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Machine-readable universal data format for bidirectional reflectance distribution function and BiRDview—An open-source web-based application for viewing and comparing bidirectional reflectance data

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Abstract

Modern studies of bidirectional reflectance distribution function (BRDF) and its applications using data and machine-driven science require formatting of BRDF data according to Findable, accessible, interoperable and reusable (FAIR) data principles. As a solution a FAIR universal BRDF file-format based on Java Script Object Notation (JSON) is proposed. JSON principles as well as file structure are explained and examples are given. Automatic validation of universal BRDF file format is realized with the help of JSON schema. Furthermore, the source code and accompanying documentation are presented in dedicated supporting material files. It is expected that after its wide adoption, the proposed BRDF file format will enhance collaboration between different research groups and benefit machine-driven science. The uptake is facilitated by introducing a BiRDview—a modern open-source web-based application for BRDF visualization.

KEYWORDS

appearance, BRDF, FAIR, machine vision, visualization

JEL CLASSIFICATION

O31, O32

1 | INTRODUCTION

The bidirectional reflectance distribution function (BRDF) is a fundamental quantity to describe the dependence of the reflectance of materials on the irradiation and collection solid angles.[1,2] Since humans as well as light-sensing instruments receive optical information about surrounding non-radiative objects mainly from reflected light, BRDF, in its essence, carries information about how different materials will be perceived. It describes whether the material is mirror-like, glossy, or matt and, in the case of spectrally resolved BRDF, what is its color and how does it change with viewing conditions.

For this reason, BRDF has found a wide application in many modern technologies and science. It plays a crucial role in computer graphics, photorealistic rendering as well as computer vision, object recognition and remote sensing.[3–6] It is employed in many physical models and can be used for functional material design, predictive physical simulations and reverse engineering.[7,8] Not to mention an extensive use of BRDF in color science and consumer industry where part of the visual quality control relies on measured reference BRDF data.[9,10]

Scientists from national metrology institutes as well as laboratories of different industries actively model and measure BRDF using different methods, equipment, and software. Large amount of data is generated and actively exchanged while new challenges arise in the growing community. Diversity of approaches in measurements and non-conformity in data handling hinders collaboration as compatibility of BRDF data files from different software is not ensured. Researchers either need to develop their own file converters or use the same software as partners. The latter option can; however, entail financial investments that may not be affordable by small-scale community contributors and start-ups.

At the same time, in the environment of scientific data, humans are not the only critical stakeholders. Computational agents, that include regular applications as well as software powered by artificial intelligence, benefit greatly from structured and uniform datasets. In 2014, a large group of scientists and private stakeholders concluded "that all research objects should be Findable, Accessible, Interoperable and Reusable (FAIR) both for machines and for people" and established FAIR Guiding Principles for scientific data management and stewardship.[11] However, despite an increasing attention to machine-driven science in the field of BRDF studies,[12,13] most of the BRDF data does not yet completely follow FAIR principles.

This problem was recognized by National Metrology Institutes, partners from industry and the research community and tackled as a part of the Joint Research Project "Bidirectional Reflectance Definitions" (JRP 16NRM08 BiRD).[14] The present article is aimed to document the solutions proposed by the community and to introduce a "universal BRDF data format" as well as BiRDview—an open-source web-application for assessing and comparing BRDF data in the agreed format.

2 | FAIR BRDF DATA FORMAT

2.1 | FAIR guiding principles and existing developments in BRDF data reporting formats

FAIR guiding principles are a set of high-level domain-independent recommendations for reporting wide range of scholarly outputs. Their main novelty is in putting machine stakeholders on the same level as humans and supporting automated deposition, exploration, sharing, and reuse of scientific data on the same level as manual. The quick overview of these principles can be seen in Table 1.

TABLE 1 Quick overview of the main points of findable, accessible, interoperable and reusable guiding principles as provided in Reference 11. The working document concerning these principles can be found in Reference 15

To be findable: • F1. metadata and/or data are assigned a globally unique and persistent identifier • F2. data are described with rich metadata (defined by R1 below) • F3. metadata clearly and explicitly include the identifier of the data it describes • F4. metadata and/or data are registered or indexed in a searchable resource
To be accessible: • A1. metadata and/or data are retrievable by their identifier using a standardized communications protocol • A1.1 the protocol is open, free, and universally implementable • A1.2 the protocol allows for an authentication and authorization procedure, where necessary • A2. metadata are accessible, even when the data are no longer available
To be interoperable: • I1. metadata and/or data use a formal, accessible, shared, and broadly applicable language for knowledge representation. • I2. metadata and/or data use vocabularies that follow FAIR principles • I3. metadata and/or data include qualified references to other (meta)data
To be reusable: • R1. metadata and/or data are richly described with a plurality of accurate and relevant attributes • R1.1. metadata and/or data are released with a clear and accessible data usage license • R1.2. metadata and/or data are associated with detailed provenance • R1.3. metadata and/or data meet domain-relevant community standards

As it can be noted, FAIR guiding principles' main implementation instrument is rich metadata that provides relevant information about the dataset it accompanies. This approach is well known, and it is widely used in different application fields for a long time. BRDF representation is not an exception. One of the best examples could be a BRDF reporting format specified in SEMI ME1392 (former ASTM 1392–96) standard document concerning "standard practice for angle resolved optical scatter measurements on specular or diffuse surfaces" published in 1996.[16] As FAIR principles, it suggests to use metadata and provides a significant number of different tags with definitions to describe data origin, acquisition means and conditions.

However, the reporting format in Reference 16 cannot be considered to follow FAIR principles completely. First, it does not include a globally unique and persistent identifier and hence does not fully comply with findability and accessibility principles. Second, even though it utilizes domain-relevant language for BRDF data representation, it targets mainly humans and is not implemented in broadly applicable machine-readable data format, which significantly reduces interoperability and hinders application of data for machine-driven science. Third, SEMI ME1392 BRDF reporting format is published in a non-free standard document and, if included in communication protocol, it will not be easily accessible by all stakeholders. This might be a reason why the abovementioned file format proposed already in 1996 is still not widely adopted and there are only few databases and software featuring it. Some users, for example Cornell University who maintain one of available BRDF databases, indicate that there are "no way to test compliance with the ASTM standard" since there are no example files nor software for this purpose.[17]

Another point to be taken into account is that many scientific and/or computer graphics software developers prefer to use their own file formats. It is done either for commercial reasons, for the ease of software development or due to development of instrument specific solutions and publishing data related to a certain research. For example, Zemax, LightTools, TracePro software have their means for saving BRDF/BSDF data, but do not have publicly available data format specifications to assess its compliance with domain-relevant community standards and FAIR Principles. Disney BRDF Explorer[18] features data format that allows only functional and parametrized modeled BRDF representation and RGL Tekari viewer[19] only supports files derived from measurements of pgll goniophotometer used by Realistic Graphics Lab (RGL) at EPFL (Swiss Federal Institute of Technology Lausanne). Of course, some of the software like Disney BRDF Explorer or BRDFLab[20] connect also to widely referenced MERL BRDF and CUReT BTF/BRDF databases, but they report BRDF data in files, the formats of which are not explicitly specified and can be understood only after reading dedicated research articles.[21,22] Such BRDF data formats cannot be considered to follow FAIR principles and do not suit for the role of universal BRDF data format that is required to support collaboration between researchers and boost machine-driven science.

It should be noted, though, that a FAIR file format alone cannot ensure the complete following of FAIR Guiding Principles. It can do this only when existing in a system that includes a clear protocol and a manageable database. However, such system is out of the scope of the current article since there already exist research domain-independent solutions like Dataverse network[23] that can be utilized when the FAIR BRDF data format emerges.

2.2 | BRDF data analysis

By theory, BRDF in spherical coordinates (Figure 1) is a continuous function $q(\theta_i,\varphi_i,\theta_r,\varphi_r)=L_r(\theta_r,\varphi_r)/E_i(\theta_i,\varphi_i)$ that equals to the ratio of radiance L_r at the direction defined by angles θ_r and φ_r to the irradiance E_i produced from the direction defined by angles θ_i and φ_i.[2] In practice, however, such ideal situation can only be achieved in the modeling of BRDF where one can define an explicit form of $q(\theta_i,\varphi_i,\theta_r,\varphi_r)$ function. This might be sufficient in case of computer graphics and art, but for other applications, that involve understanding of actual light and material interaction, evidence-based physical models are required.

However, various instruments featuring different measurement techniques that are used by many national metrology institutes and companies[24–29] cannot measure a functional form of BRDF. Measured BRDF is usually a set of discrete points acquired at specified irradiation and collection directions with known uncertainty and finite solid angles. And since we cannot generally compress measurement data to a compact functional form, this leads to a significant amount of data that should be stored, processed and exchanged.

By the definition of the BRDF presented above, a single BRDF point is the ratio of radiance and directional irradiance at four specific spherical coordinates, two describing the illumination direction and the other two viewing direction. This means that, in general form, full BRDF data is a set of points in 5D space where one dimension corresponds to the value of q, two describe the

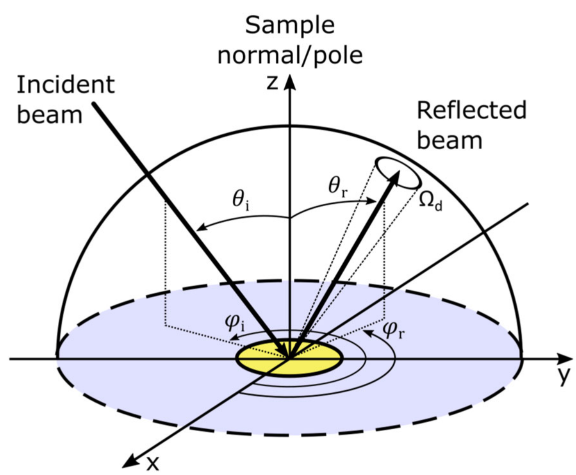

FIGURE 1 BRDF geometrical definitions in spherical coordinates. BRDF, bidirectional reflectance distribution function

illumination angles and two indicate the viewing angles. It might seem straightforward at a first glance, but from the point of view of data storage and representation this presents some challenges.

There are many ways to differently structure the BRDF data and the choice is often governed by BRDF measurement methods and instruments, the algorithms of which favor data acquisition and saving in specific order. This limits comparability of different BRDF data sets and introduces a need for additional data interconversion that might not be available in commercial software or requires additional effort from researchers to modify internal processing programs. Also, for most modern applications 5D BRDF data is not sufficient. Many laboratories are interested in spectral BRDF data to have information about color properties of the samples. Other users observe BRDF dependence on illumination as well as reflected light polarization and hence, in some cases, polarization is varied during BRDF measurements. As a result, the dimensionality of the BRDF data increases and more options for data representation emerge.

2.3 | Description of the proposed FAIR BRDF file format

To tackle the presented problems, the consortium of the BiRD Joint Research Project agreed to join efforts and create a universal BRDF data format that could be used by partners in the entire industry for streamlined storing, exchange and comparison and that would follow FAIR data principles.

Several iterations led to the decision to adapt JavaScript Object Notation (JSON) text format for the needs of BRDF data.[30] This prevented the complex process of development and integration of completely new text format as well as ensured compatibility with FAIR Interoperability principle. JSON is "formal, accessible, shared, and broadly applicable language"[11,30] that is suitable for knowledge representation. It is robust and simple and the majority of modern software used in research such as Matlab, Origin Lab, Microsoft Excel, and so forth. already support it. Even without the listed software, online and offline JSON data readers make files easily readable for humans while built-in or easily findable JSON processing libraries for C, C++, C#, Java, JavaScript, R, Python, and other programming languages enable effortless machine reading. Moreover, there are instruments for automatic validation of JSON based data formats if they are coupled with JSON schema—a specialized file thoroughly describing all valid JSON file fields.[31] This is a great benefit for users and software developers since it allows to quickly check whether the file corresponds to all format specifications and helps to prevent non-coherency in the large amount of data due to misinterpretation of file format description.

JSON syntax revolves around the data structure called "object" that in the world of programming is also known as "dictionary," "keyed list," "associative array," and so forth. Object is an unordered set of "key"/"value" pairs where "key" is a string type variable that names a "value" that can be either a string, a number, an array, a true or false value, a null or an object, that is, another set of "key"/"value" pairs. According to JSON syntaxis "key" and "value" are separated by colon and embraced by braces—{"key": *value*}. String values are embraced by double quotes like "string," arrays are embraced by square brackets, (1, 2, …, N), and numbers (integers or floating point) as well as "true," "false," and "null" can be written without any special marking. "Key"/"value"pairs in objects and elements in arrays are separated by comma.

The complete file format description can be found in JSON schema[32] and documentation web-page[33] while simplified structure of proposed universal BRDF data format is shown in Figure 2. The file is an object with two main keys "metadata" and "data" the values of which are also objects. Metadata object allows to describe data stored in the data object with a rich metadata as required by FAIR Guiding Principles for scientific data.[11] It has following predefined keys: "schema," "id," "type," "timestamp," "provenance," "license," "description," "method," "instrumentation," "software," "sample," "environment," "data_links," "comments," and "adhoc_section." Key "schema" provides a link in United Resource Identifier (URI) format to the JSON schema that was used as a reference for presented BRDF file structure. Part of the link always contains a name of the schema file, which specifies the version of the schema. This is required to allow sustainable development and upgrading of universal BRDF file format while mitigating compatibility problems. Key "id" is globally unique and persistent identifier in URI format that ensures findability of the data and it ought to be assigned when data is placed in globally available database. Key "type" is required to clearly and explicitly include the identifier of the data it describes and its value is always "BRDF." Key "timestamp" indicates when measurement or simulation was conducted in the format of YYYY-MM-DDThh:mm:ss ± hh corresponding to ISO8601 standard.

The "provenance" specifies the origin of the data presented in the file using a predefined object described in JSON schema that allows to provide the name of organization that produced the data, its

```
{
   "metadata":          *         - An object that provides the description of the data presented in data object.
   {
      "schema":         * string, - URL link in URI format specified in RFC3986 standard
                                    that points to the schema of universal BRDF file format
                                    specifying the schema version.
      "id":             * string, - An universal resource identifier (URI), according to RFC3986 standard.
      "type":           * string, - Data type identifier that in current shema version (1.0)
                                    should be a string "BRDF" that stands for
                                    bidirectional reflectance distribution function.
      "timestamp":      * string, - Timestamp of measurement or simulation as a string in the format of
                                    YYYY-MM-DDThh:mm:ss±hh of UTC time corresponding to ISO8601 standard.
      "provenance":     * provenance object, - A predefined object with various keys allowing to specify
                                    the origin of the data presented in data object.
      "license":          license object, - A predefined object that allows to specify under which license
                                    data presented in the file is published.
      "description":    * string, - A short description in the form of text (i.e. string) of the
                                    the measured or simulated BRDF data set presented within the file.
      "method":         * string, - The field that specifies whether the data was simulated or measured.
                                    Can have one of following values: "simulation" or "measurement".
      "instrumentation": * instrumentation object or "NA", - By default, it should be a predefined object
                                    that allows to thoroughly describe instrumentation that was used for
                                    acquizition of the BRDF data presented in the "data" object of the file.
                                    Hovewer, if data was simulated and this field is not applicable, a string
                                    "NA" can be used as a placeholder since "instrumentation" key is required.
      "software":       * software object or "NA", - A predefined object that describes the software that was
                                    used for measurement, processing or simulation of BRDF data presented in
                                    the "data" object of the file. If, for some reason, not applicable, a
                                    string "NA" can be used as a placeholder.
      "sample":         * sample object, - A predefined object that allows to describe either real or virtual
                                    measurement sample that was used to obtain data presented in the file.
      "environment":    * environment object or "NA", - A predefined object that allows to specify environmental
                                    conditions such as temperature, relative humidity or pressure relevant
                                    to presented BRDF data. If not applicable, a string "NA" can be used.
      "data_links":       array of strings, - An array of strings in URI format (links) that allows to refer
                                    to any available external information regarding BRDF data presented
                                    within the file.
      "comments":         string, - The field that allows to provide any comments relevant to the presented
                                    BRDF data and that cannot be provided in the other fields.
      "adhoc_section":    object  - An object that allows user to specify custom fields with user-defined
                                    key/value pairs to avoid mixing them with predefined fields.
   },
   "data":              *         - An object containing measured or simulated BRDF data in predefined "variable" objects.
   {
      "theta_i":        *         - An object that describes the variable corresponding to illumination zenith angle θ_i
                                    and stores an array of its values in degrees or radians that were set to obtain
                                    BRDF values stored under the same indices in the array of "BRDF" object.
      {
         "unit":        * string, - The field describing the unit of the variable.
                                    Can have only predefined values described in the BRDF file schema.
         "values":      * array,  - An array with variable values within the limits specified in the
                                    BRDF file schema.
         "name":,         string, - Short name of the variable as a string.
         "description":   string, - Short description of the variable as a string.
         "uncertainty":   object, - An object allowing to specify a constant uncertainty of the variable.
                                    Has the keys "value" and "unit".
         "comments":      string  - A field allowing to provide any comments regarding variable in the form of string.
      },
      "phi_i":          * phi_i object, - An object that describes the variable corresponding to
                                    illumination azimuthal angle φ_i and stores an array of its values
                                    in degrees or radians that were set to obtain BRDF values stored under
                                    the same indices in the array of "BRDF" object.
      "theta_r":        * theta_r object, - An object that describes the variable corresponding to
                                    observation zenith angle θ_r and stores an array of its values
                                    in degrees or radians that were set to obtain BRDF values stored under
                                    the same indices in the array of "BRDF" object.
      "phi_r":          * phi_r object, - An object that describes the variable corresponding to
                                    observation azimuthal angle φ_r and stores an array of its values
                                    in degrees or radians that were set to obtain BRDF values stored under
                                    the same indices in the array of "BRDF" object.
      "BRDF":           * BRDF object, - An object that describes measured or simulated BRDF values and stores them
                                    in dedicated array.
      "uBRDF":            uBRDF object, - An object that allows to describe uncertainty values of measured BRDF and
                                    store them in dedicated array.
      "wavelength_i":     wavelength_i object, - An object that describes the variable corresponding to
                                    illumination wavelength λ_i and stores an array of its values
                                    in nm or μm that were set to obtain BRDF values stored under
                                    the same indices in the array of "BRDF" object.
      "wavelength_r":     wavelength_r object, - An object that describes the variable corresponding to
                                    observation wavelength λ_r and stores an array of its values
                                    in nm or μm that were set to obtain BRDF values stored under
                                    the same indices in the array of "BRDF" object.
      "polarization_i":   polarization_i object, - An object that describes the variable corresponding to
                                    illumination polarization state p_i and stores an array of its values
                                    represented either as "s", "p" and "u" strings corresponding to s, p and unpolarized
                                    state or as Stokes vector defined as array with four numerical elements.
                                    Each polarization value element index should correspond to the index of BRDF value at
                                    which it was measured and that is stored in the array of "BRDF" object.
      "polarization_r":   polarization_r object, - An object that describes the variable corresponding to
                                    observation polarization state p_r and stores an array of its values
                                    represented either as "s", "p" and "u" strings corresponding to s, p and unpolarized
                                    state or as Stokes vector defined as array with four numerical elements.
                                    Each polarization value element index should correspond to the index of BRDF value at
                                    which it was measured and that is stored in the array of "BRDF" object.
      "adhoc_variables":          - An object that contains user-defined variables to avoid mixing them with predefined
                                    fields.
      {
         "any_name":      adhoc_variable object - An object that defines the structure that user should follow when
                                    describing custom variable.
      }
   }
}
```

FIGURE 2 Simplified structure of proposed universal BRDF file format. All keys denoted by asterisk are mandatory. Under "theta_i" key, an example of variable object is given. BRDF, bidirectional reflectance distribution function location, website, contact person and his/her contact data. Key "license" provides the legal information regarding presented file and specifies under which conditions it can be used and shared. Common practice is to use, for example, "Creative Commons" (CC) license abbreviations that can be specified alongside the rights holder and its contact information in predefined license object. Under "description" key users are obliged to provide in the form of text (i.e., string) a short description of the dataset they present. Key "method" allows to distinguish between measured and simulated BRDF data. If the data was measured, the information regarding used devices can be recorded in the predefined "instrumentation" object. It permits to specify the name of the instrument, its manufacturer, model, used illumination and detection systems, set measurement parameters as, for example, spectral bandwidth of the illumination and/or detection systems, detection aperture diameter, illumination beam shape etc. The software used for data processing and modeling can be in a similar way described under "software" object where there is also provided a way to present simulation model and its parameters. Information regarding measurement sample like its material, dimensions, shape, isotropy/anisotropy, roughness, treatment procedures etc. can be specified within the "sample" object and measurements' environmental conditions like temperature, relative humidity or pressure under "environment" object. Specific information regarding all existing fields and allowed values of abovementioned-predefined objects can be found in the JSON schema[32] and documentation.[33] Additionally, users can provide references to any available external information relevant to the data presented within the file by adding a link in the URI format into "data_links" array. Any additional comments can be provided as a string in "comments" field and user defined fields can be added to the object under "adhoc_section" key to avoid mixing them with predefined values. For an example of complete metadata structure, see Appendix 1.

The "data" object contains keys that describe BRDF data and its variables. In total 11 keys: "theta_i," "phi_i," "theta_r," "phi_r," "BRDF," "uBRDF," "wavelength_i," "wavelength_r," "polarization_i," "polarization_r," and "adhoc_variables." First five that follow the BRDF definition provided by F.E. Nicodemus in Reference 1 are mandatory and others can be added to the data object on demand. Except for "adhoc_variables," each variable corresponds to an object that specifies its "name," "description," "unit," "uncertainty," stores its "values" and allows to provide relevant information in "comments" (see example under "theta_i" in Figure 2). Together these objects form a data structure similar to a 2D array where one can treat each object as a column with header specified by keys like "name" or "unit" and data provided in "values" array. The rows in this 2D structure are vectors that specify a single BRDF point in multidimensional space for which reason the length of different variables' columns (i.e., "values" arrays) should match. The main peculiarities of each predefined variable that are also recorded in universal JSON schema[32] are provided below.

Keys "theta_i" and "theta_r" stand for illumination and reflectance zenith angles that should be presented in degrees or radians and can vary from 0° to 90° or from 0 to $\pi/2$, respectively. Keys "phi_i" and "phi_r" denote illumination and observation azimuthal angles that also have units in degrees or radians and can have values within the range from 0° to 360° or from 0 to 2π with the exact values of 360° and 2π excluded to avoid overlapping data. Keys "wavelength_i" and "wavelength_r" allow to specify illumination and observation wavelengths and can have values larger than 0 in nanometers or micrometers. Regularly, a single wavelength related variable is used and subscripts "i" and "r" specify whether the wavelength was resolved at illumination or detection system side. Both parameters can be used simultaneously, if BRDF of fluorescent materials needs to be documented. Keys "polarization_i" and "polarization_r" describe incident and reflected light polarization states that can be provided either by "s," "p," or "u" strings that correspond to s-, p-, and unpolarized states or by intensity-normalized Stokes vectors[34] that allow to present an arbitrary polarization state. First element of the Stokes vector is always 1 and three other elements vary from 1 to 1. In case of incoming radiation, the polarization state is defined in respect to the plane of incidence formed by the sample's normal and direction of illumination beam, while the polarization of reflected light relates to the plane of reflectance formed by the sample's normal and observation direction. If the sample is illuminated or viewed at 0°, polarization is defined in respect to sample's normal and 0° azimuthal direction specified by marking on the sample that user is obliged to specify in "metadata" "sample" section. Key "BRDF" represents BRDF values themselves and can have values equal to or greater than 0 in sr^{-1}. Key "uBRDF" allows to record an uncertainty for each BRDF value and can have positive values in sr^{-1} or %. Key "adhoc_variables" permits users to define their own variables by providing for each variable a name, type, description, unit, and limits for allowed values. It is important to note that, by specification of "ECMA-404 The JSON Data Interchange Standard," infinite ("Inf"), −infinite ("-Inf") and not-a-number "NaN" values in the numerical fields are not allowed and one should avoid their use even though

JSON parsing libraries for many programming languages as, for example, Python and Ruby can process such values correctly. Additionally, it is recommended that within a single BRDF data file for any unique combination of variable's values only one BRDF value exists. If for any reason there are multiple BRDF values for the same arguments, they should be separated and saved in different files if possible.

Other than stated above, the proposed file format does not impose any additional restrictions nor enforce any particular measurement method since it is not its objective to replace or recommend any standard practices for BRDF measurements. File format should allow to report data measured using any of these practices. With the conversion to spherical coordinates and use of provided predefined objects, the proposed universal BRDF file format completely fulfills its purpose. A universal BRDF file should be saved with extension ".json" or ".bird" and can be validated using the JSON schema available in Reference 32. Example file is provided in Appendix 1.

3 | BIRDview APPLICATION

3.1 | General information

Introduction of the universal BRDF file format in Section 2.3 covers only part of the needs of stakeholders. Even though it improves coherence of the BRDF data, it does not provide completely seamless experience of its use. As was noted before, various laboratories and industries use different software to view and compare BRDF data and introduction of a new file format that is not yet largely accepted may burden them with yet another file interconversion or additional software development. An alternative solution is required to facilitate uptake of the file format and encourage its application in real-life tasks. For this reason, the consortium of BiRD Joint Research Project set a goal to develop an open-source version of software that could open universal BRDF files for data visualization and comparison.

This gave birth to BiRDview—an open source web-application for validation of universal BRDF data format and visualization BRDF data within it. It is written in Python using Plotly Dash open-source framework and deployed to the web (freely available at Heroku server[35]) to allow easy access to the application through a regular browser at any place with internet connection. Alternatively, one can use a local device to run a Python code that was published on GitHub.[36] The visual interface of the applet is shown in Figure 3.

The software features three main tabs named "Applet," "BRDF json validator," and "Help." The latest tab provides a quick guide explaining how to use BiRDview as well as the information about universal BRDF file format. "Applet" shows the main data visualization screen of the applet. This contains versatile file upload field, options bar on the left side and visualization area with four interactive BRDF data plots on the right. Application allows uploading one or multiple files at a time by drag-and-drop or by calling out file explorer context window. Upon uploading, menu shows the active file name within top dropdown menu and unique values of BRDF function's parameters in the additional dropdown menus below. These dropdowns allow switching between different BRDF files and choosing the slices of data to be displayed on graphs by selecting the desired incidence zenith, incidence azimuthal, viewing zenith, and viewing azimuthal angles as well as any other parameters that were varied during simulation or measurement (wavelength, polarization, sample orientation, etc.). For each individual file, BiRDview remembers all values selected within the dropdown menus and switching between files does not require reselection of parameters since previously chosen views of BRDF data are preserved. It is also possible to present different slices of data on a single graph by pressing "Snap state" button and saving a curve with a particular set of a parameters to a separate layer that will be displayed alongside non-saved active state controllable by menu dropdowns. BRDF data slices can originate from a single file or from different files whose metadata is also accessible by "Metadata" tab in options bar.

"BRDF json validator" contains an additional upload field where users can upload their files and check whether they correspond to the universal BRDF format proposed here. If the file is not valid, an error message will point to the invalidity origin and help the user to format files correctly (see Figure 4).

3.2 | Description of BRDF data visualization options

The essential part of the presented software is the visualization of BRDF data. However, due to multi-dimensionality of the data there are many ways to represent the data points on graphs. This puts a limit on the amount of information that can be simultaneously displayed on a single graph and one needs to use multiple of them to visualize all the information simultaneously.

Currently, as can be seen in Figure 3, BiRDview features four figure spaces that allow to plot different slices of multidimensional BRDF data. Upper and lower left are

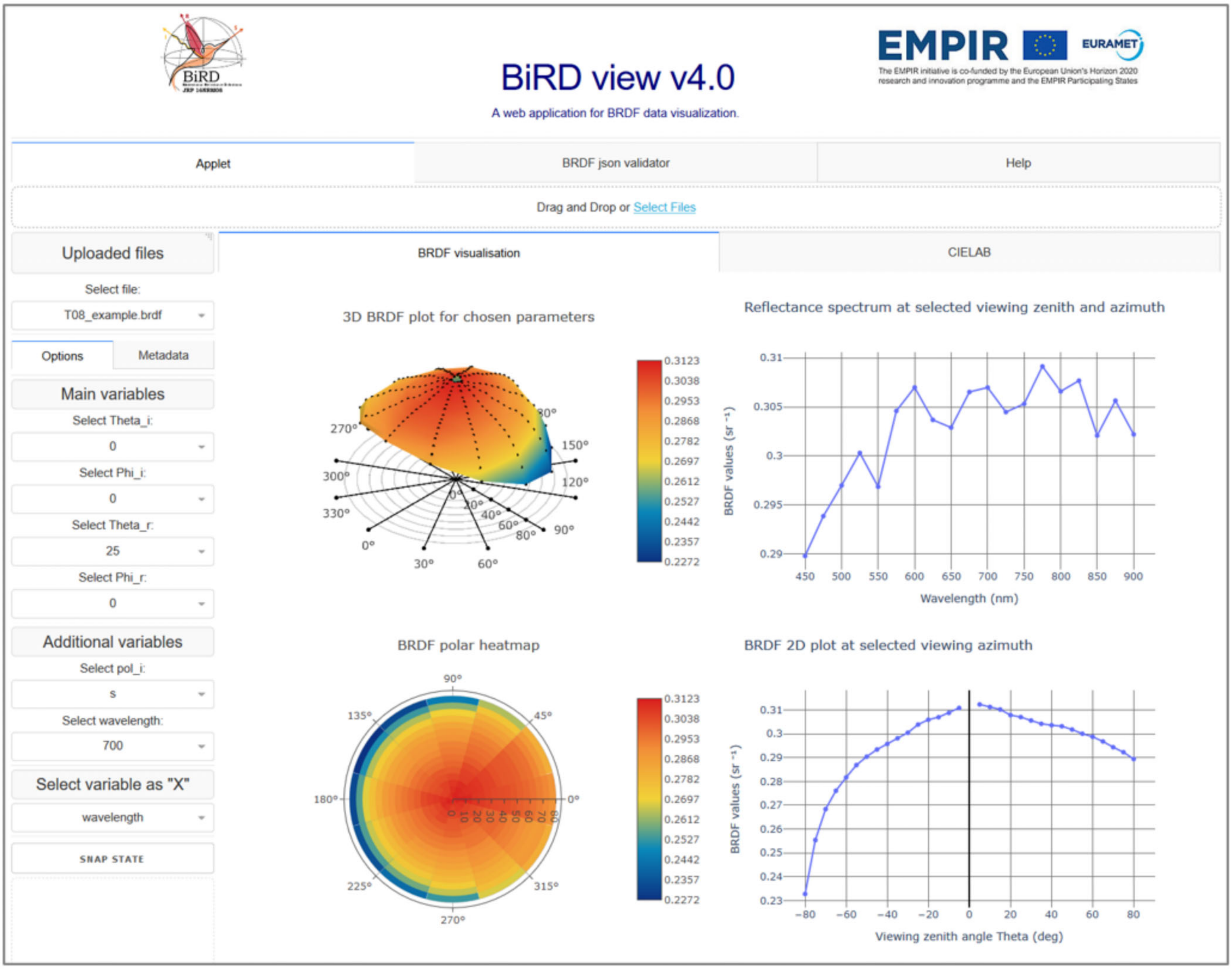

FIGURE 3 Visual interface of BiRDview. Example data is presented from BRDF measurements of an actual ceramic white tile sample. BRDF, bidirectional reflectance distribution function

dedicated to visualization of 3-dimensional $q(\theta_r, \varphi_r)$ slice on 3D and 2D plots while allowing other parameters to be selected from the menu. Both plots present $q(\theta_r, \varphi_r)$ in cylindrical coordinates (ρ, φ, z) where φ_r is the azimuthal angle, θ_r denotes the radii and BRDF values q signify the elevation along Z-axis. In 3D graph, the BRDF data is plotted with respect to a reference surface (going through 0 and normal to Z-axis) while in 2D heatmap plot q values are mapped to the colorscale. Plots in Plotly graphing libraries are highly interactive and permit users to zoom plotted data in and out, scale it properly and rotate to select the desired viewpoint. The 2D polar-plot has also a very convenient interaction option that allows the graph to be rotated around its origin to enable a very intuitive selection of φ_r to produce yet another BRDF data view at the $Z\theta_r$ plane (lower right graph in Figures 3 and 5).

The 2D plot in $Z\theta_r$ plane is dedicated to BRDF $q(\theta_r)$ data slices and its most important property is that it allows a reasonable side-by-side comparison of different data sets (Figure 5). It is practically impossible to plot multiple full BRDF data sets on a single 3D graph or heatmap without shifts in scales or other data manipulation. But it is more than sensible on 2D $Z\theta_r$ plot where multiple $q(\theta_r)$ lines can be present without affecting perception of each individual line. That is why the 2D graph in $Z\theta_r$ plane was included in the list of BRDF data views within BiRDview. Note that conventional viewing zenith angle θ_r is always positive (see Figure 1) while Figure 5 features slice zenith angle θ_{rs} which is defined as follows: $\theta_{rs} = \theta_r$ for $0^\circ \leq \varphi_r < 180^\circ$ and on the opposite side of the plane $\theta_{rs} = -\theta_r$ for $180^\circ \leq \varphi_r < 360^\circ$. This way it is possible to present in one graph all the BRDF data available for selected $Z\theta_r$ plane.

Finally, as was mentioned before, modern BRDF data accounts also for other variables like polarization, spectral (wavelength λ) variations, and so forth. Number of such variables within a single BRDF file is hard to predict

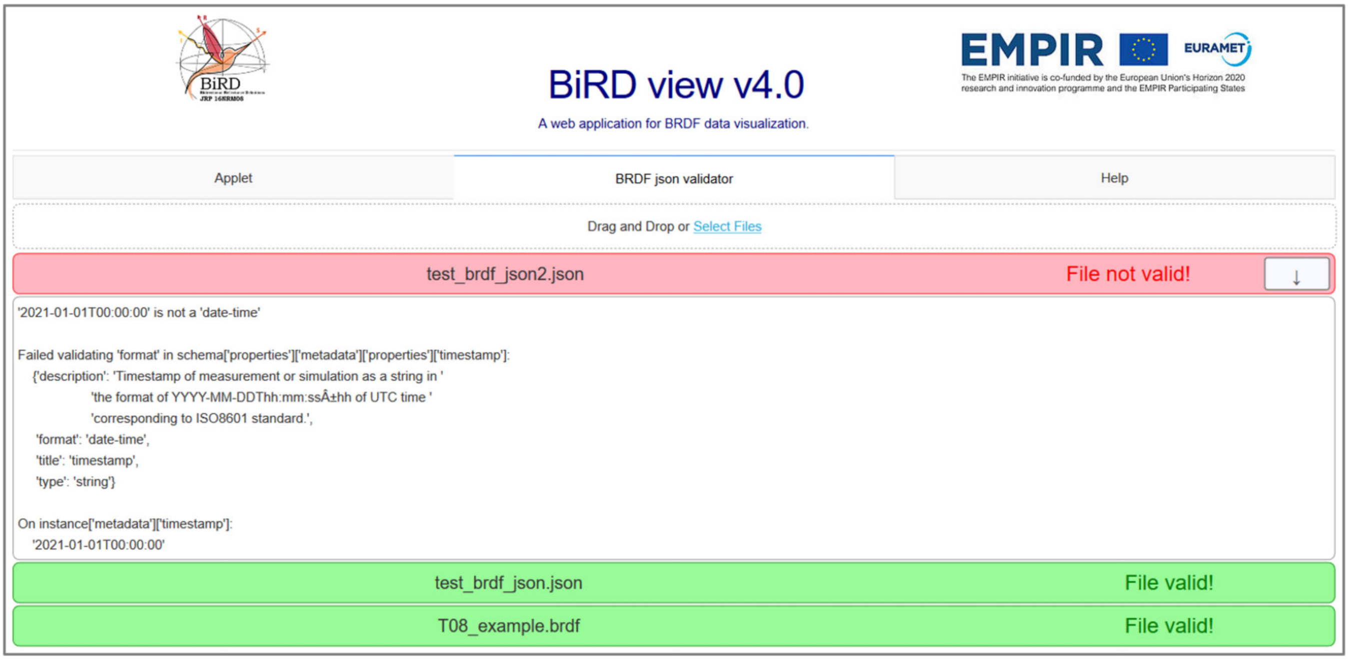

FIGURE 4 "BRDF json validator" tab with the example of an error message for an invalid file

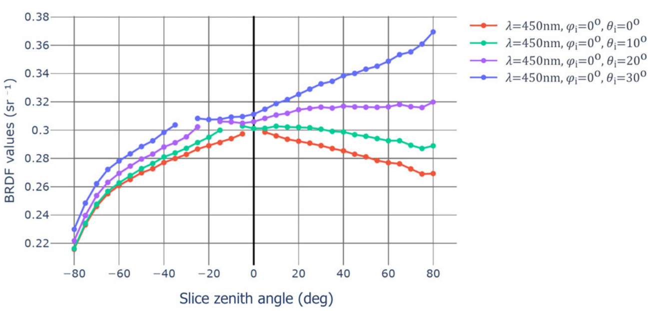

FIGURE 5 An example of BiRDview 2D graph of multiple BRDF $q(\theta_r)$ curves. The presented data is originating from a BRDF measurement of an actual ceramic white tile sample, where 450 nm incident light was s-polarized and the illumination angle was varied from 0° to 30° with the step of 10°. Angle φ_r is fixed to the plane of incidence for this graph. Orientation of the sample is 0° in respect to markings on the sample and position of the sample holder. BRDF, bidirectional reflectance distribution function

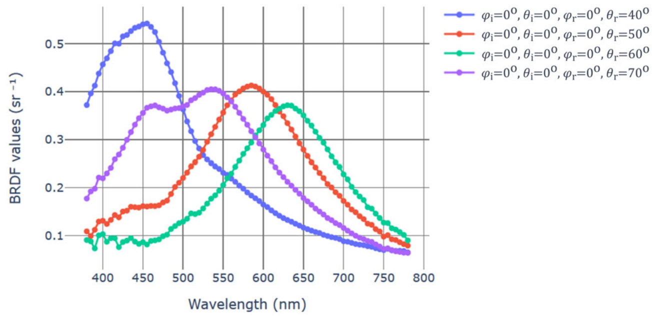

FIGURE 6 An example of BiRDview spectral graph with multiple spectral $q(\lambda)$ curves. The presented data was obtained by measuring spectral BRDF of a goniochromatic sample where the reflectance spectrum changed with viewing zenith angle θ_r. Illumination light was unpolarized. Orientation of the sample is 0° in respect to plane of incidence and marking on the sample. BRDF, bidirectional reflectance distribution function

with certainty. For this reason, for the 4th graph BiRDview allows to choose any desirable variable as x-axis while presenting recorded BRDF values on y-axis of the 2D plot at fixed θ_i, φ_i, θ_r, and φ_r angles and other variables that were not selected as x. This allows to plot and compare BRDF data originating from almost any measurement setup or simulation bringing out the full potential of universal BRDF data format. For example, if in addition to variation of illumination and collection angles, BRDF data was collected using monochromatic light at different wavelengths, user can select wavelength as the x-axis variable and obtain BRDF spectra at any set of θ_i, φ_i, θ_r, and φ_r. A close-up to this graph implemented in BiRDview can be seen in Figure 6.

4 | DISCUSSION AND FUTURE PLANS

The main purpose of BiRDview is to facilitate the uptake of universal BRDF file format by allowing validation of BRDF files and by providing basic capabilities to view and compare BRDF data. At present there is no integration of any BRDF models, and the functionality of other programs dedicated to work with BRDF like Disney BRDF explorer,[18] BRDFLab,[37] V-AMBRALS,[38] or RGL Tekari viewer[19] might seem to be more advanced. However, that might not be entirely the case. Except Tekari, the listed software is not actually dedicated for BRDF data visualization. Disney BRDF explorer is a tool to explore appearance of virtual objects when BRDF model or measured data is applied to them and has rather poor capabilities of BRDF data representation featuring mainly BRDF representation in spherical coordinates without showing BRDF values themselves. BRDFLab is dedicated more for designing BRDF rather than viewing the data describing it and similarly to Disney BRDF explorer features mainly 3D representation of BRDF in spherical coordinates. Both of the programs also allow a real-time rendering appearance of 3D objects, that is a great feature but does not allow to directly compare different BRDF datasets. V-AMBRALS is visual interface for AMBRALS—an algorithm to process the data from Moderate Resolution Imaging Spectroradiometer (MODIS) that is an instrument of two NASA satellites (Terra EOS AM-1 and Aqua EOS PM-1).[38] This is a very specific tool dedicated for viewing and processing data from a certain instrument and features mainly BRDF representation in cylindrical coordinates. Tekari was designed to view data from pgll—a goniophotometer used by RGL at EPFL. Tekari, however, has better BRDF data visualization capabilities than other software since it allows to show measured data points and spectra obtained at these points because pgll provides spectrally resolved BRDF. This is also the only visualizer that works also through the web browser. Other programs should be compiled and installed locally on user's device. BiRDview, on the other hand, is not tied to any specific instrument nor measurement method and features many different representations of BRDF data while adapting to the amount of variables in the uploaded data file.

From the feedback gathered from BiRD project members, BiRDview appeared to be a quite useful and ergonomic application with a potential to become an everyday tool for many researchers. One of its main benefits is that the software is available online without any installation. Only internet connection and browser are required to use the application and it can be run without problems on older and less powerful machines as well as on the newest ones. This became possible due to the decision to use a modern and powerful Plotly Dash framework that significantly reduces the effort required to deploy application online.

First of all, it transfers development from JavaScript that is the most popular web-development language to Python which is much more widely used in scientific community. Any researcher knowing Python can contribute to development of the scientific web-based application without the need to learn more complex and experience demanding programming language. Second, dash is very high-level framework that takes care of establishing server and communication with it by itself and saves huge amount of time for developers that only need to decide on appearance of application and write a back-end part for desired data processing. Finally, dash provides a connection to a powerful Plotly graphing library with many great built-in interaction capabilities that create a pleasant user experience without the need for significant efforts from developers.

This makes entry threshold for any possible new BiRDview developers quite low. It is important since BiRDview is an open-source software and it can have long live-time and continuous sustainable development only when there is sufficiently large and active supporting community. Present team is contributing to this by warmly welcoming new contributors, disseminating information about BiRDview and actively continuing its work on software improvements of the presented software within the BxDiff (JRP 18SIB03) project[39] that is successor to BiRD.

For example, there is a plan to add to BiRDview the capability to convert acquired spectral BRDF data to colors and express them in a standardized color space like CIELab.[40] This functionality will be introduced with addition of several graphs that would allow to evaluate color transitions with the change of illumination and viewing angles as well as to calculate color differences and compare colors of different samples. At the same time enhancing of data comparison capabilities is also ongoing. In addition to visual inspection of various BRDF graphs, calculation of the difference or the ratios between different datasets will be added. It will provide valuable quantitative information and allow data to be compared using 3D and heatmap BRDF plots as well.

Finally, when sufficient amount of data in universal BRDF format will be accumulated and concentrated in any existing or newly established FAIR scientific database, BiRDview will be connected to it so that researchers could work with the BRDF data without the need to possess it and upload from personal and/or institutional storages. This will largely contribute to the conformity with the philosophy behind the FAIR guiding principles and, perhaps, will lead to interesting human or machine-driven discoveries in the field of BRDF science.

5 | CONCLUSIONS

The community of the Joint Research Project "Bidirectional Reflectance Definitions" (JRP 16NRM08 BiRD) presented the solution to a steadily growing problem of non-conformity and non-FAIRness of BRDF data measured and processed by different instruments and software that hinders streamlined storing, exchange and comparison of this data. A universal FAIR BRDF data format was proposed, and its uptake was encouraged by introduction of BiRDview—a modern web-based open-source software for viewing and comparison of BRDF data. Main software features were introduced and data visualization methods were explained and analyzed.

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AUTHOR CONTRIBUTION

Dmitri Lanevski: Proposing universal BRDF file format concept, Working on JSON schemas and software, Preparation of supplementary materials, Writing-Original draft preparation, Reviewing and Editing. **Ferrero Alejandro:** Formulation of the problem, Writing-Reviewing and Editing. **Esther Perales:** Formulation of the problem, Writing-Reviewing and Editing. **Farshid Manoocheri:** Writing-Reviewing and Editing. **Erkki Ikonen:** Formulation of the problem, Writing-Reviewing and Editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in supporting materials referenced in 32 and 33 as well as in BiRDview application website at (https://birdview-app.herokuapp.com), reference number,[34] Github repository at (https://github.com/BiRD-project/BiRD_view), reference number[35] and documentation website at (https://bird-project.github.io/BRDF_JSON_schema_docs/).

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spectral BRDF at in- out-of-plane and retroreflection geometries. *Metrologia*. 2012;49:213-223.
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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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APPENDIX

An example of universal BRDF data file compatible with SEMI ME1392 standard


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            "values": [0, 0, 0, 0, 0, 0, 0, 0]
        },
        "theta_r": {
            "unit": "°",
            "values": [10, 10, 10, 10 ,10, 10 ,10, 10]
        },
        "phi_r": {
            "unit": "°",
            "values": [60, 60, 60, 60, 60, 60, 60, 60]
        },
        "BRDF" :{
            "unit": "sr^-1",
            "values": [0.254, 0.263, 0.267, 0.273, 0.281, 0.295, 0.296, 0.301]
        }
    }
}
```