There are many different views and definitions of total appearance. The simplest definition, recommended by the CIE report (Viénot, 2006), is as follows:

The total points out the visual aspects of the object scene.

By considering the whole scene, the expectations introduced by Hutchings (which include our feelings and individuals) can be classified into the following:

- Visually assessed safety.
- Visual identification of the scene.
- Visually assessed usefulness of the scene.
- Visually assessed satisfaction that the observer expects to get from the scene.

Therefore, total appearance is affected by many factors related to the light source and its spectral power distribution, the physical, optical, and temporal properties of the observed object, the color, and the spatial vision, as well as the age and the response of the other senses of the observer (Eugène, 2008; Hutchings, 1995a, 1995b).

1.3. Evaluation of Appearance

The term *appearance* refers to the visual sensation by which attributes of an object such as size, shape, color, texture, gloss, transparency, opacity, etc., are perceived. It can lead to acceptance, rejection, or desire for objects; consequently, it is a very important factor in decision making. For example, in many cases it determines how the quality of products will be judged, which, in turn, has an impact on sales. Therefore, many companies in different industrial fields need to have procedures to control the appearance of their products. Historically, many of these procedures have been based on subjective visual evaluations by specialized operators. However, over-reliance on individuals poses several practical problems. Expert opinion can vary and create conflicts over product acceptance. In addition, human capability varies with time, mood, age, and also from person to person. On the other hand, it is a costly method in time and resources. Nowadays, the available technology allows the development of automated methods of objective evaluation. Such methods, besides making the production chain more efficient, contribute to a considerable reduction in human assessment errors.

In order to objectively control appearance, it should be measured first. Measurement scales are needed for the various perceptual attributes of objects. However, the human visual system is shaped by one’s own experience, and appearance can be affected not only by physical conditions, but also by physiological, psychological, and sociocultural conditions. Therefore, having measurement scales that consider the personal cognitive aspects of the observer is not feasible, and the measurement of appearance should narrow its scope to objective conditions that admit generalization to any human observer. Thus, the measurement of appearance refers in this thesis to the application of techniques for measuring magnitudes that can be linked to perceptual aspects, and their expression on the corresponding perceptual scale. For appearance characterization purposes, this study will focus on the measurement of four fundamental perceptual attributes: color, brightness, translucency, and texture. All these attributes are related to how objects modify the light that reaches the observer's eyes. Thus, the study of the interaction of light with matter is fundamental to the development of appearance measurement scales and requires the measurement of physical quantities related to the reflection, transmission, refraction, absorption, and scattering of light by an object. It is also necessary to determine how light-matter interaction is linked to visual sensation. To this end, psychophysical methods are used, which involve showing a series of objects to different observers and relating their responses to the measurements of the physical quantities in these objects. In this way, it is possible to identify which physical magnitude and which conditions are the most relevant to defining a correlation of the specific visual sensation to be measured. This relationship between the physical magnitude and visual sensation is here called the measurement scale, which can be employed to calculate numerical values for the subjective experience from the objective measurement. This relationship between the subjective experience and the objective measurement that defines the scale does not have to be linear and can include the measurement of several physical quantities.

The most important example of success is the color measurement scale, accepted by the CIE since 1931. In this case, the spectral reflectance of a surface (matter) and the irradiance on it (light) are related to the visual sensation of a universal standard observer, described by functions known as matching functions. It is undoubtedly an example to be followed in the development of other scales of measurement.

In addition, the definition of the color measurement scale has served to better understand certain complexities concerning the measurement of appearance. Above all, the interaction between the various perceptual attributes of objects has been assessed, and, in general, the importance of context in appearance, i.e., how the perception of an object is affected by its environment, has been demonstrated.

The following sections will briefly explain the status of the measurement scales for color, gloss, translucency, and texture.

Color**:** color is a perception. The color of an object, by itself, is not a physical quantity but rather a purely psychophysical response (Klein, 2010). Scientists have run a variety of psychophysical experiments to describe color appearance phenomena, by asking observes to describe colors of a large number of objects, covering a wide range of colors and keeping the same texture. The conclusion was that all observers tend to characterize the colors based on the three fundamental properties listed below:

1. The dominant color (hue)
2. The intensity of the color (chroma)
3. The lightness of the color (lightness)

Even though different nomenclatures are found in the literature, it is generally agreed that these three attributes are necessary to characterize a color (Fairchild, 2013; Wyszecki & Stiles, 1982; Mausfeld, 2002; Berns, 2000; Dorsey, 2010).

Color shade (hue) is the attribute of color which describes what is commonly referred to as color. Hue allows the observer to determine color: red, orange, yellow, green, blue, purple, or intermediate between adjacent pairs of these, considered in a closed ring, red and purple being an adjacent pair (see also Munsell & Nickerson, 1915; ASTM, 2009). The basic hues in the visible spectrum are graphically represented via a circle, referred to as the color wheel (Figure 2).

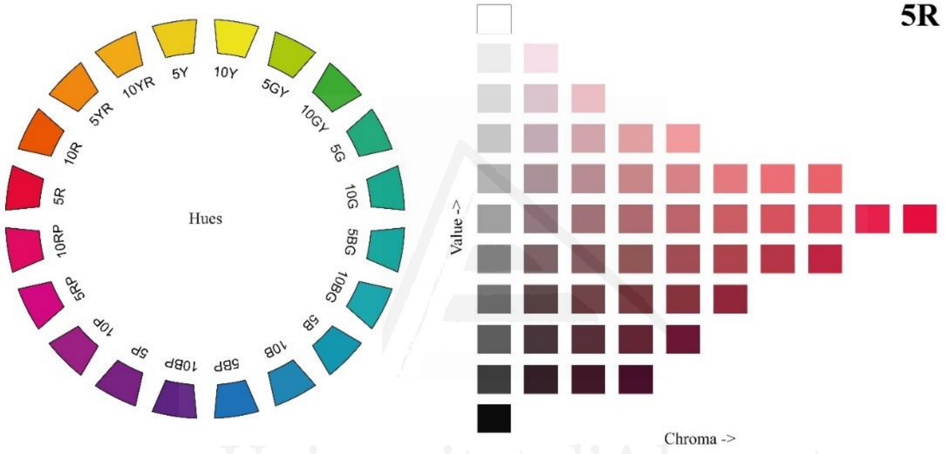

Figure 2. Munsell color system. The left-hand side of the picture represents the hue (color wheel). The right-hand side of the picture is an example of only one hue (5R). From: Classical Atelier at Home (n.d.)

Chroma is the attribute of color that is used to indicate the degree of departure of the color from a neutral color of the same lightness (ASTM, 2009). It describes the purity of a color, and it is associated with color intensity. A high chroma is seen as an intense color, while a low chroma is seen as a pale color. The words brighter and duller are commonly associated with this attribute. Chroma is independent of hue and is represented on the color wheel by its location along the radius of the color wheel (Figure 2). As the chroma of the color increases, the location of the color moves toward the edges of the color wheel.

Lightness or brightness is the aspect of visual perception whereby an area appears to reflect (or emit) more or less light of object color (ASTM, 2009). It places colors along an overall lightness/darkness continuum, with white at the top and black at the bottom. The lightness attribute is independent of hue and chroma.

The measurement and specification of color were the first appearance attributes to be studied. The first measurements of color were based on the trichromatic character of human vision and the fact that the color of light can be perceived as equal to the color obtained by mixing three different colored lights called primary colors, usually red (R), green (G) and blue (B). In color matching, the required amount of each of these three primaries is unique to every color; therefore, said amounts can be used as a measure of color. These three quantities constitute color coordinates, called tristimulus values, *R*, *G*, and *B*. Given a set of primaries, any color can be accurately communicated and reproduced through its tristimulus values. Thus, the color of any light can be measured by experimentally performing the aforementioned color matching. The CIE, in 1931, standardized a colorimetric system, through the precise specification of the three primaries, red, green, and blue, known as CIE RGB 1931 (CIE, 1986). In this experimental framework and using the properties of Grassmann's laws of additivity and proportionality (Wyszecki & Stiles, 1982), it is possible to calculate, avoiding visual equalization, the tristimulus values of any colored light from its spectral measurement and the experimental tristimulus values obtained by an observer for all the monochromatic lights of the visible spectrum. These experimental tristimulus values are known as matching functions. Based on measurements of the matching functions of 7 subjects by Guild in 1931 and of 10 subjects by Wright between 1928 and 1929, the CIE defined a standard observer in 1931. Subsequently, the CIE developed a new system with better mathematical properties, known as CIE XYZ 1931 (Smith& Guild, 1931), defining new primaries. The tristimulus values in this system are (X, Y, and Z). This CIE system was designed so that the tristimulus value Y correlates approximately with brightness or, more usually, with lightness (relative lightness). The tristimulus values X and Z, however, have no perceptual correlation.

The transition from measurements of colored light to a colored object is based on the understanding that the object will reflect, to a greater or lesser extent, each of the wavelengths of the light that illuminates it. Therefore, it will be necessary to measure the spectral emission of the light source used (spectral power distribution) and what portion of each wavelength is reflected by the object, i.e., the spectral reflectance. Different instruments are used to perform these measurements, such as spectroradiometers, colorimeters, etc.

In summary, to rigorously measure the color of an object, three elements must be characterized: the light source used to illuminate the object (spectral power distribution), the spectral reflectance properties of the object (spectral reflectance), and the spectral weighing functions, i.e., how an average observer responds (matching functions of a Standard Observer). Properly integrating these three spectral quantities yields the tristimulus values that uniquely define the color of an object perceived under a given illumination.

Historically, the development of colorimetry has been closely linked to industry, especially the textile industry. In this context, even more important than the measurement and specification of color has been the evaluation of the color difference between two samples, usually of very similar color, to ensure that they are perceived the same, i.e., that they do not exceed the *threshold differences*. Often it was a matter of comparing the color of parts on a production line with the color of a standard, with a *pass* (no perceived difference) or *fail* (intolerable difference) response. Both problems, the specification of color and the evaluation of color differences, are connected. If in a first step, the color of each sample can be specified, so that its difference can be more easily evaluated. It should be noted that, in the perceived color, both the object itself and the light source that illuminates are involved. For this reason, the use of lighting booths was standardized, to control the illumination and the environment surrounding the object in the evaluation (both instrumental and visual) of color and color differences.

It was obviously necessary and advantageous to find a mathematical formula that, from the instrumental measurements of the tristimulus values (X, Y, Z), allowed the calculation of color differences to avoid the long and expensive process dependent on the ability of an expert. Different color difference formulas began to be developed, many of them associated with different spaces for specifying color. The best strategy was to first specify the color in a space in which the color coordinates were correlated with the perceptual attributes of color: lightness, chroma, and hue. Then, in that space the color difference between each pair of points had to be calculated. The most successful color space has been CIELAB, proposed by the CIE in 1976 (CIE, 1995), where L^* represents the lightness of the color ($L^* = 0$ yields a black color and $L^* = 100$ defines a diffuse white). The polar coordinates a^* and b^* define the position of the color on the relative red-green axes and on the relative yellow-blue axes respectively. The CIELAB color space can also be expressed in cylindrical form as CIELCh$_{ab}$, where the color coordinates L^*, C_{ab}^* and h_{ab}, correlate with lightness, chroma, and hue. In this space, in addition to the Euclidean distance (known as CIELAB color difference formula), different color difference formulas have been developed and are still under research. The most recent is the CIEDE2000 formula (CIE, 2001), currently an ISO/CIE 11664-6:2014 standard.

Both the measurement and specification of color and the color differences discussed can be considered as traditional colorimetry, which is very useful in many industrial applications and production processes. However, it requires very restrictive observation conditions: samples on a neutral gray background, illumination not very different from daylight type, illumination level around 1000 lux, samples without texture, etc. (CIE, 1993). In many other applications, with more usual conditions similar to those in daily life, this colorimetry is not sufficient to characterize the color appearance of an object. In addition to the three factors mentioned above (light source, object reflectance, and observer), which are fundamental in order to specify a color, many other factors influence its perception, such as chromatic adaptation, luminance level, background, and the environment in which the object is observed, cognitive aspects, individual differences between observers, etc. Some of these factors are taken into account in new models called *color appearance models* (CAM), which have been worked on for about 30 years. The starting point of color appearance models are tristimulus values (X, Y, Z) and include a chromatic adaptation transformation and the creation of opponent channels, simulating the physiology of the human visual system, whose responses are combined to calculate magnitudes that correlate with perceived color appearance attributes: lightness, clarity, colorfulness, chroma, saturation, and hue. Currently, the color appearance model recommended by the CIE is CIECAM02 (CIE, 2004). New models also incorporate the spatial effects of the scene, such as the iCAM models (Fairchild, 2013).

However, other factors are not currently considered in color appearance models. These include temporal effects, sample texture, and iridescence, i.e., the variation of an object's color as the directions of incidence and observation vary. But to understand the interaction between color and other factors, such as texture, it is necessary to be able to measure them. In particular, the measurement of texture will be discussed later in this section.

Gloss: refers to the appearance of certain objects, with a considerably increased light reflectance at critical orientations relative to the position of the light sources. While gloss is usually characterized by physical measurement properties, it is often associated with perceptual appearance (Baar et al., 2016) and, like color and texture, is also one of the fundamental attributes of visual appearance (Eugène, 2008; Pointer, 2006).

While the spectral distribution of the reflectance of an object and the light source illuminating it are crucial to characterizing its color, the angular distribution of both illumination and reflectance is essential to gloss appearance. A cloudy day and a clear day offer different images of the world. On a cloudy day, the illumination comes from all directions equally (diffuse illumination), while on a clear day the illumination comes predominantly from the sun disk, revealing to the observer's eyes certain characteristics that allow him or her to identify types of surfaces. The reflected image on an object's surface gives information on the image forming quality of such surface, while focusing on the surface itself provides information about the size, depth, and shape of the surface structure (Streitberger & Dossel, 2008) (Figure 3). The surface structure and texture are usually given by dimensions between 10 and 0.1 mm (the human eye detection limit is approximately 0.07 mm) (Verhoeven, 2018). Smaller structures and details are not detected by naked eyes unless additional optical setups are used, although their effect becomes apparent in objects or images reflected on the surface. Structures sized 0.1 mm or less reduce the distinctness of the reflected image (DOI), structures around 0.01 mm induce haze, and structures that are even smaller than 0.01 mm can affect the surface gloss (Figure 3).

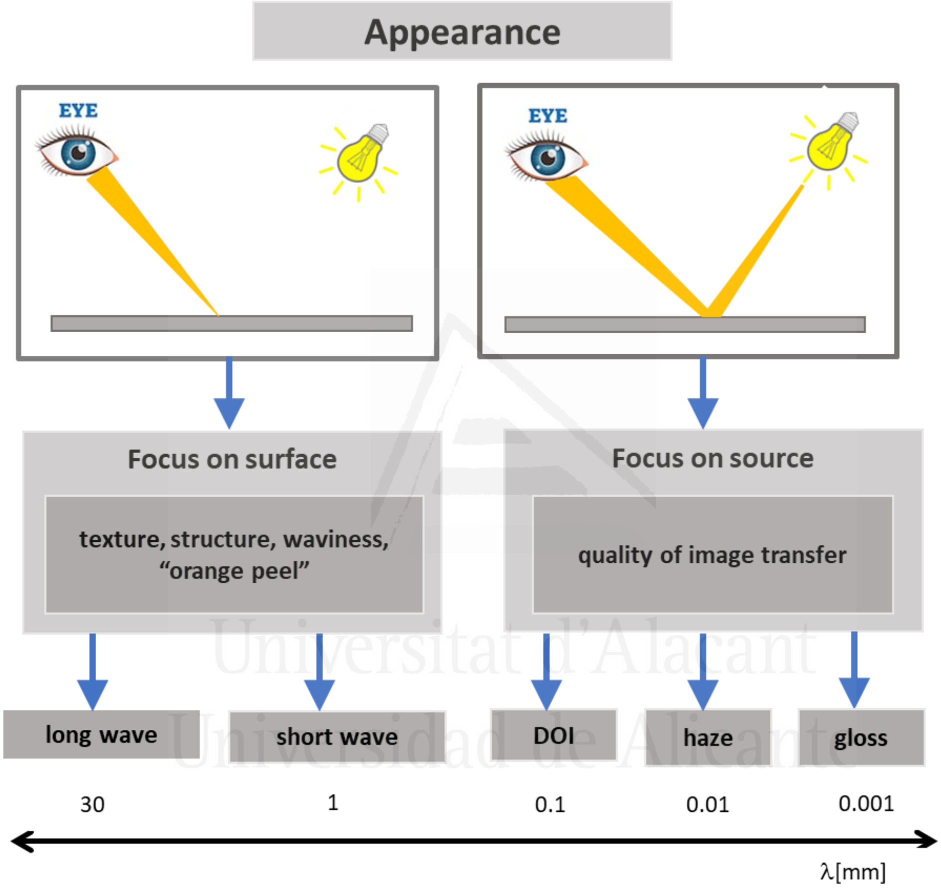

Figure 3. The appearance of reflective objects. Flow chart depicting relationships of characteristic variables of appearance (Lozano, 2017).

It is generally assumed that glossy surfaces are those whose reflectance increases steeply around the specular direction, but surfaces whose reflectance increases towards low angles of observation at low angles of incidence can also be considered glossy. When quantifying the gloss, other controversies also arise. The most important is whether to consider as higher gloss those objects that provide a sharper image of an object (DOI, distinctness of image) or those that reflect a higher proportion of light in the specular direction. Hunter and Harold (1987) already established up to six different ways of describing gloss based on the measure of reflectance (Specular gloss, Sheen at grazing angles, Contrast gloss, Haze, Distinctness-of-reflected-image gloss, and Absence-of-surface-texture gloss) and pointed out that the description of gloss was not one-dimensional, but, as in the case of color, needed more than one correlate. According to the psychophysical experiments of Wills et al. (2009), in which a multidimensional analysis was conducted, a measurement scale should be at least two-dimensional, with one dimension indicating the sharpness of objects reflected from the surface, and the other to consider the relationship between specular reflected light and light reflected in directions other than specular.

However, commercial instruments designed to measure gloss (gloss meters) only measure specularly reflected light at three given directions of incidence (20°, 60°, and 85°), with respect to a black standard. This information is generally considered sufficient for current industry requirements, and a gloss scale has been defined with GU (gloss units), between 0 GU, for no gloss, and 100 GU. These instruments do not allow users to discern between more than one gloss dimension, and, due to the difference in apertures between instruments, low inter-instrument reproducibility is observed (Leloup et al., 2014). The remaining issue is to also consider how the reflectance increases as the specular direction is approached. To do this, it is necessary to measure the bidirectional reflectance for angles very close to the specular, using mobile systems such as gonio-spectrophotometers (Rabal et al., 2012; Hünerhoff et al, 2006; Leloup et al, 2008; Baribeau et al, 2009; Matsapey et al, 2013). These measurement systems make it possible to measure the bidirectional reflectance distribution function (BRDF) of a surface, a key quantity for the study of reflectance (Nicodemus et al, 1992). A very promising alternative is to evaluate the angular distribution using cameras (Obein et al, 2014), where the value of each pixel does not correspond to a position in the object plane, but to the direction of the collected light. This allows a very high angular resolution by a simpler procedure than the use of goniospectrophotometers.

A gloss measurement scale more analogous to that of color should consider the angular distribution of reflectance and illumination. The CIE has recently formed a technical committee (JTC-17), where the recommendation of a standard observer and a more complex gloss measurement scale than the one currently used are to be discussed.

The works by Leloup et al. (2014) and Chadwick et al. (2015) are recommended readings for a wider perspective on the study and measurement of gloss.

Translucency: is the appearance effect produced by diffuse light scattering beneath the object's surface. These objects, in addition to reflecting the incident light on their surfaces, also reflect a part of the light that has propagated inside them in a significantly visible way to the incidence medium. Appropriate intermediate scattering and absorption coefficients and thicknesses are essential for the production of this appearance attribute.

As in the case of gloss, translucency depends on the angular distribution of the illumination and the reflectance of the surface, but it also depends on the scattering that occurs within the surface, which directly affects the spatial distribution of the light reaching the observer.

The physical quantity related to translucency is known as BSSRDF (Bidirectional Scattering - Surface Reflectance Distribution Function), which was defined by Nicodemus et al. (1992) in the same study where BRDF was defined and analyzed in detail.

Texture: two important cognitive categories are crucial to understanding the image of any object captured by the human visual system, namely, the shape and material of that object (Ogiela & Hachaj, 2015). This subsection is more related to the latter category and focuses on the visual aspect of surface materials which are known as visual texture, another fundamental component of visual appearance. Texture is an external quality of objects that helps to recognize them and refers to their surfaces and material. It is one of the most important visual elements, since it affects the observer's perception of these objects, creating a feeling of acceptance or rejection. Examples of texture are the grain of the wood, the skin of an orange, and the braiding of a fabric.

The word texture is derived directly from the Latin word *texere*, which means to weave; and *texturea* is a weaving, web, structure. Michal Haindl and Jirí Filip (2013) pointed out that texture means different things depending on the application area. They gave many possible meanings of texture according to the Oxford or Webster's dictionaries: the process or art of weaving, consistent natural structures, the size, or organization of small constituent parts of a body or substance, the visual or tactile surface characteristics and appearance of something, among other sentences used to define the texture appearance of materials in daily life.

Unlike the visual attributes mentioned above, it is the most complicated term to describe, since surface texture is a complex subject that does not have a mathematical interpretation and certainly does not have a clearly defined method of measurement so far. Texture has traditionally been understood as being linked to roughness, and roughness categories have been defined according to the size of the particles and their distribution on the surface. The effect of texture on perception is more complex, and the term *visual texture* has been coined, as heterogeneous surfaces appear with small details that produce their perceptual effects. The measurement of visual texture requires a somewhat different approach than the aforementioned visual aspects. There are many types of surfaces according to their visual texture, and a measurement scale for one type does not fit the others. Thus, one must clearly define the type of texture to be compared and, from there, define the appropriate measurement scale. A physical quantity that makes it possible to characterize textures that depend on the geometrical conditions of illumination and observation is the bidirectional texture function (BTF), which, analogous to the BRDF, provides information for specific illumination and observation directions. It therefore requires the use of a spatially resolved gonio-reflectometer (Dana, 1999). If color is of relevance for a certain type of texture, RGB cameras can be used, but if the dependence on the spectral distribution of the illuminant is to be taken into account more rigorously, multispectral or hyperspectral cameras can be employed. In more recent years, innovative coatings and paints with metallic particles have appeared on the market, whose evaluation is the main purpose of this doctoral thesis. These coatings generate two visual effects known as sparkle and graininess (Ershov et al., 1999; Kirchner et al., 2007; Ferrero et al., 2013a). More details on sparkle and graininess are given in *subsection 2.3*.

2. *Effect Pigments*

As already mentioned, this thesis focuses on the digital reproduction of the appearance produced by effect pigments. This section gives a detailed description of such pigments.

Effect pigments have broken new ground in color physics. Special research efforts focusing on the development and applications of these pigments in the industry are needed. They have become highly popular in the market, where an optically attractive and premium material appearance is the main customer priority in today’s time. Coatings, paints, printing inks, plastic, artist paints, cosmetics, leather, construction materials, paper, glass, and ceramics are all examples of the everyday applications of effect pigments.

Effect pigments and absorption colorants are usually classified into two separate groups, and they are referred to as modern colorants. The perceived color produced by them is only possible when they are illuminated by external light sources. For this reason, they are classified as non-self-luminous (Klein, 2010). All effect pigments are composed of flake-shaped particles in lamellar forms with characteristic diameters between 1µm and 1mm, which are 10-1000 times larger than the particles of absorption pigments. The flake thickness usually ranges from 10 nm to 1µm (Streitberger & Dossel, 2008; Kettler et al., 2016). The color effects obtained by effect pigments are mainly caused by anisotropic behaviors such as reflection, interferences, or diffraction (Berns, 2019). These optical behaviors cannot be produced by traditional absorption pigments.

The color appearance of effect pigments is extremely dependent on the illumination and the observation geometries. This characteristic results in new, impressive, and even strange color sensations for human observers, since their visual system has evolved to mainly perceive absorbent colorants. In practice, effect pigments require more sophisticated production methods compared to absorption pigments. They also need specific techniques for their characterization, measurements, application, and processing, which have evolved over time.

Effect pigments are divided into two main groups: metallic effect pigments and special effect pigments, including pearl luster pigments and interference pigments (Cramer & Gabel, 2001a, 2001b; Cramer, 2002a,2002b; Pfaff, 2009, 2021; Pfaff et al., 2021; Wißling, 2006; Klein, 2010).

The history of both subgroups of effect pigments could be studied in parallel. Although the first evidence of metallic and pearl pigments could date from the last centuries BC, it was only in the middle of the last century that the industrial production of effect pigments became significant. The reason behind this late emergence was first the autonomous technical development these pigments required, in contrast to absorption pigments. The second reason was the unusual colors and optical effects produced by these pigments, which cannot match the conventional colors obtained by absorbent pigments. The most conventional effect pigment was the metallic gloss. In fact, the earliest proof of the use of effect pigments in history could be found in Egypt 5000 years ago (Humpl, 1990). There is clear evidence that the ancient Egyptians used very thin films of beaten gold (thin foils of 1µm) to decorate jewelry, building structures, and artworks in 2500 B.C. Later, this technique spread to Asia, and evidence has been found in India, Korea, and Japan from about AD 800. The gold beating art spread from there to reach Rome. Via Greece, the technology of gold beating reached Germany. The town of Nuernberg had the first center of gold beating technology. From then on, many developments on metallic pigments happened in this region. The huge demand for gold foils led to many failures, which ultimately resulted in the creation of protective binders. Gold dust then started to be used as a pigment. These gold flitter flakes led to the impressive metallic pigments of nowadays (Wißling, 2006; Pfaff, 2009; Klein, 2010).

The luster of natural pearls captured the attention of people in ancient times. The impressive optical sensation and the 3D appearance caused by the dark and mirror areas of their surfaces increased the passion for pearls. The first attempt at imitating the color luster of pearls was 3000 years ago in China, which involved mixing various materials to obtain the special luster of pearls. In the 11th century, hand-made crystal pearls were produced by experienced Venetians, but the government banned them at that time due to the high quality of these pieces. Much later, in the 16th century, the earliest transparent luster pigments were created in Paris when Jacquin tried to imitate the color phenomena produced by pearls using the silver substrate of fish scales (Pfaff, 2009). Despite the increased cost of this technique, it was commonly used until the early 20th century. Starting from 1950, a new pigment generation based on the crystallization of suitable inorganic components and metal oxide coated mica platelets was introduced to the market (Pfaff, 2009; Klein, 2010). The development of more complex pigments with two or multi-layer pigments also started. The chromatic brilliance of these pigments is a result of the interference effect produced by the difference in the refractive index of their layers.

All effect pigments are formed by thin layers with no more than a few µm of thin platelets inducing a strong luster effect, especially when applied in parallel alignment to a painted surface. Therefore, metallic effect pigments, as well as special effect pigments, are usually referred to as *luster pigments*. The main difference between both groups is the transparent or semitransparent property of special effect pigments compared to metallic effect pigments.

Due to the pigment’s shapes, different colors are perceived depending on the morphology and orientation of the flakes on the substrate of the coating. Figure

4 shows different optical behaviors when visible light interacts with different types of pigments (Pfaff et al, 2021).

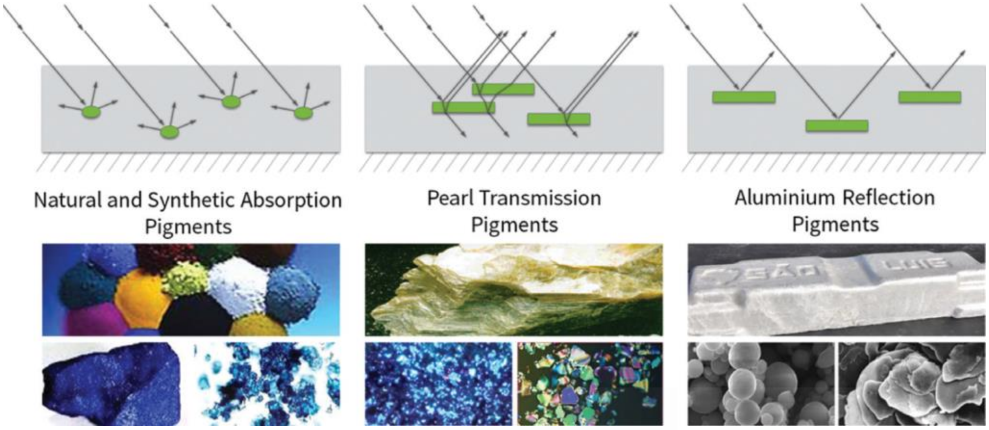

Figure 4. Optical principles for the interaction of light with different pigments (Pfaff et al, 2021).

In the literature, other classifications of effect pigments can be found. Klein (2010) refers to four different groups of metallic effect pigments regarding their production process:

- Metallic pigments
- Pearlescent pigments
- Interference pigments
- Diffractive pigments

It should be noted that some literature often includes pearl luster pigments in the interference pigment group (ASTM, 2008; CIE124/1, 1997; DIN, 2001).

This thesis will consider two main groups of effect pigments in the following two subsections, metallic effect pigments (referred to as metallic pigments for simplicity) and special effect pigments. The latter comprises pearl luster, interference, and diffractive pigments.

2.1. Metallic Pigments

Metallic pigments produce unusual color effects, caused by the metallic reflection due to the presence of the so-called metallic flakes. These platelet-like metallic particles are responsible for the metallic reflection that occurs from the flake-shaped particles, consisting mostly of aluminum (so-called silver bronzes), copper, copper/zinc (so-called gold bronzes), and zinc flakes. These pigments are usually provided in the form of powders, pastes, pellets, suspensions, or color concentrates (Buxbaum, 2005).

Metallic paints, which are widely used in the automotive industry, are the best-known example of effect pigments. Other metallic pigments and powder forms are also used for functional purposes in coatings (Pfaff, 2022; Kettler et al., 2016). The optical properties of metallic pigments are essentially controlled by the laws of geometrical optics, and those of special effect pigments, by the laws of wave optics. Metallic pigments are based on metals or alloy metals. The resulting metallic reflection is usually a combination of two reflection components: specular and diffuse. This effect is called the *metallic effect* and is caused by the directional and diffuse reflection on the surface and edges of the flakes. The flakes consist of thin aluminum platelets with diameters between circa 5 and 50 µm, lying almost parallel to the coating surface and embedded in a colored medium. The more parallel oriented to the surface the flakes are, the more brilliant they are perceived to be. This makes the visual appearance of these materials much more complex to be described qualitatively and quantitatively than for most other paints and materials. The presence of the flakes makes the color strongly dependent on the viewing and illumination angles; this phenomenon is often referred to as color flop (Pfaff, 2009), also known as *goniochromatism* or iridescence. According to the ASTM, *goniochromatism* is defined as the change in any or all attributes of the color of a specimen on change in angular illuminating-viewing conditions but without change in light source or observer (ASTM, 2009). For metallic coatings, this is particularly the case for the color attributes, lightness, and chroma. For this reason, metallic coatings are also considered goniochromatic coatings.

However, the visual appearance of metallic coatings is characterized not only by color but also by their visual texture (Huang et al, 2010; Dekker et al., 2011). This will be covered more in detail in the next *subsection 2.3*.

The metallic appearance of metallic pigments is caused by the interplay of the direct reflected light at the surface of the metallic flakes, the scattered light at the edges of the flakes, and the reflected light from the irregularities of the metal flakes' surface (Figure 5).

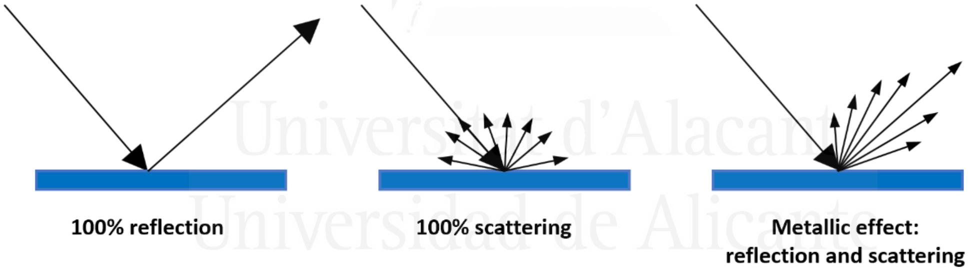

Figure 5. Principles of the metallic effect (Wißling, 2006).

To achieve an increased metallic effect, the flake platelets should be applied parallel to the surface or substrate, which increases the direct reflection at the platelet surface and minimizes the scattered light at the edges. According to Klein (2010), the optical impression of metallic pigments depends on the following factors:

- Type of metal (aluminum, copper, copper/zinc alloy)

- Wetting behavior of the pigment (leafing or non-leafing)
- Surface smoothness of the pigment particles
- Particle size and particle size distribution
- Particle thickness and particle thickness distribution
- Form factor and aspect ratio of the platelets (ratio of diameter to thickness)
- Nature of the interface (air or application medium)

During their manufacture, metallic pigments are subject to strong mechanical forces, which leads to defective surfaces. This irregularity is responsible for the high diffraction of light on the surface of the pigment. This makes the characterization of the reflected light from these coatings much more complex. Consequently, the visual impression produced by these coatings is not easy to describe. According to Wißling (2006), the visual perception of metallic pigments is a sum of various visual effects. These are:

- Hue or color shade
- Brightness or whiteness
- Brilliance
- Hiding power or tinting strength
- Optical roughness (sparkle effect)

More recently the different components of visual texture were identified as sparkle and graininess (Kirchner et al. 2007; Huang et al. 2010), as discussed further in *subsection 2.3*. The perceived metallic effect originates from the reflected light at the plane surface of the pigment flakes. High intensity and large size regular pigments shape (above 30µm) lead to high reflectance, and the metallic impression is higher.

There are two basic processes for manufacturing metallic pigments (Wißling, 2006; Kettler et al, 2016):

- The milling of atomized metal granules in ball mills using lubricants such as stearic or oleic acid to avoid uncontrolled actions like cold welding/formatting of agglomeration (Hametag or Hall process).
- The evaporation of aluminum under high vacuum to be then deposited on plastic films printed with release coat. The release coat is stripped from the film and coarse aluminum is shredded off to the appropriate size (physical vapor deposition-PVD).

Tailor-made pigment production is possible through a proper selection of the manufacturing process and by controlling the following production parameters:

Leafing and non-leafing properties: controlled through the wetting property of the pigments. When a saturated fatty acid like stearic acid, this leads to leafing pigments, which are organized parallel and close to the paint surface (leafing pigments; Figure 6). On the contrary, a better wetting is obtained when using oleic acid or PVD produced pigments; this results in non-leafing pigments, in which pigments are uniformly distributed along with the coating (non-leafing pigments; Figure 6) (Kettler et al, 2016). Leafing pigments are usually more brilliant than non-leafing pigments but show less physical and mechanical stability.

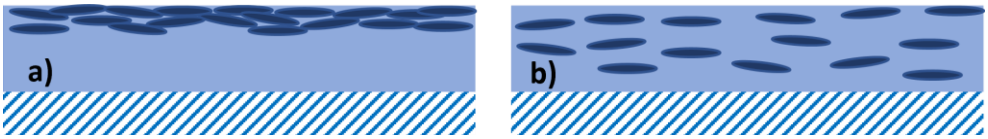

Figure 6. Wetting behavior of metallic pigments: a) leafing, b) non-leafing (Kettler et al, 2016, chapter 3.1.1).

Particle size parameters**:** the appearance of the coating is directly affected by pigment size. Usually, fine particle pigments appear darker than large particle pigments. Compared to smaller flakes, larger particles (> 20µm) are more easily distinguished by bare eyes and perceived as sparkling (Kirchner et al., 2015a).

Particle shape, thickness, and topography**:** the metallic effect is especially affected by the morphology of the flakes. Depending on the manufacturing process, different pigment shapes can be obtained. Hall's wet milling procedure typically provides irregularly formed platelets with high edge errors and a broad particle-size distribution, known as *cornflakes* (aluminum cornflakes in Figure 7, a). These particles are mainly formed by the breakdown of larger particles in the ball mill. The exerted abrasion results in uneven flake surfaces. This unevenness, together with the broken remains of the edge zones (the rugged particles), is the main responsible for the increased diffuse light scattering of the cornflakes, causing brilliance reduction and giving a grey shade. Starting from the 1980s, new grinding techniques with metal brushings or polishing pastes were developed aiming to reduce the brilliance loss of the cornflake particles. These techniques allow the generation of thicker and almost round-shape metal flakes called *silver dollars* (Figure 7, b). These particles show high direct reflections and very low scattering. They also provide an increased flop effect but less hiding power due to their high thickness. Therefore, it is evident that coatings with silver dollar pigments and clearcoat are usually lighter than the coatings containing cornflakes. It was also possible to manufacture smooth and high brilliance (mirror-like) pigment surfaces (*PVD Al flakes*) with very low scattering, thanks to the new PVD technology that appeared in the 1990s (Figure 7, c). Recently, optimized aluminum *SilverShine* pigments (Figure 7, d) were produced using the new wet-grinding methods, with an extremely increased metallic effect comparable to the quality of the PVD pigments known today.

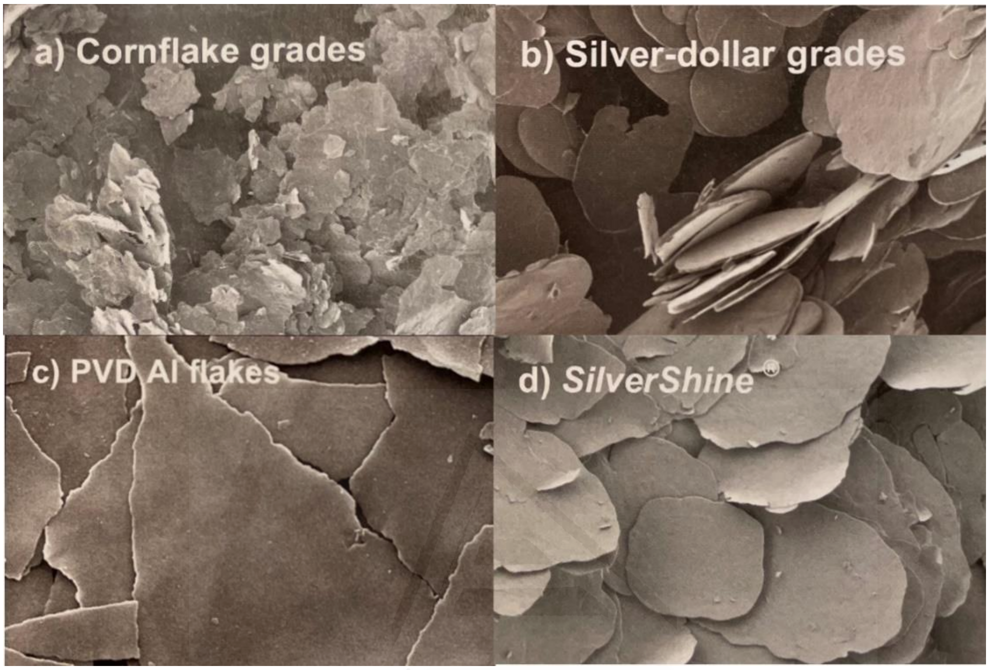

Figure 7. Scanning electron microscope (SEM) images of various pigment generations (Kettler et al, 2016, chapter 3.1.4).

***Orientation of pigments on the paint film*:** the orientation of the pigments on the substrate directly affects the resulting metallic effect. The used processing technique mainly determines the degree of alignment of the particles to the coating surface. The selected binders, additives, and substrate uniformity can influence the alignment of the particles on the coating surface. High parallel alignment of the metallic flakes produces an optimized metallic effect.

2.2. Special Effect Pigments

Special effect pigments are mainly inorganic natural or synthetic pigments. They are characterized by their high luster, brilliance, and iridescent color appearance caused by optically thin films. The optical reflection and deflection of light at these thin layers are responsible for the characteristic visual appearance of such impressive pigments. Nature has many examples of these fascinating color effects, for example in pearls, clamshells, feathers, birds, fish scales, gemstones, minerals, and insects. Research focusing on the appearance of the natural pearl luster and its optical principles demonstrates that the luster color effect is mainly attributed to patterned biopolymers and platelet layered structures, which result from the biomineralization process (Franz et al., 1992; Pfaff, 1997; Pfaff & Reynders, 1999; Snow et al., 2004; Katti & Katti 2006; Pfaff, 2009; Pfaff, 2017).

Pearlescent coatings form a special type of effect coatings (special effect coatings), which are also popular in the automotive industry. In this sort of pigments, flakes are in the form of one or more (multi-layered) structures, characterized by their high refractive index ranging from 1.5 to 2.9. They simulate the luster of natural pearls or shells of mollusks with their alternating structure of transparent layers with different refractive indices, which gives rise to iridescence by interferences. Mica is the most used substrate together with other metals and metal oxides. The permutation of the different layers, the multiple reflections at the layer’s boundaries, and the optical interferences are responsible for the specific pearl luster produced. As a result, not only lightness and chroma but also the hue of pearlescent coatings varies with viewing and illumination directions.

Pearlescent pigments that exhibit additional colors generated completely with interference phenomena are called interference pigments. These interference pigments do not require the use of mica substrates and are generated through the differing optical layers. The strong relationship between the refractive index and the thickness of the layers produces the first and higher interference orders and makes possible the observation of a variety of interference colors, which also vary with the observation geometry.

In addition to the pearlescent and interference pigments, diffraction pigments also appear in the literature as a separate subgroup of special effect coatings (Klein, 2010; ASTM, 2008; Pfaff, 2009). The color effect due to the grating structure of the diffraction pigments could also be related to the wave behavior of the light. These substrates (the diffractive grating structures) are created by ferromagnetic particles which are responsible for producing the impressive colors perceived.

Concerning the above categories, special effect pigments can be considered as pearlescent pigments and transparent or non-transparent interference pigments that, regardless of their formulation or physical structure, produce a pearlescent or non-pearlescent appearance combined with interferences in the coating surface. The ability to produce transparent synthetic platelets has been crucial for the development of special effect pigments. Such new surface films, in parallel to the mica substrates, may also be overlaid with metal oxide layers. Pearlescent and interference pigments can be either natural or synthetic, and transparent or partially light-absorbing. These new developments further expand the classes of effect pigments.

Synthetic mica (fluorophlogopite) is one of these new pigments used nowadays instead of natural mica (muscovite), in addition to other pigments like the platelets of silicon dioxide (silica flakes), aluminum oxide (alumina flakes), and borosilicate (borosilicate or flake glass) used for the production of new effect pigments. Innovative decorative effect pigments based on liquid-crystal polymers and textured surface pigments were also introduced in the last two decades (Kettler et al., 2016).

The color production properties of pearlescent, interference and diffractive pigments are dependent on the geometry of the pigment particles, especially on the light interference properties and the physical color conditions surrounding these particles. Light interference phenomena are responsible for the varied color effects produced by these pigments. The differences in the refractive indices between the different layers induce differences in the optical path lengths (*G*). As shown in Figure 8, the incident rays follow different optical paths until these are finally reflected at the surface.

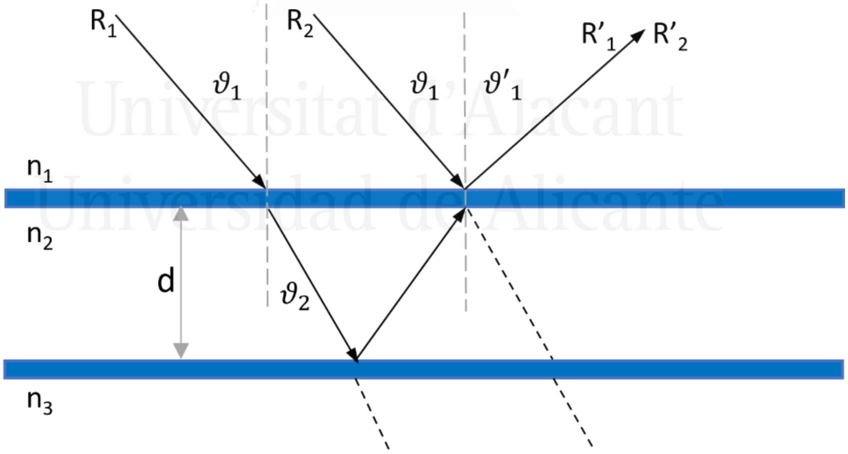

Figure 8: Interference at a parallel monolayer with different refractive indices.

According to equation (1) (Klein, 2010), the interference laws are a function of the wavelength λ, the refractive index at the interface *n*, the thickness *d* of each of the layers, and the angle of observation or interference ϑ_1.

$$G = 2d.\sqrt{n^2 + \sin\vartheta_1{}^2} + \frac{\lambda}{2} \qquad (1)$$

Different light interactions occur due to the variations in the refractive index, the morphology of the pigment particles, and the number of layers on the coating surface. Constructive interferences (on the pigment multilayers) are responsible for the intense colors that strongly change with the observation angle. Part of the perceived brightness comes from the single reflection of the interferences, while the characteristic pearlescent luster effect of pearlescent pigments is caused by the multiple reflections at different interfaces of transparent or translucent layers. Additionally, the dispersion at the pigment edges and the absorption at the coating materials both contribute to the appearance of these coatings. The former is responsible for the matt interference colors while the latter reduces the gloss depending on the coating material (Klein, 2010).

Special effect pigments can be formed by either single crystals or layer systems consisting of multiple layers, or monolayers as shown in Figure 9 (Pfaff, 2022). Technically speaking, layer-substrate-based pigments are the most important type of special effect pigments. These can come on platelets of natural mica, alumina, silica, or borosilicate flakes. These pigments are usually made through a wet chemical process and a high-temperature process. Additionally, during production, the pigments can be exposed to mechanical or other processes, like crystal growth, glass formation, and web coating processes (Pfaff et al., 2021).

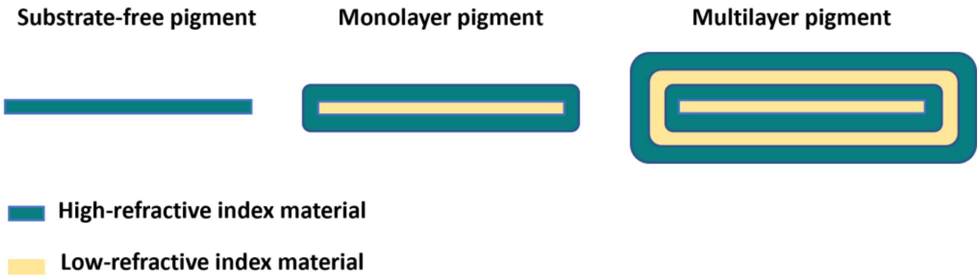

Figure 9: Basic structural principles of transparent effect pigments (pearl luster pigments, interference pigments), left: platelet-like particles consisting of an optically homogeneous material (substrate-free); middle and right: platelet-shaped particles, consisting of layer-substrate structures (monolayer, multilayer) (Pfaff et al., 2021).

Special effect pigments can also be classified according to their particle size and material substrate composition. In the literature (Pfaff, 2009; Pfaff et al., 2021; Kelin, 2010; Maisch & Weigand, 1991), there are five commonly mentioned pigment classes: silver-white (SW), gold (G), iron oxide (IO), interference effect (IE), and multi-color (MC).

Silver-white pigments: they are composed of natural mica as a substrate together with a small layer of titanium dioxide (TiO_2). At 40 to 60 nm, the titanium dioxide layer is very thin, causing a silver-white interference effect. The resulting visual impression of gloss and texture depends on the particle size of these silver-white pigments.

Gold pigments: these pigments are usually composed of a natural mica substrate with a two-layer overlay. A layer of titanium dioxide (TiO_2) is combined with a layer of iron oxide (Fe_2O_3). The titanium dioxide and iron oxide are stacked, either in two separate layers or mixed in a single layer. A golden yellow color is obtained by combining both oxides.

Iron oxide pigments: a typical iron oxide pigment is composed of a natural mica substrate with a monolayer iron oxide (Fe_2O_3) overlay. The iron oxide overlay is responsible for the rusty reddish-brown color impression.

Interference effect pigments (IE): these pigments are called so because of the strong interference effect produced in a single layer. The strong influence of the thin layer results in a considerable change in the perceived color due to the change in the geometrical configurations.

Interference pigments are composed of a natural mica substrate together with a titanium dioxide (TiO_2) layer. Unlike the previously mentioned silver-white pigments, the overlay layer of interference pigments is much thicker. Figure 10 gives a representative diagram of the reflected interference colors depending on the titanium dioxide layer thickness, ranging from yellow (60-80nm) to green (between 120 and 160nm). The transmitted light has the complementary color of the reflected light (Pfaff et al., 2021).

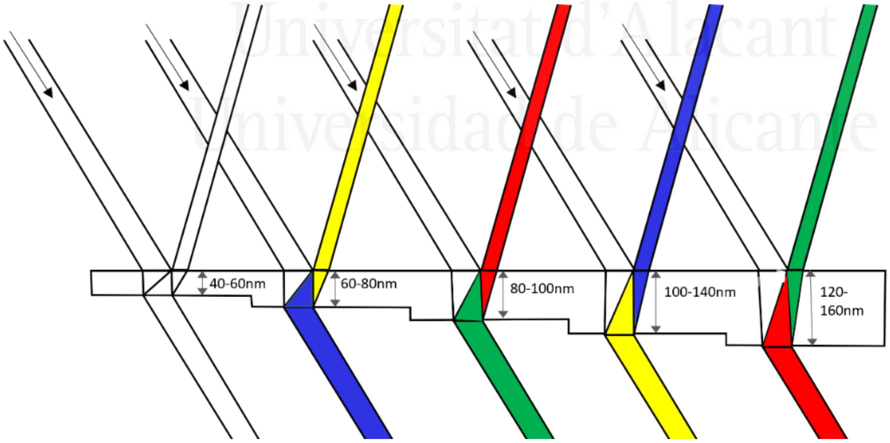

Figure 10: Interference pigment colors (Lozano, 2017).

Multi-color (MC) pigments are an improved version of the interference effect pigments (Pfaff, 2009; Cramer, 2002a). They consist of a combined multilayer with alternating refractive indices (more than one high refractive index), which leads to a stronger and much more pronounced color shift effect than for the interference pigments. Unlike in the interference pigments, in the multi-color pigments, the color shifts between two specific chromatic colors, and not from an achromatic to a chromatic color.

An intermediate layer of low refractive silicon dioxide (SiO_2) is always located between two layers with a high refractive index (Pfaff, 2009, 2022). Cramer (2002a) stated that these intense color changes of multi-color pigments are visually more interesting than the gloss or the texture appearance.

2.3. Effect Pigment Characterization

Recent years have seen the emergence of effect coatings and paints with metallic particles that generate innovative and impressive visual effects. At the end of the 20th century, McCamy (1996, 1998) gave a comprehensive overview of the appearance and visual attributes of these coatings. With dedicated visual experiments, the most important visual effects introduced by these pigments were determined, which showed that their visual appearance is characterized not only by color but also by their visual texture (Kirchner et al, 2007; Huang et al, 2010). The most relevant visual texture parameters were found to be sparkle (also known as glint impression) and graininess (also known as diffuse coarseness) (Ershov et al, 1999; Kirchner et al, 2007; Ferrero et al, 2013a). Clear definitions and quantifications of these parameters as well as a characterization of the lighting conditions under which they are visible were given for the first time by Kirchner et al. (2007). Sparkle or glint (also called sparkling or optical roughness) (Kirchner et al., 2007; Klein, 2010; Pfaff, 2009) is a non-uniform texture consisting of very bright dots distributed in a dark environment that can be observed when illuminated by a highly directional source, such as the sun. Small size and irregular pigment shapes turn the color shade to gray and the metallic sensation is reduced. Large size pigments are usually perceived as single flakes by naked eyes on the coating surface. This is due to the high intensity of the directionally reflected light on their surfaces, which also justifies the dependence of the sparkle effect on the illumination and observation geometries. This sparkling change is caused by the distortion and irregular orientation of the flakes on the coating surface.

Under diffuse illumination, such as under an overcast sky, the sparkle effect disappears completely, and a new visual effect of the lower-contrast spatial pattern of darker and lighter areas at a spatial scale of millimeters appears (Kirchner et al., 2007). This visual effect is called graininess, coarseness, or vivid “salt and pepper”. In contrast to the sparkle effect, graininess is independent of the viewing geometry. It depends on the type and size of the pigment and the irregularities of the orientation of the flakes.

As mentioned above, characterizing the color and texture of effect pigments is by no means an easy challenge. To do a complete characterization of the color of effect coatings at any illumination/detection geometry, it is necessary to measure their BRDF (Bidirectional Reflectance Distribution Function) for a large number of measurement geometries, which provides all the necessary information for a proper characterization of the color change of these coatings. This is possible by using experimental gonio-spectrophotometers like the GEFE gonio-spectrophotometer (the acronym for “Gonio-Espectro Fotómetro Español”) (Rabal et al., 2012; Bernad, 2015), which makes it possible to measure the spectral BRDF at any geometry for a large number of illumination/detection geometries, including out-of-plane and retro-reflection angles.

However, simplified numeric quantities to characterize the color flop effect of effect coatings are required in many areas. For example, for rendering applications, dealing with such an amount of data is time-consuming, computationally expensive, and requires highly efficient hardware. Research demonstrates that reflection data do not vary considerably at reciprocal geometries (Ferrero et al., 2012, 2014a, 2014b).

Moreover, Ferrero et al. (2012) proposed a mathematical model that results from a Principal Component Analysis of the BRDF, by separating geometric variables (angles of viewing and incidence) from the spectral variable (wavelength). This representation facilitates the interpretation of the color variation of the special effect coatings. It also helped in the development of spectral models of the BRDF of these coatings.

Ferrero et al. (2014a, 2014b) showed that a strong reduction in reflection data by using only in-plane measurements is possible for characterizing these coatings. These works draw on the flake-based concept proposed by Kirchner & Cramer (2012) for describing the angular variation of the reflectance of effect coatings. Prior to the flake-based parameter model, Cramer and co-authors (Cramer, 2002a, 2002b, 2006; Cramer & Gabel, 2001a, 2001b, 2003) took a huge step toward a better understanding of the color variation of metallic and special effect pigments. They introduced the concepts of the interference and aspecular lines defined on the a^*, b^*-diagrams.

The interference line represents the locus of calculated color coordinates from measurement geometries with a fixed aspecular angle (the angular distance relative to the specular direction).

The aspecular line represents the locus of calculated color coordinates from measurement geometries with a fixed irradiation angle.

The authors claim that the color variation of special effect pigments is well represented by the interference lines with low aspecular angles, while the aspecular lines could be better used for characterizing the scattering produced by absorption pigments. After conducting a physical analysis of the aspecular lines and interference lines, Kirchner & Cramer (2012) presented an interpretation of special effect coatings based on a physical flake-based parameter model instead of using the common incident and viewing angles on the coating surface. The reflectance properties of special effect coatings are mainly determined by the presented flakes inside the coatings, which makes it logical to use parameters concerning the local normal vectors to these flakes. The color variation depends on the incidence angle on the flake (θ_{inc}) more than it does for the coating (θ_i). Figure 11 shows how the flake-based pair parameters $[\theta_{inc}, \theta_{flake}]$ define the irradiation (θ_i) and viewing (θ_s) directions.

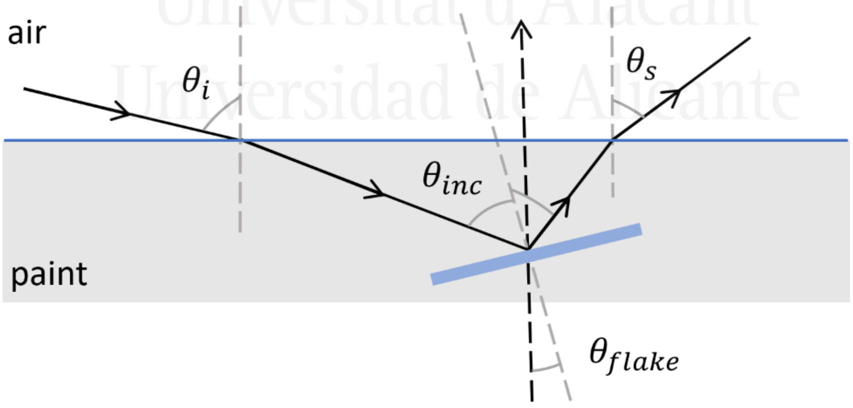

Figure 11: Geometrical description of the flake-based model parameters.

Many works demonstrate that these flake-based parameter models perform much better for representing the BRDF functions of special effect coatings than those common irradiations and viewing angles (Ferrero et al., 2014a, 2014b, 2016; Kirchner et al., 2015a; Rogelj & Gunde, 2016; Strothkaemper, 2016). This model is expected to be useful for the representation of the color change on metallic effect pigments as well. Other mathematical models that have been proposed for representing BRDF functions can be found in the following works: Pharr et al., 2016; Haindl & Filip, 2013; Dorsey et al., 2010.

The widespread use of effect pigments in many industries (automotive, cosmetics, paper, architecture...) makes it necessary to perform good quality control of their appearance (Streitberger & Dossel, 2008). For this, the most relevant aspects and characteristics of these pigments must be measured: color flop and typical texture attributes (sparkle and graininess). Therefore, in more recent years, projects related to the optical characterization of these pigments have been developed. The CIE has also shown interest, looking for convenient control methods through objective, rather than subjective methods, i.e., by using physical measurements.

To overcome these issues, a high-level collaboration between academic researchers and the industry is crucial. For this reason, the European Metrology Research Programme EMRP (EURAMET, 2017) funded the joint research project “Multidimensional Reflectometry for Industry” (xD-Reflect, 2016). xDreflect provides the industry with new efficient measurement strategies and new standard artifacts to characterize and control the visual appearance of products. Outcomes of this project were used in the Joint Research Project “Bidirectional Reflectance Definitions” (BiRD, 2017), focusing on the pre-normative work to characterize measurements on surfaces with goniochromatic, gloss, and texture visual effects. Recently, the CIE has intensified collaboration between different NMIs to define a standard and generalized measurement scale for the characterization of texture attributes based on physical reflectance measurements (Ferrero et al, 2018; Ferrero et al, 2020; Ferrero et al, 2021).

In practice, different notations of the configuration of optical measurement geometries have been used (Cramer, 1999, 2002a, 2002b; Cramer & Gabel, 2001a, 2001b). CIE technical reports TC1-65 (Pointer, 2006) and ASTM E 2175-01 (ASTM, 2001) give general information on the multi-angle geometric specification. ASTM E 2194-03 (ASTM, 2003b), ASTM E 2539-14 (ASTM, 2021) and DIN 6175-2 (DIN, 2001) list some preferred geometric configurations. All the geometrical notations used contain information about the light source position and the detection system relative to the sample surface. The statement of the angle of incidence or illumination and the angle of reflection or detection seems to be obvious. Instead of the reflection angle, the most common notation uses the so-called aspecular angle, which is defined as the angular distance between the collection and the specular directions according to CIE technical report TC1-65 (Pointer, 2006). The illumination source, the normal to the sample, and the detection system are usually in the same incidence plane (in-plane) (ASTM, 2003a; Pointer, 2006).

In the case of optical instruments, the angle of incidence is also referred to as the illumination angle. The illumination angle specifies the location of the light source relative to the sample surface. Figure 12 shows that the incidence/illumination angle is counted from the normal vector to the incidence vector.

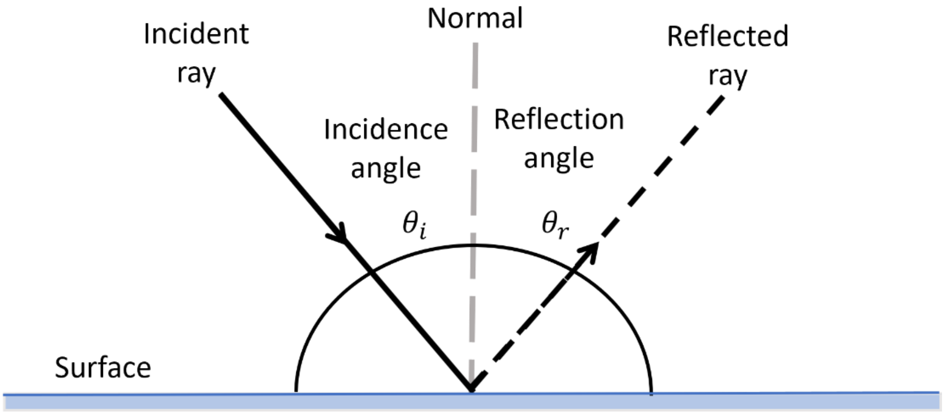

Figure 12: Incidence and reflection geometries.

The reflection angle is counted from the surface normal. In this way, the location of the detection system is specified relative to the sample surface. The reflection angle is also called the detection angle in the case of optical instruments. Another possibility to specify the location of the detection system is by using the above-mentioned aspecular angle. Geometries with a positive aspecular angle are referred to as *cis* geometries, while geometries with a negative aspecular angle are referred to as *trans* geometries.

Numerous studies and models have thoroughly investigated the variables involved in assessing the sparkle texture effect (Kirchner et al, 2009, 2015a; Ferrero & Bayón, 2015; Ferrero et al., 2013a; Ershov et al, 1999; Ďurikovič, 2002; Kirchner & Ravi, 2012). The current state of imaging technology allows the capture and analysis of effect coatings, but until 2018 the only commercially available instruments capable of quantifying texture were BYK spectrophotometers for metallic paints (BYK-mac models) (Faulkner & Schwartz, 2009).

In this thesis, this well-known device (***BYK-mac i multi-angle spectrophotometer)*** was used for the measurement of the color and texture of effect coatings. This instrument is provided by BYK-Gardner. It comes with a circular aperture of 23 mm and provides six different measurement geometries. According to DIN 6157-2 (2001) and ASTM E2194-3 (2003b) nomenclature, these illumination-viewing geometries are referred to as 45as-15, 45as15, 45as25, 45as45, 45as75, and 45as110, where the term *as* is the abbreviation of the word *aspecular*, as shown in Figure 13, b. It takes less than six seconds to perform a complete measurement. Spectral measurements are performed at wavelength intervals of 10 nm from 400 to 700 nm.

In addition to the spectral measurements of the six geometries detailed above, the BYK-mac i performs imaging measurements at three additional directional configurations and one diffuse configuration. The three directional angles of incidence of 15°, 45°, and 75° with the detector placed at 0° are shown in Figure 13, c. Figure 13, d. shows the diffuse geometry d/0° with diffuse illumination and detection at 0°.

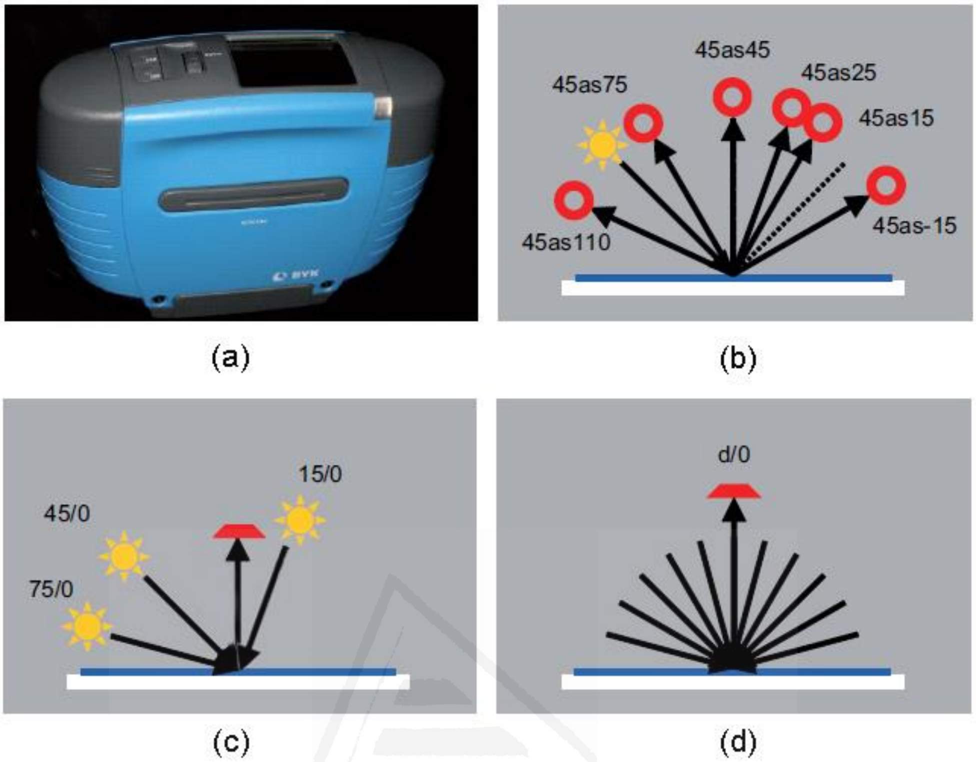

Figure 13: BYK-mac i multi-angle spectrophotometer (from Kehren, 2013).

An integrated CCD camera is placed perpendicularly (at the surface normal). The CCD sensor detects the reflected light from a white light-emitting diode (wLED). The recorded images are internally used to determine the texture parameters (sparkle and graininess). As mentioned above, these parameters are referred to as sparkle area (*Sa*), sparkle intensity (*Si*), and sparkle degree (*SG*) for each of the three bidirectional geometries, in addition to the graininess parameter (*G*) for the diffuse geometry.

The main issue with this device is that it was the only device (until 2017) capable of providing instrumental values of product texture. Furthermore, the algorithm that is applied to the images captured by the device to provide the four texture values is not revealed by the manufacturers, leading to uncertainties about its performance and reliability.

These indices are supposed to correlate well with visual perception. However, their corresponding magnitudes are not clearly defined, and therefore, cannot be measured with other instruments. Recently, the company X-Rite has introduced two new portable gonio-spectrophotometers (MA-T6 and MA-T12), which can also quantify sparkle and graininess. Both the BYK-mac and the two X-Rite multi-angle spectrophotometers have their own sparkle and graininess scales, since to date there is no standard procedure for obtaining correlations of these attributes from physical reflectance measurements. Consequently, the indices provided by these instruments are not traceable to international standards and cannot be reproduced by National Metrology Institutes (NMI) or other companies, which must develop their own scales. These issues justify the necessity of the above-mentioned collaborations conducted by the CIE with the different NMIs to define a standard and generalized measurement scale for the characterization of texture attributes of gonio-apparent materials using physical measurements of the reflectance of these surfaces (Ferrero et al, 2018; Ferrero et al, 2020; Ferrero et al, 2021). Therefore, the measurement scales are defined based on psychophysical experiments through visual evaluations of physical objects using standardized and controlled lighting environments (the famous light booths used for appearance assessments), which should correlate with the physical measurements.

C*ontrolled lighting environments* (usually called light booths) are also essential for performing visual assessments in everyday work. Many commercial light booths with a wide variety of illumination sources are available nowadays. The selection of one or other kind of light booth or illumination source for the quality assessment depends on many factors; the industrial application area, the material properties, and the usual environmental conditions of an object's place are some of these factors which directly affect the appearance of the object. However, some applications need only one kind of illumination, while some others require the use of multiple illuminations together. Some applications also require the evaluation of the same product under various illumination and lighting conditions. The use of standardized light booths helps the suppliers internally, and the customers to set up effective quality control. These identical assessment conditions allow good and fast communication, firstly, between the different departments in the production chain; secondly, with the customers and the final users. Following are some criteria that must be considered:

- The illumination used in the application: a daylight illuminant (D_{65} and D_{50}) is the most important light source for many applications since they mimic daylighting, as its name indicates. These illuminants are usually generated through filtered halogen light, although there are also fluorescent lamps that give an acceptable simulation of these daylight illuminants. Another commonly used lighting is the A-Illuminant, easily produced by incandescent tungsten lamps. Less common lightings like energy-saving lamps (F11) or office lamps (F2) are also available for some specific applications like indoor room applications.
- The illumination directions: the use of direct or diffuse illumination determines the appearance of materials.
- The observation geometries: usually, direct observation is used. For some applications, a combination of viewing and illumination geometries is required.

Objects with effect coating pigments have special requirements. The angular dependence of the appearance of such coatings makes it necessary to build specific multi-directional lighting booths and direct illumination; for instance, the Byko spectra-effect light booth (more details of it are given below), which allows the evaluation of goniochromatic texture effects like sparkle. However, non-directional light booths and diffuse illumination can also be used for the evaluation of color and some texture effects, such as the graininess effect, by following specified visual assessment methods to control the illumination and the observation geometries. Three different multi-angle evaluation methods can be applied depending on the illumination, the observation geometries, and the sample position as follows (Kettler et al, 2016, chapter III):

- Sample modulation method: sample position changes. Fixed observer and light source positions.
- Illumination modulation method: light source position changes. Fixed sample and observer positions.
- Observer modulation method: observer position changes. Fixed sample and light source positions.

In this thesis special attention was given to two well-known commercial light booths: the Byko spectra-effect multidirectional light booth (Figure 14) and the X-Rite SpectraLight QC (SPLQC) light booth (Figure 15). Both are widely used in the coating and car painting industry.

The Byko spectra-effect multidirectional light booth is developed and manufactured by BYK-Gardner, the same company that supplies the BYK-mac multi-angle spectrophotometer. The appearance of effect coatings is directly influenced by the viewing angles and conditions. With this light booth, it is possible to control both parameters to ensure an objective assessment of the overall color impression of goniochromatic effect finishes.

It supports six different viewing angles for color evaluation, controlled by a rotating platform on top of which the sample is placed (Figure 14). The swapping from one geometrical configuration to another is done by sliding the lateral handle of this rotating platform. According to DIN 61572 (2001) and ASTM E2194 (2003b) nomenclature, these geometries are referred to as 45as-15, 45as15, 45as25, 45as45, 45as75, and 45as110.

For the evaluation of the sparkle texture effect, direct illumination by a set of three LEDs is used, simulating the directional sunlight (Perales, 2011). A very important aspect to consider of this light booth when evaluating sparkle is that the illumination level is adjustable, which also allows the evaluation of the effects of this attribute on the sparkle appearance.

Figure 14: The Byko-spectra effect light booth (BYK-Gardner). The left image shows the inner structure and the rotation platform of the light booth.

The X-Rite SpectraLight QC (SPLQC) is a visual color evaluation system widely used in the paint and graphical industry for visual quality evaluation and color assessments, providing selectable light sources. As illustrated in the luminaire box sketch in Figure 15, the SPLQC integrates seven different standardized lighting sources that are placed on the overhead luminaire, illuminating a medium gloss neutral-colored viewing box. The daylight D65 and A illuminants are the most relevant for industrial practice.

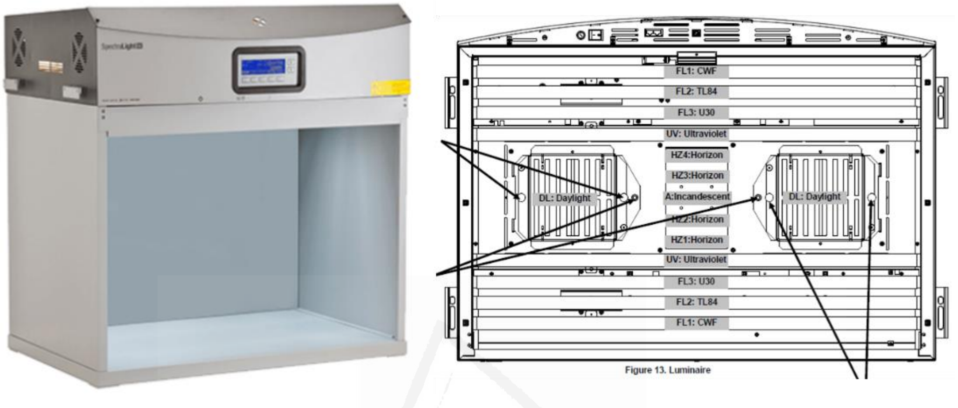

Figure 15: X-Rite SpectraLight QC (SPLQC) light booth. The right figure shows the luminaire box (bottom view).

In this study, a physically based virtual model of both light booths was built using the physically based rendering approaches developed in this thesis (details in *section 3*). All the psychophysical experiments performed as part of this thesis were done using the Byko spectra-effect light booth.

3. *Physics-based Rendering of Effect Pigments*

Rendering is a generalized term normally used to refer to the computer graphics world. However, the term computer graphics is broader, and the digitalized visualization applications existing nowadays, like gaming, virtual reality, computer-aided design (CAD), cinema and film production, advertising, and even the graphical user interfaces (GUIs) on computers, mobile phones, and many other intelligent devices in daily life are all supported by computer graphics. Akeley & Hughes (2014) gave an extended and inclusive definition of computer graphics as the science and art of communicating visually via a computer's display and its interaction devices.

Rendering is generally interpreted as a form of computer graphics, understood as the process of generating images from 2D/3D geometrical models (of an object) or scenes by means of dedicated computer software packages, whose objective is to give a realistic appearance from any perspective of the simulated model. In general, rendering means causing certain objects or images to appear on the display.

The word *model* is used to refer to two important components in the computer graphics world. These are the geometrical and the mathematical models. Geometrical models are the models of things to be simulated on the rendering scene: to simulate a house, a table, or a car, one should start by making a geometrical model of the desired object. This model is then subjected to various processes with the use of material texturing techniques, lighting, distribution, as well as photographic techniques to create a series of optical effects that simulate a specific situation in the real world (Dong, 2013). Blender (Blender Foundation, 2002), an open-source 3D modeling software, is one of the widely used 3D software packages for creating digital art and animations. It allows a complete 3D creation pipeline to be designed. The geometrical models created in this pipeline consist of 3D meshes containing a representation of each component of the desired objects and their dimensions.

On the other hand, mathematical models can be physical or computational. The rendering is processed through mathematical models, i.e., formulas and algorithms that come from the field of optics, using different optical phenomena like occlusion, reflection, refraction, caustics, etc. There are also models describing the movements of an object or defining how a camera captures a scene. When all these models are joined together and used in the right way, they arrange the pixels of the image to be created, in such a way that they look like a real image. The result is a photorealistic image with the “modeled” object being as close as possible to reality, or completely different if it has no equivalence known so far in the real world.

Graphics engines are an essential part of rendering programs. These engines are capable of performing complex techniques such as radiosity, ray tracing, alpha channel, reflection, refraction, or global illumination.

Rendering software has progressively evolved over the past decades. The improved interactive rendering technology nowadays enables important industrial processes such as computer-aided design and manufacturing, virtual prototyping, and scientific visualization and simulation (Wong & Wang, 2014). Currently, there are many rendering software packages available either commercially or through opensource, such as Maya, Keyshot, VRED (Autodesk), Revit, Corona, and Mental Ray (Nvidia) (Martín et al, 2017). The frames (images) created by these software packages suggest photorealism and sometimes are even claimed to be photorealistic, but surprisingly few articles analyze the accuracy of these images. Considering the robustness of the human visual system, producing realistic appearance images is very challenging since a simple mismatch in the brightness of the simulated scene is immediately noticeable by human observers (Akeley & Hughes, 2014). Seemingly realistic and impressive scenes are widely seen nowadays. There are spectacular, but often inaccurate, scenes in cinema and gaming, and sometimes not even the colors are natural. But critical industrial applications such as those used in the automotive industry require not only a realistic appearance but also accurate color reproduction. Displayed colors should match real-world colors as much as possible. Therefore, visual comparison of the rendered images with the real-world objects they intend to simulate shows in many cases that these are not realistic in terms of color reproduction accuracy (Günther et al, 2005; Ferwerda et al, 2004). This situation is even worse for rendering effect coatings. The challenge here is bigger due to the physical complexity of these materials. Modeling light interaction on refractive media is an important component in the appearance of materials. If the boundary of a uniform medium is smooth, these physical interactions are easily modeled using Snell's law of refraction. However, if the material surface is not uniform (as is the case, for example, for textured effect coatings), and/or when the material surface is physically rough, there is a lack of physically based and verified models for a proper rendering of such materials (Walter et al., 2007).

The first step towards improved color reproduction accuracy in rendering is to include a full spectral approach that takes into account the spectral reflectance of the object (or the paint covering the object) as well as the spectral power distribution of the environment light sources. Several spectral renderers are currently available, such as Mitsuba (Martín et al., 2017), ART, and Mental Ray. All these renderers require specialist hardware, like fast graphics cards, and would not render real-time on more modest hardware such as a tablet computer.

For representing color flop, rendering algorithms may use tabulated reflection properties. Since the color of effect coatings depends on one viewing angle and two illumination angles (two polar angles and one azimuthal angle between the directions of illumination and viewing), this would require the interpolation of large three-dimensional look-up tables. For the accurate 3D rendering of effect coatings, such methods would become expensive in terms of calculation times and required data storage.

For this reason, parametrized reflection models have become very popular, such as those proposed by Phong, Blinn, Ward, and Cook-Torrance (Pharr et al., 2016). Cook & Torrance (1982) were the first in introducing the microfacet models in computer graphics to model light reflection from rough surfaces based on the previous works by Torrance & Sparrow (1967). Since that time, researchers have proposed many variations and improvements of the microfacets model (van Ginneken, 1998; Kelemen & Szirmay-Kalos, 2001; Pont & Koenderink, 2002). This physical model is widely used in graphics for real appearance rendering approaches.

One of the most used microfacet models in computer graphics nowadays is the so-called GGX model. The GGX distribution, in its origin, is a normal distribution function (NDF) of an ellipsoid. It measures the density of a given normal orientation on the surface of the ellipsoid (Heitz, 2018). It was in the 1970s that the term GGX was introduced in the physics domain by Trowbridge & Reitz (1975). In computer graphics, Neyret introduced a similar distribution model for the representation of volumetric materials (Neyret, 1995, 1998). Later, an improved microfacet distribution function, which they called the GGX (ground glass unknown) distribution model, was introduced by Walter et al. (2007). This model was found to better model scattering glasses and give a closer match to the measured data than the previous microfacet models.

The above models all assume that the angular variation of color can be parametrized by only one angular parameter. More recently some models that use two angular parameters were introduced: Ashikhmin and Shirley, Meyer, Dumont-Bècle, and others (Pharr et al., 2016; Shimizu et al., 2003; Meyer & Shimizu, 2005; Dumont-Bècle et al., 2001). However, even these methods provide a crude interpolation of angular reflectance data, since they assume that the angular variation is mainly accounted for by the aspecular angle (i.e., the angle between the directions of viewing and mirrored reflectance) (Kirchner & Cramer, 2012). More recently, researchers have focused on providing a physics-based analysis of the reflectance of effect coatings. With the so-called flake-based parameters, a more accurate representation of the color flop effect can be obtained than with the other approaches that use two parameters (Kirchner& Cramer, 2012; Kirchner & Ferrero, 2014; Filip et al, 2019; Ferrero et al, 2013b).

However, for other industries, there is a need for rendering techniques that overcome the problems just mentioned with current CAD solutions. Such techniques would be helpful for applications such as e-commerce and other industrial software. For this purpose, a new rendering pipeline was developed as part of this thesis (in collaboration with AkzoNobel painting company and the Spanish National Research Council, or CSIC, in Madrid) to solve the issues encountered with current CAD solutions. This research collaboration focuses on developing truly realistic rendering methods that do provide high color accuracy, perceptually accurate representation of gloss, sparkle, and other texture effects. It also aims at providing fast computation times even on simple tablet computers. A detailed description of this new 3D rendering approach for complex materials such as gonio-apparent coatings, gloss, sparkle, and other textured materials is given in the following proceeding paper (Kirchner et al., 2019). This method is unique in combining several advantages over existing rendering techniques, by (1) accounting for technical specifications of display and ambient light conditions, which provides optimized color accuracy, (2) using a fully spectral rendering pipeline for further optimization of color accuracy, (3) applying a physically based method for efficient BRDF interpolation of gonio-apparent materials, which also leads to further optimization of color accuracy, (4) introducing an accurate perception-based rendering of gloss, sparkle and other texture features, (5) being fast and computationally efficient enough despite being implemented on a simple tablet computer, and still allowing live rendering.

For rendering an object in a lighting scene, it is necessary to standardize this environment. Similar to earlier works on rendering effect coatings, this thesis also focuses on describing the lighting environment through global illumination models (Valenza, 2015; Nguyen et al., 2010; Ferwerda et al., 2004; Ferrero et al., 2014, 2015, Kirchner et al., 2015b). The lighting environment for the rendering pipeline is specified in terms of the IES/EULUMDAT format. This enables the user to specify the luminous intensity distribution from lamps and reflective areas surrounding the object that needs to be rendered. Apart from the well-known Cornell box as a simulated environment, a description of the light inside a light booth was also developed as part of this thesis to test the new spectral rendering pipeline.

For this task, the Byko-spectra effect light booth (BYK-Gardner) and the X-Rite SpectraLight QC (SPLQC) were employed, both of which are widely used for color and appearance assessments in the industry. The Byko-spectra light booth was selected to perform the visual validation required to assess the performance of the developed rendering approach for effect coatings. This light booth is particularly suitable for this investigation since it was designed such as to optimize the visibility of sparkle and other texture effects in automotive coatings. A detailed description of the simulation approach used in this thesis to generate virtual models of both light booths is given in the following conference papers (Huraibat et al., 2019, 2020a; Kirchner et al., 2019).

4. *Visualization of Effect Pigments*

The quality of displays is another essential component toward accurate color reproduction of materials. Therefore, to further improve the color reproduction accuracy of effect coatings, it is necessary to improve both the absolute color representation on displays and the representation of the color flop of these coatings.

A good display technology device is crucial to assuring reproduction reliability in terms of color and spectral information. The CRT or LCD technologies that were used in the 1970s and 1980s usually showed limited capacity with low spatial resolution and small dynamic range (the ratio of the brightest to the dimmest possible pixel values) (Akeley & Hughes, 2014).

Previous studies have evaluated the validity of available display technologies for the visualization and digital reproduction of innovative colors such as effect pigments. Many studies show the limitations of conventional and even present visualization systems to reproduce these attractive color effects faithfully due to their limited color gamut (Ferrero et al., 2014; Perales et al., 2014, Kirchner et al., 2017). Although the recent increases in luminance dynamic range and image display resolution, from VGA to XVGA first and to the full HD (high definition) technology later, allow the rendering and visualization of smaller details and fine-structured surfaces (Dong, 2013), they still do not cover the real scenes of natural and artificial illuminations.

Therefore, to further improve the color reproduction accuracy of rendering effect coatings, both the absolute color representation on displays and the representation of the color flop of these coatings must be improved.

Using wider color gamut displays could cover the large color variety of effect pigments. New display technologies like quantum dots (QDs) with sharped RGB-primaries peaks, based on nanomaterials, are promising. The highly saturated primaries red, green, and blue of QDs displays assure a wider color gamut compared to current technologies, which could cover up to 80% of the ITU-R Recommendation BT. 2020 gamut (Union, 2015), as shown in the research article (Huraibat et al., 2020b) included in this thesis. Nevertheless, there is still an area that needs covering when considering the extended range of goniochromatic colors like effect coatings on the CIE-1931 xy-diagrams. Using multichannel systems is a well-known solution to create extended gamuts. These enlarged gamuts are a guarantee for achieving better reproduction of effect coatings compared to the conventional tri-RGB displays (Teragawa et al., 2012; Xiong et al., 2017). Teragawa et al. (2012) state that some regions, like yellow and cyan, are more demanding than others, such as magenta regions. Therefore, building new displays with additional primaries to cover these conflictive areas can directly improve the reproduction of demanding color materials like effect coatings.

The first research article of this thesis included in *Chapter 1* (Huraibat et al, 2020b) focuses on this issue, where a multi-primary QDs display theoretical model is proposed by taking advantage QDs technology based on sharp primary peaks. In this work, a theoretical and versatile multi-primary model with five primaries (RGBYC) based on QDs technology was tested. A commercially available QDs display was used, for which a proper spectral, spatial, and color characterization was firstly provided.

Further improvements on display reproduction capabilities should be based on the technical specifications of the display itself. New display calibration methods are a real need. It is well known that the device-independent sRGB method, which is the default technique to calculate digital color representations, is often not accurate enough for absolute color reproduction applications. The sRGB method was developed almost 30 years ago as default model parameters for gamma and color primaries focusing on the conventional CRT. Using it with current display technologies like OLED or LCD is more likely to result in failure (Gao et al., 2015; Kirchner et al., 2017). Therefore, Kirchner et al. (2017) proposed the Mobile Display Characterization and Illumination Model (MDCIM), which is an alternative to the default sRGB model that accounts not only for the technical specifications of LCD and OLED displays but also for the influence of ambient lighting.

This MDCIM model is applied to the developed spectral rendering framework presented in this thesis. More details are given in the second and third research articles (Huraibat et al., 2021a, 2021b) in *Chapter 2* and *Chapter 3*.

OBJECTIVES AND STRUCTURE

This thesis will provide an improved digital reproduction of goniochromatic materials. To achieve this, the thesis objectives will include:

1. Evaluating the currently available display technologies for the visualization of gonio-apparent materials, especially the Quantum Dots (QDs) technology.
2. Providing solutions to enlarge the display color gamut to improve the display capabilities to accurately reproduce gonio-apparent materials by developing a multichannel display model.
3. Building a specific and dedicated rendering framework for the accurate simulation of color and texture of effect coatings based on physically based and fully spectral rendering approaches.
4. Assessing the color accuracy of the developed rendering framework through psychophysical visual tests.

This thesis is composed of a total of three original research articles published in peer-review journals. These articles are given as follows:

- **Chapter 1**: Huraibat, K, Perales, E, Viqueira, V, Martínez-Verdú, FM. (2020). A multi-primary empirical model based on a quantum dots display technology. *Color Research and Application*, 45: 393– 400. DOI: https://doi.org/10.1002/col.22481

- **Chapter 2**: Huraibat, K., Perales, E., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos, J. (2021). Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements. *Journal of the Optical Society of America A*, 38(3), 328-336. DOI: https://doi.org/10.1364/JOSAA.413890

- **Chapter 3**: Huraibat, K., Perales, E., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos, J. (2021). Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements. *Optics Express,* 29, 34671-34683. DOI: https://doi.org/10.1364/OE.438477

Following, the articles are introduced successively, each article comes in a separate chapter.

PUBLISHED ARTICLES

Chapter 1

A multi-primary empirical model based on a quantum dots display technology

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Color Research and Application, 45: 393– 400.

https://doi.org/10.1002/col.22481

Summary Chapter 1

A multi-primary empirical model based on a quantum dots display technology

In this work, we built a multi-primary display model based on the new quantum dots (QD) technology to enlarge the display color gamut. In this way, first, the emission spectral radiance curves of the three RGB channels of a commercial QD display were fitted to a four-parameter function. From this modeling, it is possible to gain new theoretical color primaries by selecting new spectral peaks (cyan, yellow, magenta, and/or additional RGB primaries) and imposing some colorimetric conditions for the resulting white of this proposed theoretical multi-primary display. Proper characterization to assess the performance of the display was conducted to know if the basic “gain-offset-gamma” (GOG) model can be used for direct and inverse color reproduction (from RGB to CIE-XYZ, and vice versa). The GOG model was found to well characterize this display. The spatial uniformity of the display was also evaluated in luminance and color chromaticity terms. Finally, with the primaries modeling and color characterization based on the GOG model, a 5-primary model (RGBYC) was tested. The evaluation of this theoretical RGBYC display model confirms the gamut enlargement, which can also improve goniochromatic color reproduction.

Chapter 2

Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements

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February 2021

Journal of the Optical Society of America A 38(3), 328-336

https://doi.org/10.1364/JOSAA.413890

Summary Chapter 2

Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements

We validate a physically based and spectral rendering framework with improved color reproduction. With a recently developed model, we take into account both the colorimetric specifications of the rendering display as well as the spectral and angular characteristics of lighting and also the spectral reflectance of the objects. Therefore, it should provide much better color reproduction than those based on the common standard red, green, blue (sRGB) color space. In addition, it allows real-time rendering on modest hardware and displays. We evaluated the color reproduction of the new rendering framework by psychophysical tests using spectrophotometric measurements of 30 chromatic paint samples. They were rendered on an iPad display, as viewed inside the Byko-spectra effect light booth. We asked 16 observers to evaluate the color match by directly comparing the rendered samples with the physical samples, using two different psychophysical assessment methods. The color reproduction was found to be strongly improved with respect to results obtained with default sRGB color encoding space. The average color reproduction match was found to be equivalent to $\Delta E_{00} = 1.6$, which is a small but noticeable color difference. In 80% of the visual assessments, the color reproduction was described as being at least as good as between "difference visible but still acceptable" and "difference visible, doubtful match."

Chapter 3

Accurate physics-based digital reproduction of effect coatings

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Summary Chapter 3

Accurate physics-based digital reproduction of effect coatings

We built an improved 3D rendering framework to accurately visualize the complete appearance of effect coatings, including metallic effects, sparkle and iridescence. Spectral reflectance measurements and sparkle indexes from a commercially available multi-angle spectrophotometer (BYKmac-i) were used together with physics-based approaches, such as flake-based reflectance models, to implement efficiently the appearance reproduction from a small number of bidirectional measurement geometries. With this rendering framework, we rendered a series of effect coating samples on an iPad display, simulating how these samples would be viewed inside a Byko-spectra effect light booth. We validated the appearance fidelity through psychophysical methods. We asked observers to evaluate the most important visual attributes that directly affect the appearance of effect coatings, i.e., the color, the angular dependence of color (color flop) and the visual texture (sparkle and graininess). Observers were asked to directly compare the rendered samples with the real samples inside the Byko-spectra effect light booth. In this study, we first validated the accuracy of rendering the color flop of effect coatings by conducting two separate visual tests, using flat and curved samples respectively. The results show an improved accuracy when curved samples were used (acceptability of 93% vs 80%). Secondly, we validated the digital reproduction of both color and texture by using a set of 30 metallic samples, and by including texture in the rendering using a sparkle model. We optimized the model parameters based on sparkle measurement data from the BYK-mac

I instrument and using a matrix-adjustment model for optimization. The results from the visual tests show that the visual acceptability of the rendering is high at 90%.

DISCUSSION AND CONCLUSIONS

The results and conclusions of the research articles of this thesis are discussed more in detail here. The articles focus on improving the digital reproduction quality of color and texture of paints that contain effect pigments. Two main issues limit the digital reproduction of these kinds of pigments. The first has to do with the current display technologies, which are usually not enough for the reproduction of such a wide variety of colors due to their limited color gamut. The second issue is more related to the current rendering software. The color accuracy of the images that current software produces is often not sufficient for the reproduction of colors and effects produced by these materials. Therefore, the first research article of this thesis is focusing on the performance of the new Quantum dots (QDs) display technology for the reproduction of effect pigments and gives a new solution to improve the capability of this technology with an expanded color gamut. The second and third articles are focusing on the development of an accurate physically based rendering framework for effect coatings. Firstly, by building a specific rendering framework for this purpose, and secondly, by validating the performance of this rendering framework through psychophysical tests.

Discussion of the research article "A multi-primary empirical model based on a quantum dots display technology"

This first research article of the thesis is providing an enlarged color gamut of the recently released QDs display technology, to improve the color reproduction accuracy of goniochromatic colors such as effect coatings. These pigments are a clear example of complex and demanding colors when they are intended to be digitally reproduced (Klein. 2010; Streitberger & Dossel, 2008). The conventional and current display technologies (e.g., CRT, LCD, LED) are often not enough for accurate reproduction of such wide varieties of colors, mainly due to their limited color gamut (Kirchner et al., 2015b, 2019; Perales et al., 2014; Cooper et al., 2013; Chen et al., 2016). The new QDs displays technology come with innovative and highly saturated primaries based on a new class of nanomaterials, which guarantees an enlarged color gamut. Although it has been proved that vivid cyan and yellow colors are hardly achieved even with QDs displays (Taragawa et al., 2012), these regions require special attention since they are not well covered when evaluating the color gamut of the current displays on the CIE1931 xy-diagram. It is evident there is still a gap that needs to be covered, considering the extended range of colors produced by goniochromatic materials on the CIE1931 xy-diagram.

The solution proposed in this article is based on providing an augmented color gamut by extending the typically used tri-channel display systems (RGB), to using multichannel systems. Using multichannel systems is a well-known solution for achieving an enlarged color gamut, which also provides better efficiency than the conventional tri-RGB displays (Taragawa et al., 2012; Xiong et al., 2017). For this purpose, we took advantage of the new QDs technology, a good candidate to implement this solution due to the sharp emissions of its primary channels. A five-primary (RGBYC) display model with additional yellow (Y) and cyan (C) primaries is tested based on the math fitting of the spectral curves of a typical currently commercial QDs display (i.e., the Philips QDs display). The selection of the Y and C was to overcome the limitations of the tri-RGB displays to cover these conflictive regions.

As expected, the proposed RGBYC multichannel model expands the color gamut of the Philips QDs display. The RGBYC model was found to cover almost 90% of the area of the ITU-R Recommendation BT. 2020 (Recommendation of Parameter values for ultra-high-definition television systems for production and international programme exchange) gamut compared to the 80% covered by the Philips QDs gamut when using the RGB model for this same display. An additional evaluation was performed by comparing the gamut volume of the color solid representation in the CIELAB color space for both, the proposed RGBYC and the RGB model of the Philips QDs, where the Philips QDs gamut fitted completely inside the RGBYC color gamut. Another important achievement gained with the RGBYC model is the improved lightness reproduction capacity, with a maximum value of luminance (L) reaching 130 lightness units. Considering the wide range of the goniochromatic colors and their wide dynamic range issue, this approach seems essential toward a better reproduction of vivid yellow and cyan colors with higher luminance values. Physical evidence of these improvements was also given through the graphical representation of a measured real set of goniochromatic samples on the CIELAB color space, which was found to fit within the limits of the volumetric color solid gamut of the RGBYC model. This was not the case for the Philips QDs, where a big part of these goniochromatic colors fall right on the limits or beyond the Philips QDs color gamut.

Apart from the above-mentioned advantages, the proposed theoretical approach stands out for its simplicity. The modeling of the emission curves of the proposed model by a simple four-parameter function, and the color characterization performed using the conventional calibration GOG model (which was found to well characterize the Philips QDs display), allow different primaries configurations to be tested. The matrix-based computations of the GOG model allow the development of an extended GOG model adapted to the proposed multichannel model. Eight or more channels are possible configurations, which could be tested in future work.

On the other hand, some aspects of the proposed approach may be improved in future work. For instance, more specific criteria could be used to better select additional primary channels. A good solution is by using a large data set of measured goniochromatic colors to find the best multichannel combination to cover these colors. The selection of the Y and C channels of our model was based on an optimization loop to find the best candidates. An improved optimization loop could be implemented to optimize the number of additional channels needed to cover the colors of this sample set and the color coordinates of each of these primary candidates. This proposed selection approach is an additional versatility of our model. This approach could be extended to other applications, e.g., to serve the needs for a specific industrial application to improve the color reproduction accuracy for a specific set of colors.

The main challenge would be to put this theoretical display model in practice, i.e., to build a multichannel display prototype. This implies using more subpixels which directly affects the pixel size and the resolution of the display. In addition, specific software and extended models for color calculations would be needed to deal with these multichannel panels. However, we believe that these "technical difficulties" can be overcome with the continuous progress of electronics technology.

This continued progress also implies a continuous renewal of the standards and parameters recommendations for production and international program exchange like the aforementioned “BT. 2020” Recommendation built for the new UHD technology, which is the focus of the International Communication Union-ITU. More efforts related to this hot topic are made by the CIE. Years ago the CIE created a technical committee to investigate the real color gamut offered by the different available technologies (CIE, 2021), to know the limitations of the current technology, and to provide solutions for improving the capabilities of these technologies to match the necessities of today's huge color varieties.

Discussion of the research article "Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements"

This paper focuses on the second problem related to the limitations of the current rendering software for the digital reproduction of effect pigments addressed above. This work is part of a research collaboration of our Vision and Color Research Group at the University of Alicante with the, and AkzoNobel Coatings company from the Netherlands, in which we developed a physically based rendering framework for improving the accuracy of color and texture reproduction of effect coatings on car paints. The importance of this work requires such kind of collaboration, not only at the scientific level but also at the industrial level. The collaboration with a global industry-leading company such as AkzoNobel, and the Spanish metrology institute (CSIC), tell the rigorousness of the physical measurements as well as the industrial vision for the development of such a specific rendering tool for such innovative pigments.

As above mentioned, the currently available rendering algorithms provide impressive and realistic images, which serve the needs for many applications such as movies and gaming industries, but when it comes to more critical applications, like, for instance, automotive design, these rendered images are not accurate enough in terms of color (Günther et al., 2005; Rump et al., 2008). This becomes worse for goniochromatic and effect coatings (widely used in the automotive industry) due to the complex color and texture effects they produce. The *color change* effect of these pigments is not correctly covered by the available rendering algorithms. Additionally, the digital reproduction of their texture effects such as *sparkle*, and *graininess* is a big challenge and still hard to achieve.

The rendering approach developed here provides many advantages over the existing rendering techniques. This approach provides an optimizing color accuracy by accounting for technical specifications of display and ambient light conditions, and also by using a fully spectral rendering approach by accounting for the spectral reflectance data from materials, which are measured with spectrophotometers. It also stands out by being fast and computationally efficient enough to allow live rendering on simple tablet computers.

Accurate characterization of the local lighting conditions is essential to achieve an accurate rendering of colors on objects. Therefore, we developed a new methodology able to provide an accurate representation of controlled lighting environments. By modeling the luminance profiles of the light sources, taking into account their spectral and spatial distribution and their interaction with the surrounding, we achieve an accurate representation of the global illumination of the desired environment, which also includes an indirect-light assumption of the global illuminance surrounding an object inside the lighting environment. With this approach we achieved an accurate and physically based simulation of common lighting environments such as the well-known *Byko-spectra effect* light booth commonly used in the industry for the assessment of effect coatings (Huraibat et al., 2019). In another work (Huraibat et al., 2020a) we extended this approach to simulate environments with several light sources. This approach can be extended to simulate more complex illumination environments and serve the need for other applications. In fact, we planned to include an additional application of this approach, to investigate the effect of the different lighting set-ups on the visibility of the details of famous paintwork placed in a museum room and provide a solution to improve the color and details visibility of that paintwork. The idea was to build a physically based model of the paint itself inside a physically based simulation of the whole surrounding environment, including all the lighting sources available in the room. Unfortunately, the current pandemic situation has prevented the starting of this project.

Nevertheless, the simulation of light booths using this approach allows the creation of accurately rendered images of objects as they would appear inside a specific light booth. In turn, this allows the visual evaluation of the rendering accuracy by judging the similarity of the virtual and the real objects inside a light booth. Therefore, to test the validity of the developed rendering framework, observers had to judge simultaneously the color difference between the rendered images (virtual sample inside the virtual Byko light booth) on the iPad screen, and the real-world samples inside the physical light booth. The setup of the visual experiments performed here is a novelty of our work since no publications with a similar visual evaluation setup were found in the literature. The importance given to the observers' acceptance here makes the difference with the available rendering algorithms of effect coatings, which were developed without quantifying and optimizing the perceived quality of the rendering. The whole field of colorimetry is based on systematically quantifying visual perception, and for example, the development of color spaces and color difference formulas are based on correlating experimental data from visual and instrumental investigations. That is the reason why in this work we give such high importance to the acceptance of the rendering through visual evaluations. Additionally, this approach is intended to be integrated into a commercially available tool for AkzoNobel customers as end-users.

The current paper provides the groundwork for the final evaluation of the developed rendering framework. To this end, a first visual evaluation test was designed and performed to validate the performance of the rendering framework for the reproduction of *chromatic colors*. This visual validation was performed via two different visual evaluation methods (scoring and grayscale methods) to detect experimental biases. In the first method, observers had to evaluate the perceived color difference by giving scores ranging from 0 to 5, where a score of zero refers to the situation where the observer saw no color difference, or hardly any color difference. If the rendering shows a very bad color match to the color of the real-world sample, then a score of five is given. The grayscale method comes with a better visually defined scale, where observers had to quantify the color differences using a set of achromatic chips (nine pairs of neutral gray colored chips). Both methods provide similar results, with almost 80% of visual acceptability. The results revealed a relatively weak color reproduction for samples with reddish-blue colors. This limitation might be due to the interpolation of the spectral range (between 400nm and 700nm) used for the color representation, but we think that the limitations of using a tablet display could be the main reason behind these failures. The color gamut of this display is not wide enough to represent the huge color variety of paints and effect coatings. We believe that using a larger color gamut display like, for instance, the QDs displays would solve partially this issue. Multichannel displays have been shown to result in improved color reproduction accuracy for current innovative and complex color effects (Huraibat et al, 2020b).

It is also worth pointing out that including the device-dependent MDCIM model in this approach to account for the colorimetric specifications of the display that was used in this experiment improved considerably the color accuracy reproduction compared to previous investigations using the default sRGB color encoding.

Discussion of the research article “Accurate physics-based digital reproduction of effect coatings”

This work is a follow-up to the second article of this thesis. Here we extend the analysis to render the *color flop*, *graininess*, and *sparkle* texture effects of effect coatings. The rendering approach presented in this article comes with added advantages as compared to the earlier approach that was described in the second article. This was achieved by applying a physically based method (the flake-based reflectance model) for efficient BRDF interpolation of gonio-apparent materials such as metallic coatings, which are the focus of this work. Since the appearance of effect coatings is mainly determined by the effect pigments and flakes which are oriented not completely parallel to the coating surface, using parameters concerning the flakes themselves and not the coating surface, as common approaches do, is more suitable for making a proper spectral, angular and spatial description of the reflectance of these coatings. Therefore, using the flake-based model allows a more adequate formalism for modeling and representing the BRDF of effect coatings, which is also capable of providing efficient appearance reproduction of effect coatings from a small number of bidirectional measured geometries. These spectral reflectance measurements and sparkle indices were obtained from the commercially available multi-angle spectrophotometer (BYK-mac i) used in this work. Currently, there are only two commercial instruments that are capable to measure both color and texture, and the BYK-mac i is the one mostly used in the industry. This is the main reason behind using the BYK-mac i parameters for this research.

Our rendering approach is using the GGX microfacet model (very common in the computer graphics world) for the digital parameterization of BRDF. The three most relative parameters of the GGX model for the texture representation are related to the flake area (*fa*), the flake orientation represented by the collective roughness of all flakes (*rf*), and the roughness of individual flakes (*rm*). We applied a matrix adjustment model to find representative values for the three model texture parameters (*fa*, *rf*, *rm*) using measured texture values from the BYK-mac i. We first tried to find any linear adjustment, but we realized that the matrix adjustment method would perform better, and indeed it did. It was the best option as shown in the results. This approach makes our rendering framework an automated tool that is able to provide real-time textured simulation for any painted object, based on BYK-mac i measurements.

Similar to the evaluation process for the solid color samples reproduction of the previous work, here we extend our study to evaluate the digital reproduction of *metallic paints*. For this purpose, and since both evaluation methods used in the previous work shows similar behavior, we opted for using the scoring evaluation method due to its simplicity compared to the grayscale method where an achromatic scale is used to judge chromatic differences.

Therefore, through two initial visual tests, we evaluate the capability of the rendering approach to reproduce the color flop effect of metallic coatings with *color-only* rendered images (i.e. without including the texture rendering). In the first test, observers evaluated the color change in flat samples, while curved samples were used in the second test to simulate 3D objects. In a third (final) test, we extended the evaluation to the joint color and texture rendering (*total appearance*) of metallic samples.

The gradually increasing complexity of the rendering approach justifies the corresponding evaluation process performed at each step. Starting with the evaluation of the rendering accuracy of chromatic colors allows the validation of the spectral rendering approach presented in the previous article (with 80% of visual acceptability). In the next step, the evaluation of color-only rendering images of metallic samples presented in this article allows testing the performance of the physically based representation of the BRDF to reproduce the color-flop effect of metallic coatings. The reason behind splitting this intermediate evaluation into two different geometrical levels (flat and 3D curved objects), is that we wanted to evaluate if acceptance is different when flat samples are evaluated separately and in different viewing geometries as compared to viewing curved samples (where different viewing geometries are the result of the samples being curved). Also, the final scope of this work is to achieve an accurate rendering of 3D objects. Results showed an increased accuracy when curved panels are used compared to flat panels (93% of visual acceptability vs 80%). This increased accuracy can be explained by the gradual variation in the appearance of 3D objects, where the curvature of these objects already introduces variations in both observation and illumination angles. The final evaluation of the final version of the rendering framework by including the texture component (sparkle and graininess) as well as color on curved panels serves as a complete evaluation of the perceived total appearance. It also provides evidence about the performance of the sparkle model and the matrix adjustment model implemented for the automatic computation of the GGX model parameters based on the parameters measured with a BYK-mac i. In this final evaluation, we avoid the evaluation of texture separately. Observers were asked to evaluate the total appearance, which is the scope of this work, since focusing only on texture effects was found to be a complex and confusing task for observers. The results from the visual assessments of the total appearance reproduction of metallic coatings show that the visual acceptability of the rendering is high at 90%. Observers relate the few nonmatching samples mostly to deviations in color representation rather than to inaccuracies in texture rendering.

The limited number of observers on the initial visual tests could be critical. However, the collected data was enough to validate the performance of the rendering. The analysis of the intra-observer and inter-observer variabilities shows good agreement and results also confirm the low ambiguity of the assessment for observers in all the performed visual tests. The three repetitions performed by each observer increase the number of single evaluations. For example, in the first initial test, five observers evaluated the color difference for fifteen different painted samples. Each sample was evaluated at three different geometries, and additionally, a fourth scoring answer of the total color change was given. In this way, a total of 900 single answers was collected for the first initial test with only-color images in flat samples. In the final evaluation of the total appearance, the number of observers, as well as the number of samples tested, was increased to 15 observers evaluating 30 metallic samples.

In general, results show high accuracy for the rendering of color and texture of effect coatings using the methodology developed in this thesis. Further optimization of the accuracy of the rendering framework may be possible by improving the representation of the colorimetric properties of the display. Also, further improvement in the accuracy of rendering is expected when a larger set of samples is used for training the models to extract the GGX model parameters through the matrix-adjustment method. The parametrization and interpolation of the BRDF may also be improved to further optimize the accuracy of the rendering framework. The presented rendering approach relies on spectral measurements associated with very specific geometries, in this case, the six geometries of the BYK-mac i instrument. This is another critical aspect of this approach. This rendering method and its software implementation have been designed in such a way that they could also use data from any other combination of measurement geometries. For example, the complete BRDF might also be represented by including a large number of spectral measurements such as those provided by accurate systems such as the GEFE instrument that is used at the CSIC in Madrid. This huge amount of data could be considerably reduced by mathematical models such as the PCA model introduced by Ferrero et al. (2013b). This is expected to give an improved accuracy of the colors associated with various geometries when visualizing objects with more complex shapes than those used in this thesis, such as car body 3D models. However, using such an amount of measured data requires potential computer hardware with high memory and high processing capability. This is not possible using a simple iPad computer as we have used in these investigations.

General Conclusions

In conclusion, the work presented in this thesis provides important solutions toward an improved and accurate visualization and digital reproduction of goniochromatic materials.

We evaluated the advantages of using the new QDs display technology which comes with an enlarged color gamut that guarantees an improved representation of colors, although, it is still not enough to cover the wide variety of colors produced by the innovative goniochromatic pigments. Therefore, and by taking advantage of the QDs technology, we developed a multi-primary display model that guarantees a better reproduction of effect pigments.

We also achieved an accurate digital simulation of effect coatings on a simple tablet display by developing a multispectral and physically based rendering approach on an iPad simple computer. The visual evaluations corroborated the high color accuracy of the rendered images.

Finally, it is important to emphasize that the work performed in this thesis has already been used to introduce 3D digital visualization to AkzoNobel customers. The commercial application of these rendering methods can be found on the internet, e.g., powder coatings (https://shop.interpon.com/gb/en/nlb37i.html), and also as apps for the iPad directed at coil coatings (https://coilcoatings.akzonobel.com/us/our-digital-tool and https://apps.apple.com/nl/app/akzonobel-canopy/id1248774580), specialty coatings (https://apps.apple.com/nl/app/icolordesign/id1283228708) and powder coatings (https://apps.apple.com/nl/app/akzonobel-design/id1185866600). The renderings in these apps and software utilize the improvements in accuracy of visualization of colors and textures as developed in this thesis. These applications support color marketing and make color selection processes more efficient. These digital tools simplify the color selection process and give customers the ability to search AkzoNobel’s extensive database of products.

From all the above, we can say that this thesis achieved many advances not only in the scientific domain but also in the technology transfer to the industrial domain. This proves the importance of the efforts and all the work developed during this pre-doctoral research to come with such a great contribution to the development of innovative tools for an essential need in today's society such as the digitization of materials.

DISCUSIÓN Y CONCLUSIONES

En esta sección se analizan con más detalle los resultados y las conclusiones de los artículos de investigación que componen esta tesis doctoral. Los artículos presentados se centran en la mejora de la reproducción digital del color y la textura de los pigmentos de efecto. Puede decirse que existe dos cuestiones principales que limitan la reproducción digital de este tipo de pigmentos. El primero está relacionado con los dispositivos de visualización de datos (pantallas) y la gama de color asociada a los mismos que no suele ser suficiente para la reproducción digital de los colores ofrecidos por este tipo de pigmentos. El segundo problema está más relacionado con los actuales algoritmos y programas de renderizado. La precisión cromática de sus imágenes no es suficientemente adecuada para la reproducción digital de los colores y de los efectos producidos por estos materiales. Por tanto, el primer artículo de investigación de esta tesis se centra en la evaluación del rendimiento de una nueva tecnología de pantallas basada en *Quantum Dots* (*QDs*) para la reproducción digital de pigmentos de efecto. Además, este articulo propone una solución para mejorar todavía más la capacidad de esta tecnología consiguiendo así ampliar la gama de color asociada a esta tecnología.

En particular, este primer artículo de investigación de la tesis propone una metodología para ampliar la gama de colores de la tecnología de pantallas basada en QDs. Esta tecnología es relativamente nueva en el mercado y con la propuesta realizada es posible mejorar la precisión de la reproducción digital del color de los materiales gonioaparentes producidos con los pigmentos de efecto. Estos pigmentos son un claro ejemplo de colores complejos y exigentes cuando se pretenden reproducir digitalmente (Klein. 2010; Streitberger & Dossel, 2008). Las tecnologías de pantallas convencionales (por ejemplo, CRT, LCD, LED) no suelen ser suficientes para reproducir con precisión una variedad de colores tan amplia, principalmente debido a su limitada gama de colores (Kirchner et al., 2015b, 2019; Perales et al., 2014; Cooper et al., 2013; Chen et al., 2016). La nueva tecnología de pantalla QDs se caracteriza por tener unos primarios innovadores y altamente saturados basados en una nueva clase de nanomateriales, lo que garantiza una gama de color más amplia. En estudios anteriores (Taragawa et al., 2012) se demostró que incluso con las pantallas de QDs, determinadas tonalidades como cian y amarillo y muy cromáticas, es difícil conseguir una buena reproducción. Por tanto, en estas regiones se requiere una atención especial, ya que no están bien cubiertas cuando se evalúa la gama de color de las pantallas actuales en el diagrama *xy* de la CIE1931. Es evidente que todavía existe una brecha que cubrir teniendo en cuenta la gama de colores asociada a los materiales goniocromáticos en el diagrama *xy* de la CIE1931.

Por esta razón, en este artículo se aborda esta problemática y su objetivo principal es aumentar la gama de color asociada a esta tecnología mediante la utilización de sistemas multicanal frente a los sistemas de pantallas tri-canal (RGB) típicamente utilizados. El uso de sistemas multicanal es una solución bien conocida utilizada para conseguir una gama de colores más amplia, que proporciona además una mayor eficiencia que las pantallas tri-RGB convencionales (Taragawa et al., 2012; Xiong et al., 2017). La tecnología QDs ofrece ventajas respecto a otras tecnologías debido a las características de sus primarios como ya se ha comentado, por tanto, utilizar esta tecnología como base del sistema multicanal ofrece muchas ventajas respecto a otro tipo de tecnologías. En particular, en este artículo se propone un modelo de pantalla de cinco primarios (RGBYC) con el amarillo (Y) y el cian (C) como primarios adicionales, basado en el ajuste matemático de las curvas espectrales de una pantalla QDs comercial (QDs de Philips). La selección de estos primarios adicionales fue realizada en base a las limitaciones de las pantallas tri-RGB para cubrir la gama de color en esas regiones.

El modelo multicanal RGBYC propuesto amplía la gama de colores de la pantalla Philips QDs tal como se esperaba. Los resultados fueron evaluados en función de la gama de color BT. 2020 recomendada por la *International Telecommunication Union UTI*. Esta gama o estándar recoge la recomendación sobre los valores de los parámetros de los sistemas de televisión de ultra definición para la producción y el intercambio internacional de programas. En este sentido, se comprobó que el modelo RGBYC cubre casi el 90% de la gama BT.2020 frente al 80% asociada a la pantalla Philips QDs con su sistema RGB original. Además, también se analizaron los resultados de esta metodología en función del volumen del sólido de color teórico en el espacio de color CIELAB. Se comprobó que el sólido de color asociado a la pantalla Philips QDs estaba incluido completamente dentro del sólido de color del modelo propuesto RGBYC. Por otro lado, con el modelo propuesto RGBYC se consigue reproducir valores más altos de luminosidad o claridad, con un valor máximo de claridad igual a $L^* = 130$. Teniendo en cuenta la gama de los colores goniocromáticos y su amplio rango dinámico, esta metodología parece esencial para una mejor reproducción de estos colores, especialmente para los colores amarillo y cian vivos o saturados con valores de claridad más altos. Finalmente, para comprobar si esta metodología es adecuada para colores goniocromáticos, se realizó una representación gráfica de un conjunto de muestras goniocromáticas en el espacio de color CIELAB. Se comprobó que todos los colores representados se encontraban dentro de los límites de la gama de color definidos mediante el sólido de color teórico asociado al modelo propuesto RGBYC. Sin embargo, para la pantalla original Philips QDs una gran parte de estos colores goniocromáticos se encontraban justo en los límites o incluso fuera de la gama de color de la Philips QDs.

Aparte de las ventajas mencionadas arriba, este modelo teórico destaca por su sencillez. Por un lado, el ajuste matemático de las curvas de emisión de este modelo multicanal se realiza mediante una sencilla función de cuatro parámetros y, por otro lado, su caracterización colorimétrica se realiza en base al modelo físico denominado GOG (*gain-offset-gamma*), tras comprobar inicialmente su idoneidad para la pantalla Philips QDs. Esta metodología, debido a su sencillez permite probar diferentes configuraciones de primarios y seleccionar aquella configuración más idónea en función de su gama de color teórica, además los cálculos basados en la matriz del modelo GOG permiten desarrollar un modelo GOG más amplio y adaptado al modelo multicanal propuesto, o incluso a otras posibles configuraciones con ocho o más canales.

Por otro lado, es necesario indicar que existen algunos aspectos del modelo propuesto que pueden mejorarse. Por ejemplo, se pueden utilizar criterios más específicos para seleccionar mejor los canales primarios adicionales. Como alternativa, una buena solución sería utilizar un gran conjunto de datos de colores goniocromáticos para encontrar la mejor combinación multicanal que cubra la gama de estos colores. La selección de los dos canales utilizados en este trabajo (Y; C) está basada en un proceso de optimización para encontrar los mejores candidatos. Sin embargo, este proceso de optimización puede mejorarse para dar como salida, primero, el número de canales adicionales necesarios para cubrir la gama de color del conjunto de muestras utilizado y en segundo lugar, las coordenadas de color de cada uno de estos candidatos para ser utilizados como primarios. Este enfoque de selección propuesto ofrece una versatilidad adicional de nuestro modelo que permite extenderse a otras aplicaciones, por ejemplo, para satisfacer o garantizar las necesidades de una aplicación industrial específica enfocada en la mejora de la precisión de la reproducción del color para un conjunto específico de colores.

El principal reto del procedimiento propuesto en este trabajo sería poner en práctica este modelo teórico, es decir, construir un prototipo de pantalla multicanal basado en la tecnología QDs. Esto implica más subpíxeles, lo que afecta directamente al tamaño de los píxeles y a la resolución de la pantalla. Además, se necesitarían programas informáticos específicos y modelos complejos para el cálculo del color, a fin de lidiar con estos paneles multicanal. Sin embargo, creemos que estas "dificultades técnicas" pueden superarse con el continuo progreso de la tecnología electrónica.

Este progreso continuo también implica una renovación continua de las recomendaciones de normas y parámetros como el estándar "BT. 2020" mencionado anteriormente. La Comisión Internacional de la Iluminación (CIE, del francés *Commission internationale de l'éclairage*) también ha dedicado esfuerzos continuos en los últimos años sobre este tema tan candente. De este modo, la CIE creó un comité técnico para investigar la gama real de colores que ofrecen las diferentes tecnologías disponibles (CIE, 2021), y así poder conocer las limitaciones de las tecnologías actuales de reproducción del color, y aportar soluciones para mejorar las capacidades de estas tecnologías para ajustarse a las necesidades de las enormes variedades de color actuales.

Los otros dos artículos se centran en el desarrollo de un marco de renderizado preciso basado en medidas físicas de objetos con recubrimientos con pigmentos de efecto. Para tal fin, en primer lugar, se construyó un marco de renderizado específico y en segundo lugar, se validó el rendimiento de este marco de renderizado mediante pruebas psicofísicas. Toda esta investigación es fruto de la colaboración entre el grupo de investigación Visión y Color de la Universidad de Alicante, el Consejo Superior de Investigaciones Científicas

(CSIC) de Madrid y la empresa *AkzoNobel Coatings* localizada en los Países Bajos. Esta colaboración está enfocada en el desarrollo de un marco de renderizado basado en medidas físicas para mejorar la reproducción del color y la textura de los recubrimientos de efecto en las pinturas de automóviles. La importancia de este trabajo requiere este tipo de colaboración, no sólo a nivel científico sino también a nivel industrial. La colaboración con una empresa líder en la industria mundial como AkzoNobel y con el Instituto de Metrología de España (CSIC), destacan la rigurosidad de las mediciones físicas, así como de la visión industrial para el desarrollo de una herramienta de renderizado tan específica para estos pigmentos innovadores.

Como se ha mencionado anteriormente, los algoritmos de renderizado disponibles en la actualidad proporcionan imágenes impresionantes y realistas, que satisfacen las necesidades de muchas aplicaciones como el cine y la industria de los videojuegos, pero cuando se trata de aplicaciones más críticas, como por ejemplo el diseño de automóviles, estas imágenes renderizadas no son lo suficientemente precisas en términos de color (Günther et al., 2005; Rump et al., 2008). Esto se agrava en el caso de los recubrimientos goniocromáticos (muy utilizados en la industria de automoción) debido a los complejos efectos de color y textura que producen. El efecto de cambio de color de estos pigmentos dependiendo de la geometría de iluminación y/o observación no está correctamente cubierto por los algoritmos de renderizado disponibles. Además, la reproducción de sus efectos de textura, como el *sparkle* y el *graininess*, es un gran reto todavía difícil de conseguir.

El procedimiento de renderizado desarrollado aquí proporciona muchas ventajas sobre las técnicas existentes de renderizado. Este enfoque proporciona una precisión de color optimizada al tener en cuenta las especificaciones técnicas de la pantalla y las condiciones de la luz ambiental. Además, se trabaja con medidas espectrales de las muestras obtenidas con espectrofotómetros. Este procedimiento destaca también por ser lo suficientemente rápido y eficiente desde el punto de vista computacional como para permitir un renderizado en vivo en un simple iPad y sin necesidad de ordenadores potentes.

Como es bien sabido, el color está bien caracterizado si el sistema de iluminación está bien caracterizado y controlado. Por este motivo, el primer objetivo para conseguir un buen renderizado fue el desarrollo de una metodología capaz de proporcionar una caracterización precisa de los sistemas de iluminación. De esta forma, al modelar los perfiles de luminancia de las fuentes de luz teniendo en cuenta su distribución espectral y espacial y su interacción con el entorno, se consigue una representación precisa de la iluminación global del entorno deseado, y también permite caracterizar la iluminación indirecta de la iluminancia global que rodea a un objeto dentro del entorno del sistema de iluminación. Con este enfoque, se consigue una simulación precisa basada en medidas físicas de diferentes sistemas de iluminación, como la cabina de luz *Byko-sepctra effect* de BYK-Gardner, comúnmente utilizada en la industria para la evaluación de muestras con pigmentos de efectos (Huraibat et al., 2019). En otro trabajo (Huraibat et al., 2020a), se amplió este enfoque para simular otros entornos con varias fuentes de luz. En general, esta metodología puede ampliarse para simular entornos de iluminación más complejos y poder ser utilizados para otras aplicaciones. De hecho, otro objetivo de esta tesis doctoral era incluir una aplicación de este procedimiento para investigar o estudiar el efecto de las diferentes configuraciones de iluminación en la visibilidad de los detalles de famosas pinturas colocadas en la sala de un museo, y proporcionar una solución para mejorar la visibilidad del color y los detalles de esa pintura. La idea era construir una simulación de la propia pintura mediante un modelo basado en medidas físicas tanto de la propia pintura, así como de todo el entorno, incluyendo todas las fuentes de iluminación disponibles en la sala. Sin embargo, debido a la situación pandémica acontecida por la Covid-19 no fue posible el inicio de este proyecto debido a las restricciones de movilidad y de acceso al museo situado en Ámsterdam, Países Bajos.

La simulación de las cabinas de luz con esta metodología permite crear imágenes de objetos renderizados con la precisión necesaria para asegurar un buen renderizado de las condiciones reales de iluminación y poder evaluar así el renderizado obtenido mediante comparación entre objeto real en cabina y objeto simulado. Por tanto, y para comprobar la validez del algoritmo de renderizado desarrollado, se diseñó un experimento psicofísico donde los observadores tenían que juzgar la diferencia de color entre las imágenes renderizadas (muestra virtual dentro de la cabina Byko virtual) en la pantalla del iPad, y las muestras físicas dentro de la cabina real. La realización de los experimentos visuales es por sí una considerable novedad de este trabajo, ya que en la literatura no existen trabajos sobre renderizado validados con evaluaciones visuales realizadas por un número determinado de observadores, por tanto, es un hito que marca la diferencia con otros algoritmos de reproducción digital o renderizado de materiales con pigmentos de efecto disponibles en la actualidad. El color es una percepción visual y, por tanto, en colorimetría o la ciencia del color, todos los estudios o avances que se han realizado han sido siempre en base a la percepción visual, por ese motivo, el desarrollo de los nuevos espacios de color y fórmulas de diferencia siempre tienen como objetivo encontrar esa correlación visual e instrumental. De esta forma, en esa tesis doctoral también se ha querido buscar esa correlación, y se ha dado importancia a la aceptación del renderizado mediante evaluaciones visuales. Por otro lado, todo el trabajo desarrollado en esta tesis doctoral pretende ser integrado en una herramienta comercial disponible para los clientes de AkzoNobel como usuarios finales.

El segundo artículo que contiene esta tesis doctoral (*Chapter 2*) presenta las bases para la evaluación final del marco de renderizado desarrollado. Para ello, se diseñó y se realizó una primera prueba de evaluación visual para validar el rendimiento del renderizado conseguido con la metodología propuesta para la reproducción digital de colores sólidos. Esta validación visual se realizó mediante dos métodos psicofísicos diferentes (métodos de puntuación y de escala de grises) para detectar sesgos experimentales. En el primer método, los observadores tienen que evaluar la diferencia de color percibida entre muestra real y muestra renderizada (digital) dando puntuaciones que iban de 0 a 5, donde, una puntuación de cero se refiere a la situación en la que el observador no percibe ninguna diferencia de color, o apenas ninguna diferencia de color (*no/hardly any difference*). Si por el contrario el observador percibe una gran diferencia entre muestra real y muestra renderizada la puntuación otorgada es de cinco (*Large difference, very bad match*). El método psicofísico basado en la escala de grises consiste en cuantificar las diferencias de color percibidas entre muestra real y muestra renderizada mediante comparación con diferencias de color establecidas entre un conjunto de muestras acromáticas (nueve pares de muestras de color gris neutro). Ambos métodos proporcionan resultados similares, con casi un 80% de aceptabilidad visual. No obstante, en este primer ensayo, los resultados revelaron una mala reproducción digital del color para las muestras con colores rojos-azulados. Esta limitación podría deberse a la interpolación de la gama espectral (16 bandas entre 400 nm y 700 nm) utilizada para la representación del color, aunque la principal hipótesis se centra en las limitaciones de utilizar una pantalla como la tableta iPad. La gama de color de esta pantalla no es lo suficientemente amplia como para representar la enorme variedad de colores de las pinturas y los revestimientos de efecto. Por tal motivo, el uso de una pantalla con una gama de colores más amplia como, por ejemplo, las pantallas QDs, podría resolver en parte este problema ya que, se ha demostrado que las pantallas multicanal son útiles para mejorar la precisión de la reproducción digital del color de los pigmentos innovadores y complejos de hoy en día como son los pigmentos de efecto (Huraibat et al., 2020b).

También cabe señalar que la inclusión del modelo de MDCIM (modelo de calibración de la pantalla independiente del dispositivo) en el algoritmo de renderizado propuesto para tener en cuenta las especificaciones colorimétricas de la pantalla utilizada mejoró considerablemente la precisión de la reproducción digital del color en comparación con investigaciones anteriores que utilizaban la codificación de color sRGB por defecto.

El tercer artículo (*Chapter 3*) es una continuación del segundo artículo de esta tesis, donde se incorpora al algoritmo desarrollado el renderizado de los efectos del cambio de color (*flop*, en inglés), y de los efectos de textura de los pigmentos de efecto como el *sparkle*. De esta forma, el algoritmo de renderizado desarrollado en este artículo presenta ventajas añadidas a la versión anterior del segundo artículo basadas en las medidas físicas y el modelo *flake-based reflectance* que permiten una interpolación eficiente de la BRDF (funciones de distribución de reflectancia bidireccional) necesaria para la reproducción digital de los materiales gonioaparentes, que son el centro de este trabajo. La apariencia visual de los revestimientos gonioaparentes viene determinada principalmente por los pigmentos de efecto y la disposición de las láminas de estos pigmentos respecto a la superficie del revestimiento. Por esta razón, utilizar un modelo basado en los parámetros relativos a las propias láminas de pigmento y no a la superficie del revestimiento, como hacen los algoritmos habituales, es más adecuado para realizar una descripción espectral, angular y espacial válida de la reflectancia de estos revestimientos. Por lo tanto, el uso de este modelo permite un formalismo más adecuado y riguroso para modelar y representar la BRDF de los revestimientos de efecto, que además es capaz de proporcionar una reproducción eficiente de la apariencia de los revestimientos de efecto a partir de un pequeño número de geometrías medidas bidireccionales. En este caso, las medidas de reflectancia espectral y los parámetros para caracterizar el *sparkle* se obtuvieron con el espectrofotómetro multiángulo comercial (BYK-mac i). Actualmente, sólo existen dos instrumentos comerciales válidos para medir el color y la textura, sin embargo, instrumento el BYK-mac i es el que más se utiliza en la industria, y es la razón principal por la que se utiliza este instrumento en esta tesis doctoral.

Por otro lago, el algoritmo de renderizado propuesto utiliza el modelo de microfacetas GGX (muy famoso en el mundo de los gráficos por ordenador) para la parametrización digital de la función de distribución de reflectancia bidireccional (BRDF, *bidirectional reflectance distribution function*). Los tres parámetros más importantes del modelo GGX para la representación de la textura están relacionados con el área de las láminas (*flakes* in inglés) (fa), la orientación de las láminas representada por la rugosidad colectiva de todas las láminas (rf) y la rugosidad de las láminas individuales (rm). Para determinar valores representativos de estos parámetros de textura del modelo (fa, rf, rm), se aplica un modelo de ajuste matricial En primer lugar se intentó realizar un ajuste lineal, sin embargo, el método de ajuste matricial tuvo un mejor rendimiento. Así, la metodología desarrollada en esta tesis doctoral para realizar el marco de renderizado es en una herramienta automatizada capaz de proporcionar una simulación de textura en tiempo real para cualquier objeto pintado con solo proporcionar las medidas del BYK-mac i.

Siguiendo el planteamiento anterior con las muestras sólidas, también se realiza una evaluación visual del renderizado conseguido. Para ello, y dado que los dos métodos psicofísicos utilizados descritos anteriormente muestran un comportamiento similar, se optó por utilizar el método de evaluación por puntuación debido a su simplicidad en comparación con el método de escala de grises en el que se utiliza una escala acromática para juzgar las diferencias cromáticas, lo que puede generar confusión para algunos observadores.

Por lo tanto, inicialmente se diseñaron dos experimentos visuales para evaluar la capacidad de la herramienta de renderizado desarrollada para reproducir el efecto *flop* del color de muestras metálicas. En este caso el renderizado se centró solo en el color de las muestras, sin considerar los efectos de textura. En la primera prueba, los observadores evaluaron el cambio de color en muestras planas, mientras que en la segunda se utilizan muestras curvadas para simular objetos tridimensionales (3D). En un tercer y definitivo experimento visual, se realizó la evaluación de la representación digital conjunta de color y textura (apariencia total) de las muestras metálicas.

El aumento gradual de la complejidad en esta herramienta de renderizado a lo largo de la tesis doctoral justifica el correspondiente proceso de evaluación realizado en cada paso. La evaluación de la precisión o exactitud de la representación digital de los colores sólidos permitió validar el procedimiento de representación espectral presentado en el artículo anterior (con un 80% de aceptabilidad visual). Mientras que la evaluación de las imágenes renderizadas de las muestras metálicas con sólo color presentada en este artículo permitió comprobar el rendimiento de la reproducción digital basada en las medidas física de la BRDF para reproducir el efecto *flop* en las pinturas metálicas. La razón de dividir esta evaluación intermedia en dos etapas con geometrías diferentes (objetos planos y curvados), fue para evaluar si la aceptación por parte del observador es diferente cuando se evalúan las muestras planas por separado en diferentes geometrías de medida en comparación con la visualización de muestras curvadas (donde es posible evaluar al mismo tiempo diferentes configuraciones de medida producidas por la curvatura de las muestras). Además, el objetivo final de este trabajo es conseguir una representación precisa de objetos en 3D, y el hecho de utilizar muestras curvadas se aproxima más a objetos en 3D. Los resultados mostraron una mayor precisión cuando se utilizan paneles curvados en comparación con los planos (93% de aceptabilidad visual frente al 80%). El hecho de utilizar muestras curvadas que implica la variación angular tanto en la dirección de iluminación como de observación permite al observador percibir la complejidad de las muestras en su conjunto y su aceptabilidad podría ser mayor. La evaluación final de la versión completa del algoritmo de renderizado incluyendo el componente de textura (*sparkle*) así como el color en las muestras curvadas sirve como una evaluación completa de la apariencia total percibida. También proporciona evidencias sobre el rendimiento del modelo del *sparkle* y el modelo de ajuste matricial implementado para el cálculo automático de los parámetros del modelo GGX, basado en los parámetros medidos por BYK-mac i. En esta evaluación final, se evita la evaluación de la textura por separado tal como se hizo con el color, y a los observadores se les pidió evaluar la apariencia total, ya que centrarse sólo en los efectos de la textura es una tarea compleja y confusa para los observadores. Los resultados de las evaluaciones visuales de la reproducción digital de la apariencia total de los revestimientos metálicos muestran que la aceptabilidad visual del renderizado es alta, con un 90%. Cabe destacar que los fallos o errores reportados por los observadores en ese 10% de muestras rechazadas se debían a problemas en la reproducción del color y no en la textura.

Cabe mencionar, que a priori el número de observadores participante en las pruebas visuales iniciales podría ser crítico al tratarse de un número reducido. Sin embargo, los datos recogidos fueron suficientes para hacer una buena evaluación del rendimiento del renderizado. El análisis de las variabilidades intra-observador e inter-observador muestra una buena concordancia y los resultados también confirman la baja ambigüedad de la evaluación para los observadores en todas las evaluaciones visuales realizadas. Las tres repeticiones realizadas por cada observador aumentan el número de evaluaciones individuales realizadas. Por ejemplo, en la primera prueba inicial, cinco observadores evaluaron la diferencia de color de quince muestras pintadas diferentes. Cada muestra fue evaluada en tres geometrías diferentes y, además, se hizo una evaluación adicional en la que se evaluó el cambio total de color (*total color flop*). En otras palabras, solo en esta prueba inicial se recogieron un total de 900 evaluaciones, lo que significa unas 900 respuestas individuales recogidas sólo para esta primera prueba inicial con imágenes con solo color en muestras planas. Sin embargo, en la evaluación final de apariencia total, se aumentó el número de observadores, así como el número de muestras evaluadas (15 observadores evaluaron 30 muestras metálicas).

En términos generales, los resultados obtenidos muestran una alta precisión en la reproducción digital del color y la textura de los pigmentos de efecto utilizando la metodología desarrollada en esta tesis doctoral. Para optimizar los resultados obtenidos con el algoritmo de renderizado desarrollado, una posible opción podría consistir en mejorar las propiedades colorimétricas de la pantalla utilizada. Asimismo, sería esperable obtener mejores resultados si se utilizara un conjunto más amplio de muestras para el entrenamiento del modelo con el fin de extraer los parámetros del modelo GGX mediante el método de ajuste matricial. La parametrización e interpolación de la BRDF también podría mejorarse para optimizar aún más la precisión del algoritmo de renderizado. El algoritmo de renderizado desarrollado se basa en mediciones espectrales asociadas a geometrías muy específicas, en este caso, las seis geometrías del BYK-mac i. Este es otro aspecto crítico del trabajo presentado aquí. Sin embargo, esta herramienta está diseñada para utilizar cualquier otra combinación de datos, como sería, por ejemplo, la BRDF completa con un gran número de mediciones espectrales proporcionadas por sistemas más complejos como el Gonio-Espectro Fotómetro Español (GEFE). Esta enorme cantidad de datos proporcionada por el GEFE podría reducirse considerablemente mediante modelos matemáticos como el modelo basado en componentes principales introducido por Ferrero et al. (2013b), que daría una mayor precisión del color correcto asociado a cualquier geometría al visualizar objetos, incluso con formas más complejas que las utilizadas en esta tesis, como los modelos 3D de carrocerías de un coche. Sin embargo, el uso de tal cantidad de datos medidos requiere mayor potencial informático y sería necesario el uso de dispositivos con gran memoria y alta capacidad de procesamiento, lo cual no es posible utilizando un simple procesador de una tableta como lo que se ha utilizado en este trabajo.

Conclusiones Generales

Para concluir, el trabajo presentado en esta tesis doctoral aporta importantes soluciones para una mejor y más precisa visualización y reproducción digital de los materiales goniocromáticos.

En esta tesis doctoral, se han evaluado las ventajas de utilizar la nueva tecnología de pantallas QDs, que proporciona una gama de color más amplia que garantiza una representación de colores mejorada. Se ha demostrado que estas mejoras que proporciona la tecnología QDs aun no son suficientes para cubrir la amplia variedad de colores producidos por los innovadores pigmentos goniocromáticos. Por lo tanto, y aprovechando la tecnología de los QDs, se ha proporcionado un modelo de pantalla multicanal que garantiza una mejor reproducción de los pigmentos de efecto.

En esta tesis también se ha logrado una simulación digital precisa de los pigmentos de efecto en una simple pantalla de tableta desarrollando una herramienta de renderizado multiespectral y basada en medidas físicas utilizando un simple procesador de un iPad. Las evaluaciones visuales corroboraron la gran precisión cromática de las imágenes renderizadas con las metodologías desarrolladas para construir esta herramienta.

Por último, es importante destacar el papel de todo el trabajo realizado en esta tesis para mejorar la aplicación comercial de visualización digital 3D ya disponible para los clientes de AkzoNobel. La nueva versión disponible en la web de la compañía (https://coilcoatings.akzonobel.com/us/our-digital-tool) presenta una visualización mejorada del color y de las texturas de sus aplicaciones para mejorar el marketing del color y hacer los procesos más eficientes. Esta aplicación simplifica el proceso de selección de colores y ofrece a los clientes la posibilidad de navegar en la amplia base de datos de productos de la compañía.

Por todo lo anterior, podemos decir que esta tesis doctoral ha logrado muchos avances no sólo en el ámbito científico sino también en la aplicación de la tecnología en el ámbito industrial. Esto demuestra la importancia de los esfuerzos y de todo el trabajo desarrollado durante este periodo de investigación predoctoral para llegar a proporcionar una contribución considerable para el desarrollo de herramientas innovadoras para una necesidad esencial en la sociedad actual como es la digitalización de materiales.

Curriculum Vitae

My name is Khalil Huraibat. I was born in Hebron, Palestine on the 18th of April 1990. Since I was very young, I had the idea of going abroad to study, to discover new countries, and to look for different opportunities. After finishing high school in 2008, I made the best decision of my life by moving to Spain, particularly to Granada, to start my university studies. After two hard years learning Spanish, and at the same time preparing for the university entrance exam, in 2010 I was admitted to the University of Granada to study Optics and Optometry. I was always passionate about physics, but I also wanted a profession that deals with people and has to do with healthcare. Fortunately, the Optics and Optometry degree had exactly what I was looking for. During the first years, I realized that everything in optics is based on one word, "light"; what we see is light, colors are light. That's where my passion for light, radiometry, photometry, and color science in general started. Lecturers like Dr. Juan Luis Nieves encouraged me to apply for the prestigious international master of color (Erasmus Mundus in Color in Informatics and Media Technology-CIMET) and so I did. In fact, I had the admission letter for the CIMET master's one month before my graduation in the summer of 2014. During the second year of the master's (2015/2016), I had the opportunity to join the university of Jean Monnet at Saint-Etienne, France. Then I had the opportunity to move to Belgium to work on my master’s thesis at one of the leading companies (Barco NV) that specializes in digital projection and imaging technology, under the guidance of Dr. Alain Treméau, together with the expert engineers at Barco NV. There I worked on developing a specialized algorithm for the color calibration of wounds Photography. In 2016, a few months after completing the master's program, I joined the Vision and Color

Research Group-GVC of the University of Alicante, Spain, with a pre-doctoral fellowship. My Ph.D. research focuses on developing an improved digital reproduction of goniochromatic materials, which was part of a collaboration between three parties, the GVC, AkzoNobel painting company from the Netherlands, and the Consejo Superior de Investigaciones Científicas (CSIC) of Madrid, Spain. The main effort of this work was dedicated to the development of a new 3D rendering tool for improved and accurate visualization of the complete appearance of effect coatings, including metallic effects, sparkle, and iridescence. During this period at the GVC, I was lucky to be involved in an interdisciplinary environment that allows me to grow as a researcher. There I drafted various research papers related directly to my thesis, and I also collaborated on other research tasks and projects which was carried out by our research group. Additionally, I collaborated in a variety of national and international congresses covering different areas like optics, imaging, displays, and color. During these last years, I also had the opportunity to join the Technology Group of Color of AkzoNobel at Sassenheim, Netherlands in two different short stays to work hand in hand with engineers in the industrial domain. This educational journey has helped me to grow professionally and also to polish my personality. Therefore, I consider myself an ambitious and highly motivated person, a team worker, and highly adaptable.

Scientific or Technological Activities

1. Name of the project: Predoctoral fellowship (BES-2016-077325)
   Your role in the project: Scientific coordinator
   Body where the project took place: University of Alicante
   City: Alicante, Valencian Community, Spain
   Head(s) researcher(s): KHALIL HURAIBAT

Number of participating researchers: 2
Funding body or bodies: Ministerio de Economía y Competitividad
Start date: 15/05/2017
Duration of the project: 4 years

2. Name of the project: Bidirectional reflectance definitions (16NRM08 BIRD)
   Your role in the project: Researcher
   Body where the project took place: University of Alicante
   City: Alicante, Valencian Community, Spain
   Head(s) researcher(s): VALENTIN ESTANISLAO VIQUEIRA PEREZ
   Number of participating researchers: 6
   Funding body or bodies: EUROPEAN COMMISSION
   Start date: 01/05/2017
   Duration of the project: 3 years

3. Name of the project: Advanced digital reproduction of visual appearance of gonio-apparent objects (DPI2015-65814-R)
   Your role in the project: Researcher
   Body where the project took place: University of Alicante
   City: Alicante, Valencian Community, Spain
   University Head(s) researcher(s): FRANCISCO MIGUEL MARTINEZ VERDU
   Number of participating researchers: 5
   Funding body or bodies: Ministerio de Economía y Competitividad
   Start date: 01/01/2016
   Duration of the project: 3 years

4. Name of the project: Soluciones de alto valor añadido sector cosmética. estudio de análisis de la termocromía de un colorante capilar con respecto a un colorante patrón (AITEX6-18T)
   Your role in the project: Researcher
   Body where project took place: University of Alicante
   City: Alicante, Valencian Community, Spain
   Head researcher: FRANCISCO MIGUEL MARTINEZ VERDU
   Number of participating researchers: 5
   Funding body: AITEX (INSTITUTO TECNOLOGICO TEXTIL)
   Start date: 24/07/2018
   Duration of project: 3 months

5. Name of the project: Estudio del color en los productos facilitados por la empresa (COSENTINO2-17i)
   Your role in the project: Researcher
   Body where project took place: University of Alicante
   City: Alicante, Valencian Community, Spain
   Head researcher: FRANCISCO MIGUEL MARTINEZ VERDU
   Number of participating researchers: 6
   Funding body: COSENTINO RESEARCH AND DEVELOPMENT, S.L.
   Start date: 30/11/2017
   Duration of project: 1 year - 1 month

6. Name of the project: Asesoramiento en diseño estadístico de experimentos (doe) para la optimización de la caracterización óptica y colorimétrica de la transmitancia de materiales plásticos delgados (SRGGLOBALLIRIA1-17APA)

Your role in the project: Researcher
Body where project took place: University of Alicante
City: Alicante, Valencian Community, Spain
Head researcher: FRANCISCO MIGUEL MARTINEZ VERDU
Number of participating researchers: 6
Funding body: SRG GLOBAL LIRIA S.L.U.
Start date: 29/06/2017
Duration of project: 1 month

List of publications

1. Perales, E., Micó-Vicent, B., Huraibat, K., Martínez-Verdú, F. M., Dietz, C., & Yamanoi, Y. (2019). Review of instrumental inter-agreement study of spectral and colorimetric data of commercial multiangle spectrophotometers. *Color Research & Application*, 44(2), 168-175. https://doi.org/10.1002/col.22320

2. Micó-Vicent, B., Perales, E., Huraibat, K., Martínez-Verdú, F. M., & Viqueira, V. (2019). Maximization of FDM-3D-objects gonio-appearance effects using PLA and ABS filaments and combining several printing parameters: “a case study”. *Materials*, 12(9), 1423. https://doi.org/10.3390/ma12091423

3. Perales, E., Micó-Vicent, B., Huraibat, K., & Viqueira, V. (2020). Evaluating the Graininess Attribute by Visual Scaling for Coatings with Special-Effect Pigments. *Coatings*, 10(4), 316. https://doi.org/10.3390/coatings10040316

4. Huraibat, K., Perales, E., Viqueira, V., & Martínez-Verdú, F. M. (2020). A multi-primary empirical model based on a quantum dots display technology. *Color Research & Application*, 45(3), 393-400. https://doi.org/10.1002/col.22481

5. Huraibat, K., Perales, E., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos, J. (2021). Visual validation of the appearance of chromatic objects rendered from spectrophotometric measurements. *JOSA A*, 38(3), 328-336. https://doi.org/10.1364/JOSAA.413890

6. Huraibat, K., Perales, E., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos, J. (2021). Accurate physics-based digital reproduction of effect coatings. *Optics Express*, 29(21), 34671-34683. https://doi.org/10.1364/OE.438477

Conference papers

1. Authors: Huraibat, K.; Perales, E.; Kirchner, E.; van der Lans, I.; Ferrero, A.; Campos, J.; Martínez-Verdú, F. M.
   Title: Spectral and Color Characterization of a Quantum Dots Display for Gonio-Apparent Colors
   Conference: 25th Color and Imaging Conference (CIC). Lillehammer, Norway, 12/09/2017. In Proceedings of 25th Color and Imaging Conference: ISBN 978-0-89208-328-2

2. Authors: Gómez, O.; Perales, E.; Micó-Vicent, B.; Viqueira, V.; Huraibat, K.; Martínez-Verdú, F.M.

Title: Statistical design of experiments applied on sparkle visual detection
Conference: 25th Color and Imaging Conference (CIC). Lillehammer, Norway, 12/09/2017. In Proceedings of 25th Color and Imaging Conference: ISBN 978-0-89208-328-2

3. Authors: Huraibat, K.; Perales, E.; Kirchner, E.; van der Lans, I.; Ferrero, A.; Campos, J.; Martínez-Verdú, F.M.
   Title: Spectral and Color Characterization of a Quantum Dots Display
   Conference: Association Internationale De La Couleur (AIC). Jeju, Corea, 16/10/2017

4. Authors: Gómez, O.; Perales, E.; Micó-Vicent, B.; Huraibat, K.; Viqueira, V.; Martínez-Verdú, F.M.
   Title: Analysis of the lighting influence in the sparkle detection by applying statistical design of experiments
   Conference: CIE 2017 Midterm Meeting. Jeju, Republic of Korea, 20/10/2017

5. Authors: Perales, E.; Viqueira, V.; Micó-Vicent, B.; Huraibat, K.; Martínez-Verdú, F.M.
   Title: Adaptive learning in the master's degree in Color Technology for the Automotive sector
   Conference: International Conference of Education, Research and Innovation (ICERI). Sevilla, Spain, 15/11/2017

6. Authors: Huraibat, K.; Perales, E.; Martínez-Verdú, F. M.; Micó, B.; Viqueira, V.

Title: Development of a Multi-Primary QD Display Model for GonioApparent Colors
Conference: edC electronic displays Conference. NuernbergMesse, Germany, 28/02/2018

7. Authors: Perales, E.; Micó, B.; Huraibat, K.; Martínez-Verdú, F. M.; Viqueira, V.
   Title: Estrategias de mejora continua en el máster propio de Tecnología del Color para el sector de automoción a partir del "feedback" de alumnos Egresados
   Conference: XVI Jornadas de Redes de Investigación en Docencia Universitaria- REDES 2018 II Workshop Internacional de Innovación en Enseñanza Superior y TIC- INNOVAESTIC 2018. Alicante, Spain, 16/06/2018. ISBN 978-84-697-9429-6

8. Authors: Huraibat, K.; Perales, E.; Martínez-Verdú, F. M.; Micóy, B.; Viqueira, V.
   Title: Multi-Primary QD Display Model for Digital Reproduction of Gonio-Chromatic Colors
   Conference: National Spanish Optics Meeting. Castellón, Spain, 03/07/2018. ISBN 978-84-09-03559-5

9. Authors: Perales, E.; Garay, O.; Huraibat, K.; Micó-Vicent, B.; Viqueira, V.; Martínez-Verdú, F.M.
   Title: Diseño y validación de colores mezcla en plastilina para observadores daltónicos para crear soluciones de diseño
   Conference: National Spanish Optics Meeting. Castellón, Spain, 03/07/2018. ISBN 978-84-09-03559-5

10. Authors: Kirchner, E.; Van del Lans, I.; Koeckhoven, P.; Huraibat, K.; Martínez-Verdú, F. M.; Perales, E.; Ferrero, A.; Campos, J.
    Title: Real time accurate rendering of color and texture of car coatings
    Conference: IS&T International Symposium on Electronic Imaging. Burlingame, California, United States of America, 13/01/2019. ISBN 2470-1173

11. Authors: Huraibat, K.; Perales, E.; Ferrero, A.; Martínez-Verdú, F. M.; Kirchner, E.; Van der Lans, I.; Campos, J.
    Title: Characterization of Byko-spectra effect light booth for digital simulation in a rendering tool
    Conference: Quadrennial Session of the CIE. Washington DC, United States of America, 14/06/2019. In Proceedings of 29th CIE Session 2019, ISBN 978-3-902842-74-9

12. Authors: Bermejo, R.; Micó-Vicent, B.; Perales, E.; Huraibat, K.; Martínez-Verdú, F.M.; Viqueira, V.
    Title: Using laminar nanoclays for phycocyanin stabilization and application as new natural blue pigments from microalgae extraction
    Conference: International Conference on Biobased and Biodegradable Polymers (BIOPOL-2019). Stockholm, Sweden, 17/06/2019

13. Authors: Perales, E.; Micó-Vicent, B.; Huraibat, K.; Viqueira, V.
    Title: Evaluation of colour difference formulas for gonio-apparent materials
    Conference: Iberian Conference on Perception. El Escorial, Spain, 20/06/2019

14. Authors: Perales. E.; Viqueira, V.; Micó-Vicent, B.; Huraibat, K.; Espinosa, J.; Chorro, E.; Jordan, J.; Martínez-Verdú, F.M.
    Title: Using the self-evaluation as a motivational and learning tool
    Conference: International Conference on Education and New Learning Technologies (Edulearn). Palma, Spain, 01/07/2019. ISBN 978-84-09-12031-4

15. Authors: Padilla, J.L.; Viqueira, V.; MArtínez-Verdú, F.M.; Perales, E.; Micó-Vicent, B.; Huraibat, K.; González, S.
    Title: Estudio espectroraidométrico de los cambios de color de dos protocolor de revascularización pulpar y su posterior blanqueamiento
    Conference: Spanish Nacional Congress of Color. Linares, Jaén, Spain, 25/09/2019

16. Authors: Perales, E.; Ortiz, M.; Micó-Vicent, B.; Huraibat, K.; Viqueira, V.
    Title: Estimación visual del graininess mediante el método psicofísico de ordenación de estímulos
    Conference: Spanish Nacional Congress of Color. Linares, Jaén, Spain, 25/09/2019

17. Authors: Micó-Vicent, B.; Bermejo, R.; Perales, E.; Huraibat, K.; Viqueira, V.
    Title: Optimización de las respuestas colorimétricas de B-Ficoeritrina tras su estabilización mediante el empleo de nanoarcillas laminares
    Conference: Spanish Nacional Congress of Color. Linares, Jaén, Spain, 25/09/2019

18. Authors: Huraibat, K.; Perales, E.; Viqueira, V.; Kirchner, E.; Van del Lans, I.
    Title: Byko-spectra effect light booth simulation for digital rendering tool
    Conference: Congreso Nacional de Color. Linares, Jaén, Spain, 25/09/2019. In Libro de Actas del XII Congreso Nacional del Color: 45-48

19. Authors: Huraibat, K.; Perales, E.; Ferrero, A.; Campos, J.; Van der Lans, I.; Kirchner, E.
    Title: Physics-based modelling of a light booth to improve color accuracy of 3D rendering
    Conference: London Imaging Meeting. Online. London, UK, 30/09/2020. The Society for Imaging Science and Technology, ISBN 978-0-89208-346-6

20. Authors: Huraibat, K.; Perales, E.; Kirchner, E.; van der Lans, I.; Ferrero, A.; Campos, J.
    Title: Multiangle visual validation of a physically based rendering of goniochromatic colors
    Conference: 14th International Color Association (AIC) Conference. Milan, Italy, 30/08/2021 to 03/09/2021. In Proceedings of the International Colour Association (AIC) Conference 2021: 185-189, ISBN: 978-0-6484724-3-8

21. Authors: Huraibat, K.; Perales, E.; Kirchner, E.; van der Lans, I.; Ferrero, A.; Campos, J.

Title: Visual validation of an accurate 3D digital reproduction of effect coatings
Conference: XIII Spanish National Meeting on Optics, 22-24/11/2021

Research Stays in R&D&I Centers or Companies

1. Body where the project took place: Barco N. V Company
   City: Kortrijk, Belgium
   Start date: 29/02/2016
   Duration: 6 months
   Name of program: Intern Master Thesis: Wounds Photography Calibration

2. Body where the project took place: AkzoNobel Performance Coatings
   City: Sassenheim, Holland
   Start date: 01/03/2019
   Duration: 2 months - 3 days
   Name of program: Color Digital Rendering

3. Body where the project took place: AkzoNobel Performance Coatings
   City: Sassenheim, Holland
   Start date: 11/09/2017
   Duration: 7 days
   Name of program: Training week 3D Color Visualization Framewor

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Huraibat, K., Perales, E., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos, J. (2021b). Accurate physics-based digital reproduction of effect coatings. *Optics Express*, 29(21), 34671-34683. https://doi.org/10.1364/OE.438477

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Huraibat, K., Perales, E., Viqueira, V., Kirchner, E., Van der Lans, I., Ferrero, A., & Campos Acosta, J. (2019, September). Byko-spectra effect light booth simulation for digital rendering tool. *In proceedings of XII Congreso Nacional del Color* (pp. 45-48).

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