Final Publishable JRP Summary Report for IND52 xD-Reflect "Multidimensional reflectometry for industry"

Overview

A customer will often choose a product based on the way it looks. Consequently, many industries invest a large amount of time and money in developing sophisticated visual effects such as metallic paints, sparkle effects and matt finishes. Visual attributes such as colour, gloss, texture, transparency, sparkle and graininess all combine to give the appearance of a particular surface. To characterise and control these visual effects, companies currently develop a range of optical measurements for their particular product or rely on a human visual expert evaluation. This project developed standard measurement techniques to characterise surface finishes with traceability and lower uncertainty, so that industry can ensure reproducibility and compliance with specifications.

Need for the project

The appearance of a product is important for many industries, such as the automotive, cosmetics, paper, printing, packaging, coatings, plastics and steel; and is frequently one of the most critical parameters affecting customer choice. Over the last 20 years, significant effort has been made by manufacturers to propose new and sophisticated visual effects, like metallic paintings, iridescence (goniochromatism), matt finishes or sparkle effects (the phenomenon where a material is caused to glitter or shine). These have been very popular with customers and commercially successful, but they depend on visual checking rather than objective measurement techniques.

From a metrological, or measurement, perspective, the most relevant quantity is the Bidirectional Reflectance Distribution Function (BRDF), which is the ratio of the amount of light reflected in a given direction to the amount of light illuminating sample from another direction, at a given wavelength. The BRDF is measured with a goniospectrophotometer which illuminates a sample from different directions and provides a full angular and spectral characterisation of the light reflected by the sample. The optical properties of surfaces require knowledge of its structure and its interaction with the incoming light. It is also important that the measured optical properties correspond to views made by a human observer, therefore how the human visual system uses the light that comes into the eyes to encode and construct the visual attributes needs to be understood.

Current standards and artefacts proposed by NMIs to industry to ensure traceability of measurements are very limited, and are insufficient for novel surfaces that show strong directional effects resulting from metallic, interference or diffractive pigments. New measurement methods, set ups and standards are required to provide the quantitative data that will ensure reproducibility and quality control of the new visual effects. For these new measurement methods to be taken up by industry, they need to be quick to make and easily interpretable. In addition, the methods should be highly correlated with the visual sensation of the human observer.

This project aims to provide the measurement tools, methods and transfer artefacts to industry, to characterise modern surfaces and ensure traceability of measurement to the standard systems of units. The research must be carried out on a European level because the skills and equipment required is not present in a single country. A European effort that takes the lead in this area could give industry a competitive advantage by influencing research and development. Furthermore, standardisation from regional or international organisations such as the International Commission on Illumination (CIE) are important for encouraging adoption of new standards.

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Scientific and technical objectives

The first group of objectives for the project aimed to improve the measuring equipment and instruments, and compared the results from different set ups and different NMIs. The BRDF can generate large amounts of data, so the second group of objectives used modelling to interpret the data efficiently and potentially reduce the number of measurements required. The project then compared the BRDF with the experience of industrial visual experts. The final objectives developed standard procedures and transfer standards.

Improvement of primary goniospectrophotometers in order to progress in BRDF measurements and reduce the measurement uncertainty

1. Enhance the spectral and spatial resolution of reference goniospectrophotometers developed by each participant, using modern detectors, Fourier optics, charge-coupled device (CCD) cameras, line scan camera, modern light sources, etc
2. Reduce the measurement uncertainties on BRDF measurements by implementing modern detectors and modern light sources in the concerned facilities and validate the results by a comparison;
3. Improve the 1 % uncertainties to 0.2 % - 0.5 % in the measurement of luminescent radiance factor of fluorescence standards
4. Evaluate uncertainty and sensitivity coefficients for BRDF measurements and psychophysical measurements

Development of models for data compression, data representation and data handling for BRDF measurement

5. Reduce the total measurement time that is a significant restriction for calibration capacities
6. Reinforce the link with industry by creating a BRDFpublic domain database for new advanced functional surfaces such as those used in the automotive industry
7. Propose recommendations for data handling of the large amount of data generated by BRDF measurements

Understanding of correlation between the visual appearance and the BRDF

8. Improve in the comprehension and the definition of the visual attributes such as colour, gloss, sparkle, graininess, fluorescence, from a visual point of view
9. Correlate visual intensity and response stimuli to the advanced BRDF measurements, material characteristics (structural features) and environment attributes

Developing standard procedures and transfer artefacts in order to develop applied metrology for visual appearance attributes

10. Set the optimal geometries for colorimetric measurement of advanced surfaces like metallic colours, or sparkle/graininess effects and gloss measurement, in particular by the development and characterisation of advanced transfer standards
11. Propose a new standard and recommendations for gloss measurements that take into account the visual perception, the background and is adapted to modern surfaces
12. Propose new types of reference artefacts for calibration and characterisation of goniochromatism, gloss and fluorescence

Results

Improvement of primary goniospectrophotometers in order to progress in BRDF measurements and reduce the measurement uncertainty

Objective 1:
A fully robot-based goniospectrophotometer was developed during the project. The spectral range was extended from the visible range before the project, to include ultra violet and infra-red, opening the field of BRDF for aerospace and terrestrial solar applications. Results were validated by comparisons between project partners PTB and CSIC's BRDF measurements. Using a Fourier optic based detection system combined with

a robot-based classical goniospectrophotometer an angular resolution for the BRDF measurement of 0.018° was achieved, which is the lowest resolution ever reached, This allowed access to the light reflected by the surface with the same acuity as the eyes of a trained industrial expert, which in turn led to progress in the field of gloss measurement and in the understanding of gloss visual perception mechanisms. A high dynamic CCD camera was implemented in three facilities, making it possible to study the sparkle effect in more detail.

Objective 2 and 3:
In order to reduce the measurement uncertainty in BRDF measurement, a new low noise silicon based detector was developed, with a limit of detection below 2 fA, which extends the capability to measure dark samples. The total uncertainty was reduced on primary goniospectrophotometers thanks to the development of techniques for calibration of illumination/observation geometry and better characterisation of non-linearity and stray light effects on CCD camera detectors used in several NMIs. Uncertainties were reduced by a factor 2 for the bispectral luminescent radiance factor.

The first comparison of reflectance factor measurements carried out by several different participants demonstrated that the BRDF is not as well controlled as expected, particularly for blue or red samples. It indicated where each participant had room for improvement and allowed better confidence in the uncertainty claimed. It also revealed that reflectance standard artefacts may show a dependence on light polarisation, which is important for progress on the comprehension of systematic effects in BRDF measurements. The same samples were measured with different commercial multi-angle spectrophotometers which showed that the control of the BRDF is about 5 times better at the NMI level than at industrial level.

Objective 4:
A virtual computer experiment was developed to allow a better comprehension of uncertainties propagation in goniospectrophotometers for special effect coatings and glossy samples. The experiment revealed that due to the high dimensionality of the BRDF, standard computation schemes used to evaluate the difference between two measurements are likely to be inappropriate for BRDF measurements. A new metric to access the distance between BRDF was developed and published, based on the evaluation of the difference in the “3D shape” of the BRDF, and mimicking what the visual expert does when comparing two different shapes.

Together PTB, CSIC and MSL developed a method for the evaluation of the popular CIELAB colour space, and the uncertainties. This is in line with the current guide to the expression of uncertainty in measurement (GUM).

The conclusion for this first group of objectives is that progress was made by each partner on its goniospectrophotometer system. There is now an increased capacity of BRDF measurement in Europe with different facilities having slightly different capabilities; i.e. one increased the angular resolution, one the spectral range and the third the dynamic range. A common understanding has been developed to allow the comparisons that were carried during the project to guarantee the control of the quantity. European NMIs are now ready to face the current needs of industries in the field of BRDF measurement, and are also ready to face future innovation on visual or functional effects on materials.

Development of models for data compression, data representation and data handling for BRDF measurement

Objective 5:
Normally, the characterisation of iridescence coatings requires extensive measurements because their BRDF strongly varies with the directions of observation and illumination. A new methodology based on just 10 measurement geometries was developed. Based on this restricted set of geometries and using a data analysis scheme, the user can assess the range of colours and appearances at all other geometries. This has the potential to drastically simplify the characterisation of special effect coatings. The same approach was attempted on gloss samples, but this was not successful, as it revealed that a new generation of BRDF models is required to characterise gloss samples.

Objective 6:
The project produced high level BRDF measurements on a large variety of samples including sparkly and iridescence ones. The measurements have been made available through the project website as an open access database of BRDF measurements. This database (see http://www.xdreflect.eu/brdf-data/) is particularly useful for instrument manufacturers and the digital imaging and computer graphics community, who need real and trustable BRDF measurement data in order to test their new models of compression, rendering algorithms, or visualisation tools and devices.

Objective 7:
The foundation of a mathematical framework was built to allow new techniques to be applied to the statistical design of experiments and machine learning, in order to establish more efficient BRDF sampling and measurement strategies. A data representation algorithm for BRDF measurements in order to create a standard format of data files was established. The adoption of this universal file format by a large community of users is important to strengthen the communication between metrologist, instrument manufacturers and end users.

In conclusion, as BRDF is a 6 dimensional quantity (2 angles to describe the direction of illumination, 2 angles to define the direction of observation, 1 wavelength and 1 polarisation), the elaboration of the strategy for its measurement is, by itself, a challenge. It is also difficult to archive, exchange and exploit measurements. The results for this group of objectives made significant progress in the way to sample, control, plot and share BRDF measurements. The recommendations must now be consolidated and promoted to instrument manufacturers, the computer graphics community and industrial end users, using support from a standardisation body such as the CIE.

Understanding of correlation between the visual appearance and the BRDF

Objective 8 and 9:
Light booths were constructed and delivered for visual experiments on sparkle, iridescence and gloss visual effects. Based on visual experiments and a principal component analysis, a threshold for colour tolerances and formulation for gonio-apparent colours was produced. This is important for the automotive industry because it puts a limit below which no effort is requested in painting or retouching work and is directly linked to monetary savings.

Correlations between sparkle sensation and particles characteristics have been identified according to the illuminance level, the geometry of illumination and the colour rendering index. The comparison of visual performances under LED and fluorescent lighting associated with the visual experiments on perception threshold of sparkle and graininess according to the distance of observation, provided important information on sparkle visual effect. LED lighting was adapted to show the effect. For pigment manufacturers the work provides a structure for new effects, and for instrument manufacturers it provides information on what matters visually in this effect, which is essential information if you want to measure and reproduce the visual effects.

Visual experiments made on gloss and high gloss samples have shown that the perception of gloss is not dependent on the shape and size of the light source, the observer sees the same level of gloss under either a cloudy or sunny sky. This is not true for mid-matt and matt samples, where sensitivity is better under a “sunny” illumination. In the entire gloss range, the sensation is enhanced when the samples are presented in a natural environment rather than a full black room. This result is important for industries who work with observer panels because it allows them to enhance the sensitivity of the panel. The project also determined that it would be possible to develop “gloss metrology” based on the experience of a “standard observer”.

In conclusion, this group of objectives focused on the two visual attributes that currently have a high impact in industry and are not well measured: i.e. gloss and sparkle. Clear indicators have been identified in sparkle that generate the visual sensation and open the route for its measurement. This topic is now ready to be investigated at an instrumental level as part of EMPIR project 16NRM08 BiRD. The effect of the shape and size of the light source on gloss sensation were understood in the current project and the first step toward the creation of a ‘gloss standard observer’ has been made.

Developing standard procedures and transfer artefacts

Objective 10:
Two new measurement lines were set up for the measurement of sparkle and graininess and an image based measurements procedure for the measurement of sparkle was developed. This was essential for the automotive industry, where more than 80% of their global production uses sparkle effect, but no clear measurement proposal to control the quality of the product previously existed.

Based on the work on measurement time (see Objective 5), a set of 10 optimal geometries for colorimetric measurement of iridescence samples based on interferometric pigments were produced. The uptake of this result by spectrophotometers manufacturers has the potential to launch a new generation of multi-angle spectrophotometers that would be more efficient than the existing ones. To visualise the colour for these samples on a screen, a new colour representation and interpolation from BRDF measurements was developed to support industry in monitoring the quality control of the appearance of coatings. Comparisons of specular glossmeters by the project, demonstrated weakness in the glossmeter's geometries and specifications.

Objective 11:
Based on psychophysical experiments made on gloss scales with different lightings and environments, recommendations were produced for the right way to evaluate visual gloss. However, due to the high complexity of the specular peak BRDF, which was not known before the project, it was not possible to find a correlation strong enough between the visual result and the optical results to develop new standard measurements. Further investigations are planned in the follow-on EMPIR project 16NRM08.

Objective 12:
A set of 18 ceramic samples were developed for inter-laboratory comparisons on the reflectance factor.

A new type of reference material for fluorescence measurements was produced which shows better Lambertian angular fluorescence emission profile (used for matt surfaces) than currently commercially available materials. A spectral change in the angular profiles of reflectance for fluorescent material was also discovered. This spectral change may impact the quality control of pulp and paper or textile industries, where fluorescent dyes are used.

A novel gloss scale made of 40 samples was constructed. The roughness, the BRDF and the specular gloss of these samples were characterised. From these measurements, the high complexity of the BRDF in and around the specular direction was demonstrated for the first time, and a link with the roughness has been identified.

Artefacts for sparkle and colour assessment have been designed and selected for two different campaigns, in collaboration with Merck (a global healthcare company) and Azko Nobel (a leading global paints and coatings company and major producer of specialty chemicals), industrial stakeholders. Based on the measurement of 66 samples, 9 were identified as representative of full range of effect pigments for visible iridescence effects and are now available for industry to use.

In conclusion, in this last group of objectives a method for the measurement of sparkle, and a protocol to characterise iridescence samples were developed. The project also built a new generation of standard artefacts for sparkle, gloss and fluorescence effects that will form the basis of the traceability and dissemination of the reflectance based quantities in the future. All these samples are now available for industrialists and researchers to carry out further investigations on BRDF measurements and models, to test measurement equipment or to work on visual perception.

Actual and potential Impact:
This project validated reliable optical measurements, with traceability to the SI, to describe the overall appearance of modern surfaces. It developed new efficient measurement strategies and new standard

artefacts that will enable industries to characterise and control the visual appearance of the surfaces they produce.

Dissemination activities and stakeholder engagement

22 papers were published by the project in relevant journals, including Applied Optics, the Journal of the Optical Society of America, Optics Express, Metrologia, and Colour Research and Application.

46 papers were presented at conferences, including leading conferences in the field such as the Colour & Imaging conference, CIE Expert Symposium and NewRAD. 7 training courses and workshops on such topics as the ‘Goniometric characterisation of sources and materials’ and the ‘Fundamentals of colorimetry’ were also held which were attended by around 200 people.

At the close of the project, in September 2016, CMI, with the scientific support of the xDReflect consortium, organised the 4th CIE symposium on visual appearance in Prague. 162 persons attended the event, from 27 different countries. There was a one day workshop on Visual Appearance Fundamentals and Measurement and was attended by 89 people. At the event the project’s guidelines on standard test method for visual evaluation of goniochriomatic samples, on lighting arrangements to improve visual experience in exposition, on viewing cabinets for sparkle evaluation, on the influence of the pigment particle size on sparkle and a recommendation for visual assessment of gloss were presented.

By the end of the project, its website http://www.xdreflect.eu had received over 59 000 visits.

Contribution to standards

15 presentations were given to regulatory bodies, including the BIPM Meeting of representatives of State Parties to the Metre Convention and of Directors of National Metrology Institutes, EURAMET Technical Committee for Photometry and Radiometry (TC-PR), DIN NA 025 on colorimetry, CIE Div2 annual meeting, ASTM E12 on colour and appearance, ISO TC 06 on Paper, board and pulp and the BIPM Consultative Committee for Photometry and Radiometry (CCPR).

The following 7 good practice guides and guideline documents were produced and have been published on the project website:

1. Guidelines for standard test method for visual evaluation of goniochromatic samples
2. Guidelines for lighting arrangements to improve visual experience in exposition
3. Guidelines for viewing cabinets for sparkle and graininess sample evaluation
4. Guidelines on the influence of the pigment particle size on the comparison of sparkle and graininess
5. Guidelines for new standard test method for visual evaluation of gloss
6. Good practice guide for fluorescence measurements of solid surfaces by the two-monochromator method
7. Good practice guide for colour measurements

Early impact

Examples of the project's outputs being taken up by the relevant communities include:

- St Gobain Research (a leading producer of building materials and glass) has used the high angular resolution BRDF measurement set up by CNAM to characterise its new functional surfaces.
- A presentation of the measurement strategy and global colour estimation extrapolation for goniochromatic samples was given to coatings scientists at the companies Merck and BASF (the largest chemical producer in the world).
- Most of the project’s work on sparkle, including the detection distance, a method for the estimation of iridescence colours outside Rösch-MacAdam colour solids, and an interpretation of imaged based BRDF capture, has been taken up by Merck and BASF.

- The project's procedure for the measurement of sparkle was used by one of the world leading portable spectrophotometer manufacturers to characterise samples.
- A PhD has been launched between Merck and the University of Alicante to develop new visual and instrumental correlations for sparkle based on the visual and metrological results of this project
- A PhD has been launch between Seat and the University of Alicante to develop new improvements in visual harmony management of the car body based on the visual and instrumental results of the project.
- The colour difference methodologies produced by the project were tested at Toyota Motor Europe
- The project's method for testing the colour difference on iridescence samples has been tested by the University of Granada, the University of Alicante and AUDI.
- Partially driven by the project's results, CIE has launch the technical committee TC2-85 on *"Recommendation on the geometrical parameters for the measurement of the BRDF"* .

Potential impact

The results from this project are expected to have impact on European industries through:

- Accurate and stable BRDF measurements, traceable to NMI reference standards, leading to improvements in quality control during the production process (gloss uniformity, iridescence reproduction).
- Providing objective and scientific means of checking that specifications agreed at the contract level have been met rather than using subjective expert judgements, and therefore improving client-supplier relations and ability to deliver.
- Reducing the costs in production due to a better knowledge of the border between "the things that are seen" and "the things that are not seen", allowing the manufacturer to know more accurately its production tolerances.
- Encouraging industry to develop new measurement devices in the field of reflectometry and visual effect characterisation, for example iridescence, gloss, fluorescence, sparkle and graininess.
- Fluorescent agents are used extensively by textile and paper industries and better control of the measurement, and thus less error, will make them use less fluorescent agent, save money and reduce pollution.

List of Publications

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