Publishable Summary for 18SIB03 BxDiff
New quantities for the measurement of appearance

Overview

Product appearance and visual branding are important drivers for consumer purchase decisions, as they underpin perceptions of 'quality' and 'desirability'. The project aims to advance primary metrology in spectrophotometry to meet industrial needs for the quantitative measurement of appearance. This will be accomplished by i) defining new spectrophotometric quantities, ii) taking previously ignored corrections terms into account, and iii) developing new traceable spectrophotometric primary references which will provide new tools for quality control and more realistic solutions for virtual prototyping. This research will benefit different industrial sectors like automotive, paper, cosmetic, 3D-printing and virtual reality rendering as well as scientific related applications like aerospace missions.

Need

Industry is developing increasingly complex materials that produce visual effects made to look beautiful and appealing (like iridescence or sparkle), or to accomplish a given function (like retroreflection). To develop and control their appearance properties, traditional colorimetry is not adapted anymore, and industrials increasingly start to use bidirectional reflectance measurements in various contexts. Traditional reflectance references based on a single angular measurement configuration will be deemed obsolete in the future. New commercial bidirectional spectrophotometers are diverse, flexible and high performing. National Metrology Institutes (NMIs) must continue supporting the ongoing revolution in spectrophotometry by providing bidirectional reflectance calibration services for angular configurations in addition to the classical 0°:45° configuration. The primary scales kept by participating NMIs have never been compared for e.g. out-of plane angular configurations that are representative of those used in the new generation of commercial products. Furthermore, the influence of common optical phenomena like speckle and polarisation has never been thoroughly studied in Bidirectional Reflectance Distribution Function (BRDF) measurements and might have a non-neglecting effect in uncertainty budgets.

The appearance of objects depends not only on the material(s), colour, shape and lighting environment, but also on the observation distance and object size. Therefore, the optical properties of materials must be measured at different scales: from the macroscopic to the microscopic.

Bidirectional Transmittance Distribution Function (BTDF) as a quantity, is the angle dependent radiance in transmission, referred to the irradiance on the sample. While BTDF measurements have been widely carried out, a standard definition for this measurand does not currently exist. BTDF measurements are of interest for diverse applications ranging from diffusers for aero-space applications, for green-houses, luminaires and to functional glasses for photovoltaic panels, because they could allow better performance, characterisation and efficiency. Thus, the measurand of BTDF must be studied, primary facilities must be set up and traceability must be consolidated with sphere-based measurements.

Total appearance, as defined by the International Commission on Illumination (CIE), is the contribution of four main visual attributes: colour, gloss, texture and translucency. Currently, there is no metrology infrastructure in place for measuring translucency, even though this attribute is ubiquitous and crucial in many fields such as cosmetics, food, packaging, dermatology, architecture, virtual reality and 3D printing. Quantifying translucency requires traceable measurements of the Bidirectional Scattering Surface Reflectance Distribution Function (BSSRDF), which are not presently available.

Objectives

The overall goal of this project is to advance primary metrology in spectrophotometry. This will involve defining the new quantities Bidirectional Transmittance Distribution Function (BTDF) and Bidirectional Surface

Scattering Reflectance Distribution Function (BSSRDF), developing primary facilities for their realisation, and further improving the measurements of Bidirectional Reflectance Distribution Function (BRDF). The specific objectives of the project are:

1. To address advanced metrological issues, i.e. speckle and polarisation, related to measurement of the BRDF with the aim to reduce the measurement uncertainty by a factor of two, down to 0.1 % (k = 2) in the visible wavelength range,
2. To establish a full metrological traceability of the BRDF from very small objects (micrometre scale) to regular objects (centimetre scale),
3. To develop primary reference facilities and reference samples (artefacts) for the measurement and dissemination of the BTDF as a traceable quantity with a relative target uncertainty of 0.5 % (k = 2),
4. To develop primary reference facilities and reference samples (artefacts) for the measurement and dissemination of the BSSRDF as a traceable quantity with a relative target uncertainty of 5 % (k = 2),
5. To facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, spectrophotometer manufacturers), standardisation organisations (ISO, CIE) and end users (e.g. automotive industry, video game developers, healthcare sector, visual arts sector, architectural materials manufacturers).

Progress beyond the state of the art

Improvement of the measurement uncertainty of BRDF

Building on previous projects EMPR IND52 - xDReflect and EMPIR 16NRM08 - BiRD, the measurement uncertainty for BRDF measurements will be improved by addressing advanced metrological issues such as polarisation and speckle induced side effects. This project aims to go beyond the state of the art on this by reaching an uncertainty of 0.1 % (k=2) at 550 nm on white diffusing samples. Additionally, to address the growing need for calibration points performed out-of-the-plane of incidence, the first comparison of BRDF scales realised with primary facilities will be performed at angular geometries including out-of-plane geometries.

Metrological traceability of the BRDF from micrometre to centimetre scale

Metrological traceability of BRDF will be extended by focusing on specific metrological issues related to scalability of BRDF measurements of small size area. These issues must be understood and accounted for, along with the requirements for such measurements. For the first time, a clear and traceable link between micrometre scale measurement areas and centimetre scale measurement areas will be provided.

Primary reference facilities and standard artefacts for BTDF

The most important classes of diffusers will be reviewed, which will be important for the determination of the measurand for BTDF with the lowest uncertainty. Two dedicated primary BTDF facilities will be developed to provide traceability for different sample classes or types, like frosted glass and volume diffusers. The congruence of the scales will be verified by a comparison, aiming at an expanded uncertainty of 0.5 % (k=2). The traceability will then be tested in a second round of comparisons using existing gonio-spectrophotometers at NMIs, as well as commercial set-ups.

Moreover, a greater insight into the precise BTDF will be investigated in order to improve the results obtained with existing integrating sphere measurements, as the results for artefacts with properties being far off from the Lambertian model may generate considerable errors.

Primary reference facilities and standard artefacts for BSSRDF

At present, the BSSRDF is not clearly defined as a physical quantity. Moreover, because no primary measuring equipment exists, traceable measurements of subsurface scattering or translucency cannot be provided. This project will go beyond the state of the art by defining the measurand and developing primary reference facilities and standard artefacts for the measurement and dissemination of the BSSRDF as a traceable quantity, with a targeted uncertainty of 5 %. Based on accurate BSSRDF measurements, scattering and absorption coefficients of materials as well as the phase function, will be computed. This will be the first step towards calibration and measurement capabilities for BSSRDF at NMIs.

Results

Improvement of the measurement uncertainty of BRDF

Existing gonio-spectrophotometers at participating NMIs have been upgraded to decrease their uncertainty before the interlaboratory reflectance scale comparison. CI has entirely rethought the way they control the rotation of the sample by replacing their robot arm by independent rotation stages, which gives a better angular control. CNAM and CMI have modified the optical design of the illumination part of their setup to include a control of polarisation. CSIC has added a second polariser to its existing facility in order to finely study the effect of polarisation on BRDF measurement. As this work focused on BRDF & polarization, a paper that describes methodology to assess polarization-related effects for the measurement of the BRDF has been published in Metrologia in June 2020 (link). Relative systematic errors due to polarizing conditions are calculated as a combination of the instrument polarization bias and sample type, for four different samples, classically used for BRDF calibration. The impact of the proposed methodology on the uncertainty is discussed. This methodology will be applied by the participants implicated in the comparison of BRDF scales and should help to decrease the uncertainty of the comparison.

CNAM has modified its high angular resolution BRDF measurement facility to allow a control of the spectral bandwidth. It has allowed to show evidence of speckle effects in BRDF measurements. The impact of speckle on BRDF is more important when measuring glossy surfaces and becomes the major component of uncertainty for an angular resolution below 0.1° even with wavelength spectral bandwidth higher than 50 nm. To support this work, NCS modified their existing technique for producing the famous NCS gloss scale to manufacture a large set of glass-based samples to be used for evaluating speckle effects in BRDF measurements. To achieve satisfactory results, this required a trial-and-error process when selecting and applying primers and paint to the glass. The result is a set of high-quality uniform samples well suited for the speckle task. In parallel, UJM has adapted the theory of speckle to the specific field of BRDF measurement. Simulations based on this theoretical work show results that are similar to measurements. Theoretical and experimental approach are now being merged to find a way to clean the speckle from BRDF measurements.

The “out of plane” BRDF comparison will be carried out in 5 angular configurations: i) [45°:0°], ii) [0°:45°], iii) [45°:-60°], iv) [45°: (45°,90°)] and v) [45°: (50,1°, 33,4°)]. All measurements will be done at 550 nm. 3 samples will be tested (white diffuse, grey diffuse and white satin). Labsphere, the manufacturer of the well-known Spectralon material, supplied several samples sets for the comparison. These samples have been custom made to fit the consortium’s need for mounting and handling.. Rotation of the measurements at the 5 participating NMIs has been agreed. First participant (CSIC) has already completed its measurements.

Metrological traceability of the BRDF from micrometre to centimetre scale

To support the multiscale traceability study, two types of micropillar structured glass samples and five different types of glass fibre samples have been developed and supplied by St Gobain. Their general knowledge about glass and its potential and limitations for use as artefacts with specific properties being very helpful for the project. Two other categories of samples (regular cylindrical structures and imitation leather) will also be used. Additionally, a Si roughness standard has been procured. The bibliographic study on BRDF measurements of small size areas has been completed and is available to the project members on the project's website. Gonio-spectrophotometers have been adapted at METAS, CNAM and CSIC to measure on small surfaces. CNAM has developed a broadband illumination beam that has a diameter of 50 µm. CSIC and METAS have on their side beams that can expand from millimetre to centimetre size. Collaboration between these NMIs will provide traceable measurements on the targeted range. Measurements will start in spring 2021.

Primary reference facilities and standard artefacts for BTDF

A “measurand team” agreed, via web meetings, on a specific set of samples and geometries suitable for the proposed BTDF comparisons and on the definition of the measurands. 50 % of samples requested for these measurements are already available and the more complicated are ordered. A possible link between BSSRDF and BTDF measurands, discussed in the “measurand team” was worked out in more detail and lead to the publication of a scientific paper (link).

PTB is developing a new gonio-spectrophotometer for BTDF measurement within the time of BxDiff project. A PhD student has been hired in September 2020 to carry on this work. Most parts of the set-up are delivered even if there is still a delay in delivery of the rotation stage. Alternative measurement possibilities are explored to guarantee expected measurements. Aalto is adapting its existing 3D gonio-spectrophotometer to reach a wide-angle range of transmission measurements for in-plane BTDF measurements. They are facing technical issues to make it working with sample heavier than 500 g. Despite current difficulties, both institutes should be on track to carry out the first measurements in summer 2021.

Innventia has developed four types of cellulose nanofibrillar (CNF) films with different scattering properties and in cooperation with temicon, specialized holographic diffusers will be made available. All these samples will be used for BTDF investigations.

Primary reference facilities and standard artefacts for BSSRDF

CSIC, in collaboration with CNAM, DFM, DTU and UJM, has reviewed existing theoretical and experimental work on BSSRDF. A reportership has been opened by CIE Div2 on "Definitions for bidirectional scattering surface reflectance distribution function (BSSRDF)" with the label DR2-86.

Discussion on the definition on BSSRDF measurement has quickly merged with the one of the BTDF measurand. The "measurand team" had a thorough discussion and both measurands have been defined. Names, symbols and measurement equations have been agreed and this forum published an important article in Optics Express (link). This paper discusses the adequate use of BRDF, BTDF and BSSRDF quantities when assessing translucent materials. For these materials, the radiance in a given direction depends not only on the directional irradiance but also on the size of the irradiated area of the surface, because for translucent materials, the radiance is produced by both the in-surface reflection and the sub-surface scattering. By explicitly considering both contributions, two other scattering quantities have been defined: one that accounts exclusively for the in-surface reflection and the other that accounts for sub-surface scattering. In this regard, these quantities might be considered more fundamental than BRDF, BTDF and BSSRDF.

CSIC has developed an image based BSSRDF primary facility for measuring the BSSRDF with an expanded uncertainty lower than 5 %. This facility uses camera detection and a spectral narrowband light source irradiation. It is based on the measurement of the spatial distribution of the reflected luminous flux when irradiated with a sub-centimetre spot size. A draft for a peer-review journal, describing design, principles, measuring procedure, measurement equation and uncertainty budget is under preparation. CNAM is developing a new goniospectrophotometer for BSSRDF measurement during the project. The optical design is completed. The illumination light beam, that is based on an LDLS broadband light source associated with a specific optical system has been set up. It allows illumination of the sample with a 50 µm diameter light beam. The detection, that is composed of a commercial spectrophotometer mounted on a 2-axis translation stage combined with a custom-made optic allows accessing the radiance inside a 300 µm area. Both systems are now being exploited on samples and first results are expected for February 2021.

The stakeholder Covestro, the manufacturer of different type of polymers, has been collaborating closely with the project partners to produce several sets of custom-made samples for BSSRDF measurements. By adding particles of different size, material and concentrations to polycarbonate in a well-controlled process, samples with suitable scattering properties were achieved.

A literature study has been done to determine the state-of-the art in the field of modelling of light diffraction and propagation, with a special emphasis on translucent materials. It covers the different model categories as Monte Carlo path tracing, aperiodic rigorous coupled-wave analysis (ARCWA), finite difference time domain (FDTD) solutions, microfacet models, Rayleigh-Rice and Harvey-Shack models and colloidal suspension methods. This survey has been published in Computer Graphics Forum (link). Based on this work, the consortium has chaired and presented a full session with five presentations (2 from DTU, 2 from DFM, 1 from KULeuven) on "Acquisition of Optical Properties" at Eurographics 2020, the 41st annual conference of the European Association for Computer Graphics.

Work is still going on to use the measurements points and develop and validate models to access appearance of translucent 3D objects separating the effects of surface- and subsurface scattering, to model the scattering properties given the intrinsic parameters of a translucent material or to extract the roughness parameters of a reflecting surface from the BRDF data. These contributions are expected to be of great value for the graphics community in terms of simulating the appearance of complicated objects.

Impact

The project website, which is hosted by CMI, has had more than 4500 visits so far. Additionally, 21 stakeholders from different sectors, e.g. pigments, spectrophotometer manufacturers, pulp & papers, automotive, cosmetics have attended the first progress meeting.

Four publications have been published in peer reviewed journals (Computer graphics forum, Optics Express, Metrologia, SPIE). Outputs of the project have been presented at 3 international conferences and 3 national conferences in France, Germany and Spain. Among these 6 presentations, 3 were invited talks. Members of standardisation groups (CIE, DIN, DfwG and ISO/TC6) have given 10 presentations during progress or annual meetings to inform members about BxDiff launch and results.

Due to the pandemic, the workshop on BTDF measurement that should have been organised at the end of January 2021 by Aalto and PTB has been postponed by one year. All other training events and workshops planed in the project protocol have been postponed by 6 months.

Impact on industrial and other user communities

The field of spectrophotometry is evolving quickly, and new commercial devices are continuously coming to the market. The appropriate characterisation and calibration of all these different types of goniospectrophotometers requires a coordinated effort between European NMIs. By the end of this project, the consortium will be able to provide new and improved calibration services to manufacturers of novel spectrophotometers, R&D industries and others.

The reduction of the BRDF measurement uncertainty and the validation and improvement of BRDF scales will reduce the uncertainty of the calibration for spectrophotometer manufacturers, which will have an immediate effect at the industrial level.

Virtual prototyping is very common in industry nowadays. However, virtual scenes calculated with existing rendering software used for image synthesis are still far from realistic when dealing with sparkle effects, aluminium brushed surfaces, complex environment such as car's cockpit, or translucent materials such as skin. Traceable BRDF measurements on microscopic surfaces will be used in rendering models to simulate the macroscopic appearance of the object. By providing those tools, this project will have a direct impact on rendering models and virtual prototyping.

The definition and realisation of BSSRDF will have a direct impact on different industries e.g. cosmetics, automotive, plastics, pulp and paper as well as on rendering software developers as it will provide the first calibration solution for devices that have already been developed.

Impact on the metrology and scientific communities

Better control of BRDF will have a direct impact on measuring quantities such as diffuse reflectance, gloss and colour. This will lead to reduced Calibration and Measurement Capability (CMC) uncertainties at several participating NMIs, therefore improving the quality and the visibility of European metrology in the field of spectrophotometry. New references for BTDF and BSSRDF measurements will lead to new calibration services at NMIs. This will promote the future development of new Certified Reference Materials (CRM), which will make traceability more accessible to the European metrology community.

Impact on relevant standards

This project focuses on the improvement and development of traceable quantities for the characterisation of the visual and optical properties of materials, which forms the terms of reference of CIE Division 2. It is anticipated that the project will have an impact on the work carried out in several CIE technical committees such as CIE TC2-85 (normalisation on BRDF), CIE JTC12 (measurement of sparkle and graininess) and CIE JTC17 (measurement of gloss). The CIE international vocabulary will be extended by the project through the definition of BSSRDF. International metrology committees such as CCPR and EURAMET-TC-PR will be periodically informed about the progress of this project. New calibration and measurement capabilities (CMCs) will be submitted on BTDF and, after the end of the project, on BSSRDF. As a consequence of this project, normalisation work on the measurement of BTDF and BSSRDF is foreseen.

Longer-term economic*, social and environmental impacts*

By providing new and reliable metrological references in spectrophotometry, this project will improve the quality control of the appearance of objects and its virtual reproduction. The control of appearance is directly linked to the success and the competitiveness of goods. The project will lead to improved rendering models able to better simulate the appearance of complicated objects. The uptake of outputs of the project will benefit computer generated imagery in movies and video games, digital prototyping of products, skin appearance rendering for medical and cosmetic industries, 3D printing, and energy assessment of buildings with glazing materials.

List of publications

A. Correia, P. Hanselaer, Y. Meuret, 2019, “Accurate and robust characterization of volume scattering materials using the intensity-based inverse adding-doubling method”, SPIE Vol **11057**, https://lirias.kuleuven.be/2825988?limo=0

A. Calderón, A. Ferrero and J. Campos, 2020, “Accounting for polarization–related effects in the measurement of the bidirectional reflectance distribution function”, *Metrologia* **57**(4), https://iopscience.iop.org/article/10.1088/1681-7575/ab804f

J. R. Frisvad, S. A. Jensen, J. S. Madsen, A. Correia, L. Yang, S. K. S. Gregersen, Y. Meuret, P.-E. Hansen, 2020, “Survey of Models for Acquiring the Optical Properties of Translucent Materials”, Computer Graphics forum (**39**)2, pp 729-755, https://diglib.eg.org/handle/10.1111/cgf14023

A. Ferrero, J. R. Frisvad, L. Simonot, P. Santafé, A. Schirmacher, J. Campos, and M. Hebert, 2021, Fundamental scattering quantities for the determination of reflectance and transmittance“, *Optics Express* **29**(1), https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-29-1-219&id=445047

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 May 2019, 36 months
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Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. CNAM, France	9. DTU, Denmark	13. CI, New Zealand
2. Aalto, Finland	10. Innventia, Sweden	14. Labsphere, United States
3. CMI, Czech Republic	11. KU Leuven, Belgium	15. Lucideon, United Kingdom
4. CSIC, Spain	12. UJM, France	16. NCS, Sweden
5. DFM, Denmark		17. St Gobain, France
6. METAS, Switzerland		
7. PTB, Germany		
8. RISE, Sweden		
RMG: -		