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Physics and Measurement of properties linked to appearance

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Abstract

The measurement of the appearance of objects as perceived by individuals is necessary to meet industrial needs (quality control at the end of the production line, realistic reproduction of a 3D object, generation of new visual effects) and societal needs (development of virtual reality, creation of digital twins of cultural heritage objects). This need for measurement, initially addressed by colorimetry, has become more complex over the past 20 years with the arrival of new effects such as "sparkle" in the automotive industry, iridescence in cosmetics, and new demands such as measuring translucency for 3D printing or satin finish for natural-looking objects. To characterize these new effects, traditional measurement techniques have naturally evolved toward bidirectional quantities such as BRDF, BTDF, SVBRDF, or BSSRDF! Metrologists have developed instruments capable of measuring these new quantities. Today, there are solutions for acquiring them all, using rotation platforms, robotic arms, HDR imaging sensors, and very bright LED sources.

Introduction

For metrologists, the measurement of appearance is a particular activity because, unlike other metrological fields, the measurand is located in the observer's head and is not directly accessible by the instrument. The technique involves developing two parallel scales. A physical scale, which characterizes the optical properties of surfaces using mainly spectrophotometric techniques. A visual scale, which characterizes the perceptual properties of the object using psychophysical techniques. Once these two scales are established, correlations are sought that allow for proposing numerical indices that are acquired by spectrophotometric means and that correlate with visual sensation. The best example of achievement in this field is the adoption in 1924 by the CIE of V(λ), the spectral sensitivity curve of the standard observer, which links radiometric measurements (optical measurement based on the watt) to photometry (perception measurement based on the lumen)[1]. Another great example is that of "traditional" colorimetry, which extracts a numerical triplet from the spectral reflectance factor, that identifies a given colour in people's perceptual colour space [2]. Thanks to this approach and these tools, it became possible to finely control the colour of manufactured objects using colorimeters. Some famous brands have even gone up to appropriating certain colours, making them a signature. Think about Coca Cola's "red," Pepsi's "blue," or Veuve Clicquot's "orange-yellow," for example. This makes life easier when it comes to finding the desired bottle among all the others.

The story could have ended there, but that was without counting on the inventiveness of our engineers.

These engineers realized that adding highly reflective mica particles to painting subtract generates tiny bright spots that shine on the surface of the object under the direct light of the sun, like stars in the sky. The paint becomes almost alive… Visual fascination and romance mixed? The public loves it. The sparkle effect was born (fig. 1a). It now covers more than 80% of new vehicles produced worldwide. Adding sub-micrometre streaks to these flakes causes them to diffract light, and the stars become individually coloured. Sublime! Let’s now change the light and move from the sun to a cloudy sky. The shiny dots disappear and the appearance of the coating changes. Now it looks more like the visual appearance of a granitic stone that has been sculpted by thousands of years. It is the graininess effect.

It is also possible to play with the transparency of multilayer coatings, inspired by certain butterflies or beetles. Then, the colour changes with the direction of illumination and observation. If the change is rapid and describes the entire visible spectrum, it is called iridescence (fig. 1b); if the change is slow and limited to a few colours, it is called goniochromatism. In any case, these effects allow the edges of objects to be emphasized and the shapes to be sublimated.

In the 2000s, laptops became democratized. We know their complexity, which underlies the feeling of fragility. But we take them everywhere! The user is reassured if the outer shell of his laptop appears solid, like the good old machine tools of yesteryear. Sandblasted aluminium or brushed steel finish appeared (fig. 1c). The effect is anisotropic and metallic. It conveys a feeling of robustness. Its success is such that it has quickly invaded the household appliance and furniture market.

In the 2010s, perhaps it is the awareness of the human footprint on our planet that drives us to return to surfaces that appear more natural, more biological. Gloss, which was a symbol of luxury in the 20th century, becomes "bling-bling." We prefer

Figure 1. *Sparkle (a), iridescence (b), brushed metal (c), matt (d). Visual effects follow that the societal needs and its evolution.*

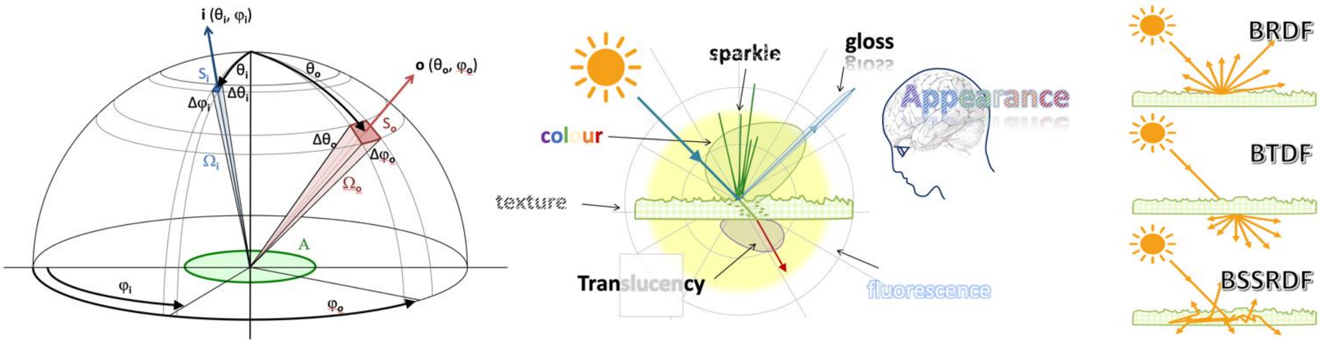

Figure 2. *Left : BRDF is the ratio of the radiance in a given direction* **o** *of a surface A by the irradiance of this surface coming from a given direction* **i**, *at a given wavelength and a given polarization. Angular resolution is limited by max(Ω_o ; Ω_i). (middle) The visual system exploits the information at different locations of the BRDF in order to extract visual attributes of appearance. (right) BRDF for colour, gloss & sparkle, BTDF for transparency, BSSRDF for translucency. (Right) BRDF, BTDF, BSSRDF are the bidirectional radiometric quantities linked to appearance*

the satin of the patina of old wooden furniture or the matte of cork or stone. Matte or satin finishes are emerging (fig. 1d).

Radiometric quantities

All of these new effects are directional. To grasp their subtlety, the surface must be illuminated from multiple directions, and for each of these directions, the light they reflect must be measured in multiple directions. The appropriate radiometric quantity is the Bidirectional Reflectance Distribution Function. CIE defines this quantity as

> *"function describing the change with direction of irradiation* **i** *and direction of observation* **o** *of the quotient of the element of radiance of the surface element in the given direction of view at the given wavelength* $dL_\mathbf{o}$ *, by the corresponding element of irradiance incident on the medium from the given direction of irradiation at the given wavelength,* $dE_\mathbf{i}$*"* [3] (fig. 2, left).

Unit is inverse steradian [sr^{-1}]. It is a radiometric quantity. It has six degrees of freedom.

The BRDF characterizes the reflection of light on the surface of a material. It contains the information exploited by observers to analyse the different visual attributes of appearance.

Colour comes from the light that has been through the interface, has interacted with pigments or multiple layers, and has been re-emitted in the hemisphere in a random direction. To access it, an accurate control and a tied sampling of the wavelength is requested. But it doesn't need to get it for a lot of angular configurations. After all, a uniform surface roughly has the same colour in all directions and a goniochromatic surface, whether it is interferometric or diffractive, presents "soft" angular variations, manifesting themselves to the order of a degree or even a dozen degrees [4][5].

For gloss, it's a bit the opposite. Gloss comes from the light reflected by the surface. It is localized around the mirror direction, in what is called the "specular peak". The sharper the peak, the glossier the material is. To access gloss, it is necessary to measure the BRDF with very fine angular resolution and with very high dynamic range, to be able to analyse this sharp peak [6][7]. But what's the point of covering the entire hemisphere? And why acquire spectral information? We know that gloss is confined in the specular and is not spectral.

For sparkle, we have seen that it consists of tiny luminous dots, that shine like stars. In the BRDF, very thin luminance peaks will appear in different directions, like a hedgehog. Here again, a very fine angular resolution is required, but this time covering a much larger part of the hemisphere. Quantifying sparkle effect is still under works today [8]. The problem is well broken down. Indicators correlating with the visual sensation are proportional to the density and to the intensity of these peaks [9]. The recent addition of colour in this effect further complicates the task because now we must be spectral. For this type of measurement, the use of an imaging system becomes mandatory. This type of device must be calibrated, which requires meticulous work [10].

Texture comes from the variation of the BRDF as a function of the displacement of the measurement surface A (fig. 2 left). We then speak of acquiring the SVBRDF, the Spatially variable BRDF. This is the favourite quantity of the computer graphics community. It is a eight degrees of freedom quantity, easier to model than to measure [11].

Transparency is located in the other hemisphere. To characterize it, we do not make "reflectance" measurements but "transmittance" measurements. We then speak of measuring the BTDF (Bidirectional Transmittance Distribution Function) (fig. 2 right). This quantity is similar to the BRDF but in transmission. Recent work has made it possible to define it clearly [12]. Metrology laboratories have developed instruments to measure it.

The measurement of translucency must be approached with an even more complex quantity. Indeed, the sensation of translucency appears when the object has the property of letting the incident light travel into its body and re-emits a part of it in a given direction in space. The quantity that characterizes this type of behaviour is the BSSRDF, for Bidirectional Surface Scattering Distribution Function (fig. 2 right). It is probably the ultimate quantity to characterize the optical properties of materials. The BSSRDF is the ratio of the luminance at a point on the surface, in a direction given by the incident flux, when the surface is illuminated by a collimated and punctual beam, at a wavelength λ and according to a polarization ρ. It is expressed in [$sr^{-1}\cdot m^{-2}$] [13][14]. As for SVBRDF, we reach 8 degrees of freedom. Many recent works have been carried out on the measurement of the BSSRDF [15][16].

To conclude this inventory of the quantities involved in the measurement of appearance, we can finally attempt to acquire information on fluorescence. This requires illuminating the sample at a given wavelength and measuring the BRDF for another wavelength. It must be repeated, combining all the visible wavelengths, as well as UV for the incident beam. This must be done for different illumination and observation directions, as researchers have realized that fluorescence is not completely Lambertian. We are talking about measuring the bi-spectral and bidirectional reflectance distribution. This may seem insurmountable, but metrologists have carried out this type of measurement in recent years [17][18].

Measurement devices

In this context, manufacturers of spectrophotometers are developing a new generation of instruments, able to access the light reflected by objects in several pre-established angular configurations, we talk then of ”multi-angle spectrophotometer”, or able to make the light source and the detector rotate around the object, we talk then of ”goniospectrophotometer”. Some of them integrate a spectral and/or high dynamic camera to collect millions of measurement points in few seconds [19]. Others take advantage of the recent progress in LEDs to provide compact devices [20] or to develop huge light domes [21]. This approach, combined with image processing tools is promising. This market is definitively dynamic, innovating and exiting.

Nevertheless, all these instruments work usually in relative mode. They compare, in a given angular and spectral configuration, the signal emitted by the test sample with the one emitted by the calibrated artefact. In order to ensure the on-purpose calibration service for this new generation of spectrophotometers and to ensure that traceability to national standards is available, National Metrological Institutes (NMI) are developing on their side so called ”primary goniospectrophotometers”, that allow the realisation of absolute BRDF, BTDF and BSSRDF measurements [22].

The challenge here is to realize a mise en pratique of BRDF/BTDF/BSSRDF quantities that can satisfy the diversity of industrial needs. Some of them need a high angular resolution device devoted to gloss, others a high spectral resolution for gonioschromatism. Sometimes a few angular configurations are enough to characterize quasi-lambertian standard, sometimes its several millions that are mandatory to establish the traceability of sparkle measurement devices. In front of this situation, NMI have no other option than developing versatile goniospectrophotometers that can adapt to the demand [28][29][30]. But unfortunately, versatility works against uncertainty. Since 2012, European NMIs have adopted a coordinated approach in the frame of EMRP and EMPIR funded programs [24]. The facilities developed in each country have been built to cover the diversity of measurement needs with complementarity while keeping an overlapping area to allow comparisons of national scales [25]. Therefore, each NMI can develop its specificity and push the uncertainty at its limit for one given application like fluorescence [26], gloss [27], iridescence [28][29][30] or µBRDF [31]. Often, more than one device is requested. It is the case when a new quantity or a new index is proposed. For sparkle for instance, an index has been proposed. Once it’s accepted, at least 2 NMIs must realize the measurement based on the definition of this index, in order to check that they get compatible results [32]. If yes, the index is validated. If not, it means that the definition is not robust enough and a new proposal have to be done [33]. This is the way of development of new measurements.

In 2016, 8 NMIs have compared their BRDF scales at one given angular configuration in the plane of incidence. Agreement between scale was at around 2% within the visible [34]. This comparison pointed out the sensitivity of primary goniospectrophotometers to polarization and to misalignment. Both phenomenon have been studied and ameliorations have been implemented [35][36]. In 2021, a new BRDF comparison has been carried out between 6 NMIs. This time, the agreement was at around 1% [37]. Uncertainty on the BRDF scale has been reduced by a factor 2 in 5 years at the highest level.

Now NMIs are moving on the development of primary scales for BTDF and BSSRDF and on multiscale traceability for BRDF. New facilities have been built. Work is still in progress, but soon, absolute scales of these quantities will be ready, allowing the development of a traceable metrology that will go to the end user. On those stable foundations, commercial advanced spectrophotometers, new rendering models, new 3D printer checker protocols, news numerical index correlating with visual attributes will grow up.

All put together, progresses in the field of the measurement of optical properties that are linked to the appearance of surfaces are there. Today we are almost capable to measure reflected light from a surface with the same angular, spectral and spatial acuity than the human eye !

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