Rendering of Translucent Objects, Verification and Validation of Algorithms

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ABSTRACT

An approach to verification and validation of algorithms that render transparent objects (media) is described. Rendering of transparent *optically isotropic* objects has been studied extensively. However, the papers devoted to optically anisotropic objects are few in number. The main goal of the present paper is to suggest a collaboration in creating and supporting an open database of tests. To prepare a real scene with a crystal specimen, to photograph it, and to describe the corresponding virtual scene is a complex problem. Obviously this is an almost impossible task for many devolopers of rendering algorithms. Well-known examples of translucent media are crystals. They are convenient for testing purposes as they have permanent solid shapes. Although the crystals are rendered by a recursive ray tracing algorithm, the tests considered in the paper can be applied to other algorithms.

Keywords

Anisotropic media, crystal, birefringence, pleochroism, optical dispersion, ray tracing, polarized light, rendering algorithm, test repository, verification, validation.

1. INTRODUCTION

The difference between isotropic and anisotropic media is explained in [Hay06]: "There are two types of optical crystals, isotropic and anisotropic crystal. The isotropic crystals have the same refractive index for all directions. The anisotropic crystal has a different refractive index in a different direction, and has two different values for the same direction. However, there are one or two particular directions where these two refractive indices have the same value. These particular directions are called optic axes and the crystal having one optic axis is called uniaxial or monoaxial crystal, while the one having two optic axes is called biaxial crystal. Since the anisotropic crystal has two refractive indices, there are two refracted rays in crystal for one incident ray and so-called double refraction or birefringence occurs".

In the literature on computer graphics there are not many papers on crystal rendering devoted to rendering by polarized light and the optical phenomena (the major properties are optical dispersion, birefringence, and pleochroism). A comprehensive review of early works can be found in [Guy04] and [Wei08]. The latter paper is devoted to rendering of uniaxial monocrystals. The paper [Deb12] describes an algorithm to render isotropic and uniaxial crystalline aggregates. The paper [Lat12] describes also computations of refracted rays in biaxial crystals.

The above papers provide with different 3D scenes. It would be useful to combine the test sets. This would allow third parties to provide improvements of the algorithms.

A good example is the site [Mat], which represent a repository of test data for use in comparative studies of the algorithms of numerical linear algebra. Any new numerical algorithm has an opportunity to be examined for accuracy and steadiness and compared with the other algorithms.

A similar role in global illumination is played by the Cornell Box [Cor]. The Cornell Box has become a de facto standard. It contains an exhaustive test scene definition. Later this test was extended to semitransparent surfaces; see [Far05]. In [Smi00] are proposed a number of tests devoted to global illumination algorithms which are available on the Internet. The description of the tests is a paper text. It would be more useful to separate the papers devoted to a description of simulation and those with test specifications.

In paper [Deb10] an approach is proposed to create a database for verification and validation of algorithms that render transparent optically anisotropic objects. As an appendix to the paper an Internet resource is made with exact specifications of test scenes' geometry and illumination. At the present time the resource is under reconstruction to adjust the ideas proposed in the above paper.

We recall that the purpose of the present paper is to create a common test database for the algorithms that render optically anisotropic translucent objects. No analysis and criticism of the algorithms are given. We describe our process of verification and validation in section 2. Section 3 is devoted to a survey of tests used by developers. Section 4 describes a real scene, techniques, and tricks used to recover the geometry and other parameters. A typical virtual scene is considered in Section 5. Section 6 describes some additional parameters of the rendering process to determine uniquely the calculated image. In section 7 additional useful tests are described. In section 8 conclusive remarks on our test repository are given.

2. PROCESS OF VALIDATION

After a local model of light interaction with transparent optically anisotropic crystalline media [Deb12] was developed we decided to create a rendering algorithm to verify and validate the model. Our algorithm is based on recursive ray tracing. One criterion of validation is to reach the maximal coincidence between a photograph of a real scene and a simulated image of a virtual scene similarly to an approach used in the Cornell Box project. In other words, the purpose is to compute a visually plausible image corresponding to a photograph of a real scene.

The algorithm is implemented in the following steps:

1. Selection of a test mineral specimen. It must be a transparent monocrystal with strong birefringence.
2. Cutting the specimen to obtain a simple geometric shape. In our case it is a hexahedron.
3. Recovery of the geometry.
4. Determination of scene illumination.
5. Creating a real test scene of crystal and light sources.
6. Selection of a photo camera.
7. Obtaining a photograph of the real scene.
8. Creating a virtual scene, i.e., a computer model of the test scene.
9. Selection of the computer model of the virtual camera. In our case it is a well-known pin-hole camera.
10. Single view calibration of the pin-hole camera from the photograph of the real scene.
11. Spectral Rendering. It is necessary to have the spectral characteristics of all objects of the real test scene or their approximate values. While rendering a spectral image representation is obtained. We call it a SRGB image.
12. Tone reproduction: transformation of the SRGB image to a RGB image.
13. Visual comparison of the photograph and the synthesized image.
14. Pixel by pixel comparison of the photograph and the synthesized image. The image resolution must be equal to the photograph resolution.

The purpose of this comparison is to test the assumptions and operation of the algorithm and determine the field of its application.

Below we will consider the steps in detail.

3. RELATED WORK

In [Guy04] several crystals are described without detailed specifications of the specimens geometry, camera, optical axis, etc. Although the authors claimed that models of standard gemstone cuts are readily available on the Internet they performed an additional investigation to justify geometry of an available specimen of tourmaline. Authors worked also on the acquisition of light illuminating their test scene. No data on the geometry obtained, virtual camera, and lighting (cube-map) are available in the paper.

Another paper [Wei08]: a calcite specimen was used for a real test scene. Again, the paper contains no detailed specifications of the specimen geometry, landscape grid pattern, virtual camera, optical axis, and illumination.

The paper [Lat12] describes algorithms based on a recursive numerical method in contrast to both papers mentioned above, which contain closed form formulas for exact calculations. Actually, this paper allows calculating the refracted rays for a ray incident onto a boundary of a crystal of different types: isotropic, uniaxial, and biaxial. The authors produce test images using a convex calcite plate in a virtual scene. The paper includes computed images that illustrate birefringence. Note, that exact geometry of virtual scenes and camera parameters, illumination, and image resolution are not specified in the text. Although the algorithms [Lat12] do not compute the correct colors of the resulting images, those images allow comparing with images obtained

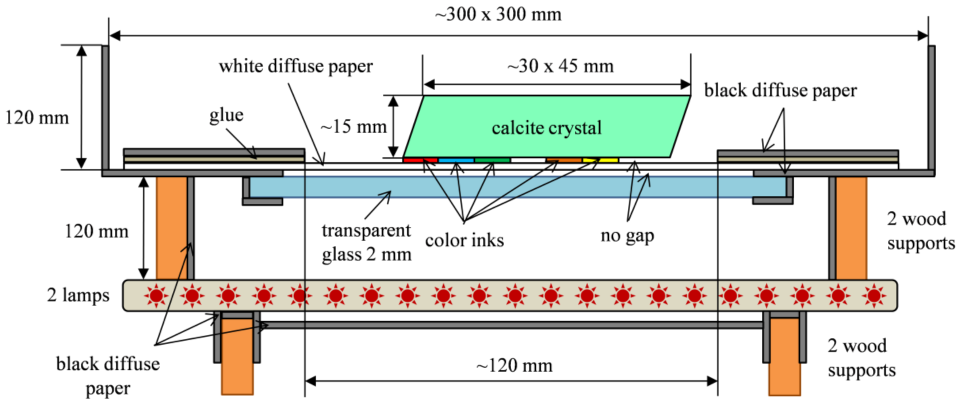

Figure 1. Scheme of a real scene.

by other algorithms in order to examine the correctness of birefringence.

The paper [Deb12] is devoted to derivation of closed form formulas to calculate a local illumination model for interaction of a light ray with the boundary of two transparent media of isotropic and uniaxial optical types. It includes also: a photograph of a calcite uniaxial crystal over a color checkered pattern, a corresponding virtual scene with the recovered geometry of the specimen, a synthesized image, and several virtual test scenes with corresponding rendered images. In spite of the fact that the paper contains detailed description of validation experiments, nevertheless, the data presented are insufficient to reproduce them thoroughly.

The paper [Deb10] has a similar purpose to create a testbed for algorithms rendering transparent isotropic and anisotropic media with polarized light. There the following groups of tests are suggested in the paper:

- Low level test based on some clearly formulated physical laws like Snell's law, Brewster's angle, etc. These tests allow us to assess, e.g., the accuracy of algorithms.
- Special virtual scenes demonstrating the physical phenomena: ortoscopic and conoscopic images, internal conical refraction, etc. [Bor80]. The authors thoroughly describe a 3D scene to render the effect of internal conical refraction. Instead of giving the exact scene specifications they describe some guidelines how to construct such scenes. Since the camera parameters and computed image are not described, it is difficult to compare the algorithms.
- Comparison of a real scene photograph with a computed image of the corresponding virtual scene. Note that the photograph of a real scene in the paper is much different from the image of the virtual one. Moreover, the real calcite specimen used is not a monocrystal but a crystalline aggregate. Besides, the camera parameters are not known.

No detailed specifications of the virtual test scenes to be rendered are available also in the papers mentioned above.

We suggest a different approach: to create a special appendix that stores exact specifications of the virtual test scenes described in a paper. It may be a personal Internet site. Note that the data presented at the site recommended in our paper [Deb10] are also incomplete and poorly documented. At the present time this site is being reconstructed.

Our main objections concern fact that the information on test scenes is often incomplete and does not allow one to reproduce the rendering of scenes and comparing of the images obtained. However, all the above-mentioned papers present numerous pictures that illustrate the approaches and/or algorithms being described. Also a limited length of papers does not allow authors to present all details which could overload a text. We expand an idea proposed in [Deb10] and suggest creating a testbed as a common Internet resource devoted to detailed information on the test data. We expect that new efficient algorithms to render anisotropic crystals will appear in the near future. This test repository, being an expandable database, can be helpful in debugging them.

4. REAL SCENE

A real scene is selected in steps 1–7 mentioned in section 2. We spent more than a year to find a crystal, cut it, take a photograph, and calibrate the virtual camera. The above repository can be helpful to save time and efforts of the developers of renderers. Otherwise the community will be limited to those who have stones, able to cut a specimen and calibrate the virtual camera, etc. The majority of researchers are programmers rather than geologists or jewelers. Therefore all photographs of proper specimens or gemstones are important. First we consider specimens that have simple geometric shapes: cube, sphere, or convex polyhedron. Jewelry shapes are more complex and require additional efforts to recover the exact geometry, see [Guy04].

It seems that recovering the geometry of transparent crystals is a difficult task. For example, calcite is too fragile, so the faceted shape of a specimen may get chipped and peeling. The KDP (a Potassium Dihydrogen Phosphate) crystals are not waterproof (expired air also), and require additional care, e.g., mask, gloves, etc. The crystals are not expensive, and have visible strong birefringence. Measuring the linear sizes of edges by standard tools may produce errors due to the possible chipped vertices of the specimen.

Often knowledge of the construction of a real scene may be useful. A scheme of a real scene and its approximate sizes are shown in Fig. 1. A specimen lies on a sheet of white paper with a printed color texture. The sheet is put on a transparent glass plate and covered by a sheet of black paper with a rectangular window. Two cylindrical luminescent lamps are placed under the plate in such a way as to provide an approximately uniform illumination of the sheet. Other light sources are absent. Specifically, a window with the printed texture and lamps determine the geometrical shape and spectrum of the light source.

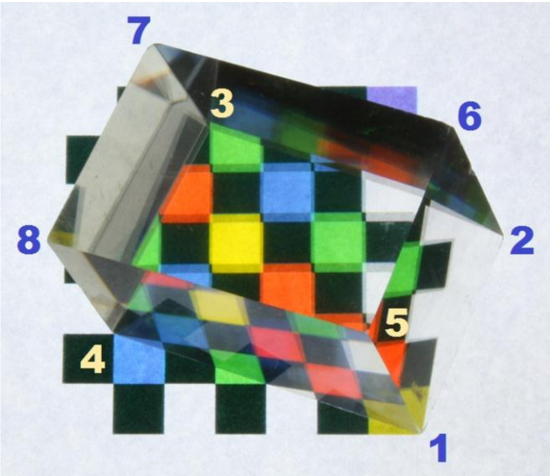

Figure 2. Photograph of a calcite specimen.

Consider a photo with enumerated vertices (Fig.2). In our experiment we took a calcite specimen (hexahedron). Using a scanner we obtained some images of the faces (like one in Fig.3) and determined the lengths of edges of all faces, see Fig.4.

A source of illumination in the scene is a rectangle with a color texture, Fig.2. There were problems of coincidence of the spectra of real and virtual textures: a) the spectra of the lamps being used are usually unknown; b) the spectra of transmittance of the paper and inks are unknown; c) the lens adds some unknown distortions to the spectrum of transmitted light; d) the sensitivity of the camera matrix to various parts of the spectrum is unknown too, etc. In our calculations we used a light source as shown in

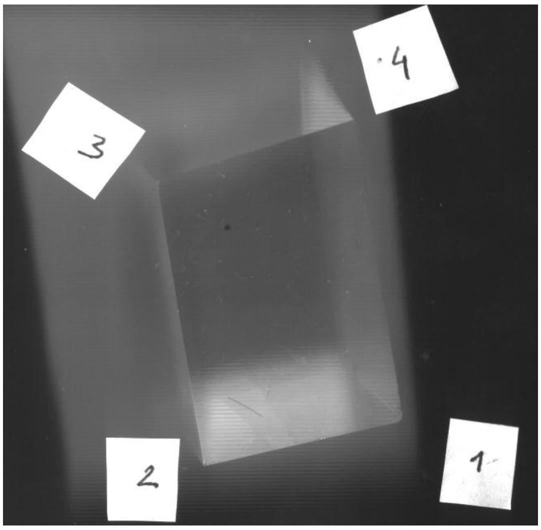

Figure 3. Scan of the face with vertices 1234. The fat black dot is the exit of the optical axis.

Fig.5. In order to decrease the difference between the textures colors in the photo and the calculated image ones, the colors of the virtual texture can be taken from a blurred (unfocused) photograph of the real texture made with the same camera parameters and exposition.

The only optical axis was determined from scans of two opposite faces, 1234 and 5678, a look through which results in the absence of doubling of the texture. On each face we selected a dot that belonged to the axis. An important point: the dots were selected manually, which can lead to small errors in the direction of the axis.

Some specifications of the photo camera being used may be useful too, for example, a camera Canon 450D with a lens EFS18-55 mm F:3.5-5.6 IS. A minimal matrix sensitivity of ISO100 was selected to decrease noise. To minimize the lens's aperture, the

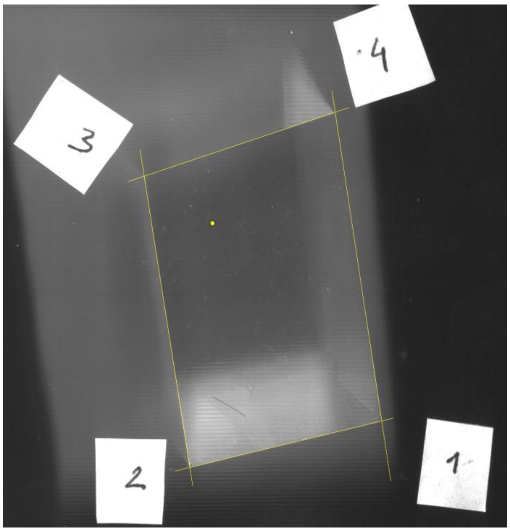

Figure 4. Scan of the face with vertices 1234. Lines approximating edges are shown.

Figure 5. The texture used as a light source in the virtual scene.

diaphragm was set to a maximal value of F:36. In this case diffraction does not affect significantly the image. The exposition must be taken considerably longer than the blinking lamp period (if luminous lamps are used).

The vertices of the hexahedron are obtained as the intersection points of lines approximating the edges (Fig.6), e.g., vertex 7 in Fig.2.

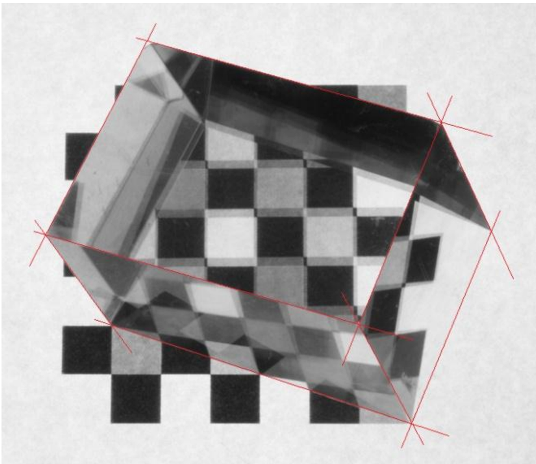

Figure 6. Gray scan of the photograph with lines approximating edges.

Thus, we have obtained some specifications of the geometry and illumination of the virtual scene with some errors at each step.

Finally, the camera parameters (camera calibration) were determined manually with the help of an interactive application. A photograph (Fig.2) and a gray scan (Fig.6) were used for calibration.

5. VIRTUAL SCENE

Our test environment is quite similar to that used in [Guy04], [Wei08], [Deb10], [Deb12]. It is not clear what illumination was used in [Lat12] as according to [Lat12, Fig.13] the test scene was illuminated by a point light source at the camera tip.

A typical virtual scene is shown in Fig.7: a specimen, a camera, and an axis aligned box around the specimen. The latter can be positioned and resized by the user. It plays the role of a cube-map which determines illumination. Arranging the box the user can put one of specimen's faces just onto the box's face. In such a way virtual scenes similar to those used in [Wei08] and [Deb12] were constructed. The six textures used allow one flexibility with assigning of illumination of the scene.

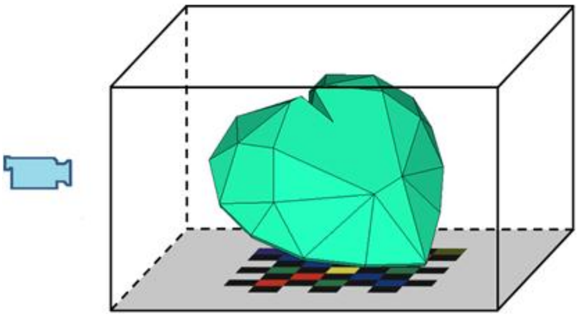

Figure 7. Virtual scene environment.

Note that all the textures are one-sided, and are invisible from outside. They illuminate unpolarized light inside the box. It is best to use a spectral representation but, in practice, only a RGB representation is available. Other *explicitly defined formats* can be applied, e.g., those in [Guy04]. Various formats can be considered as additional information, and a source of data. We believe that the spectra being used must always be provided.

Generally, the scene is filled with air or vacuum, sometimes, it may be any of transparent media: isotropic, uniaxial, and biaxial. The substance is called filler.

The following optical characteristics are specified for the scene filler and the specimen:

1) Axes. The only optical axis $\mathbf{c}$ is specified for a uniaxial medium and two axes $\mathbf{c}_1$ and $\mathbf{c}_2$ for a biaxial one. For biaxial media the directions of optical axes depend on the wavelength therefore they must be specified for each wavelength used in the image calculation, even if the directions are calculated. Obviously, isotropic media require no axis specification.

2) Main indices of refraction: one for an isotropic medium n_i, two for a uniaxial (n_o, n_e), and three for a biaxial one (n_1, n_2, n_3). The corresponding values are specified for each wavelength used in the image calculation, even if the calculation of samples is done with the Sellmeier's equation, Laurent's equation [Bor80], or in another way.

3) Absorption. In the case of a transparent colorless medium no absorption data are required. In the general case the modeling of absorption is challenging problem because of the following two facts. First, the refraction and absorption properties are not independent [Bor80]. Second, the rays propagating in absorbing anisotropic media are elliptically polarized but in transparent anisotropic media they are linearly polarized [Bor80]. These facts are usually ignored, see e.g. [Guy04]. Therefore majority of crystalline media require the determination of one, two, or three attenuation spectra. Apparently, this format satisfies the absorption data from [Guy04].

Similarly to the above remark about the format of illumination data, we believe that some parameters of a virtual scene as the spectra must be determined.

Note that a source of possible errors in the final per pixel comparison of a photo and a calculated image are the unknown physical conditions of the specimen, namely, the temperature, external forces and fields, etc. These parameters are usually taken from references where they are evaluated accordingly to certain conditions.

All the virtual scenes must be placed in the repository, even if there are no corresponding photographs of the real scenes. This may help in comparing the algorithms being used.

6. VIRTUAL TEST SCENES

A most important group consists of tests of comparison of the photograph with the computed image is as considered above.

A second group of tests consists of virtual scenes that do not require the existence of the corresponding real scenes.

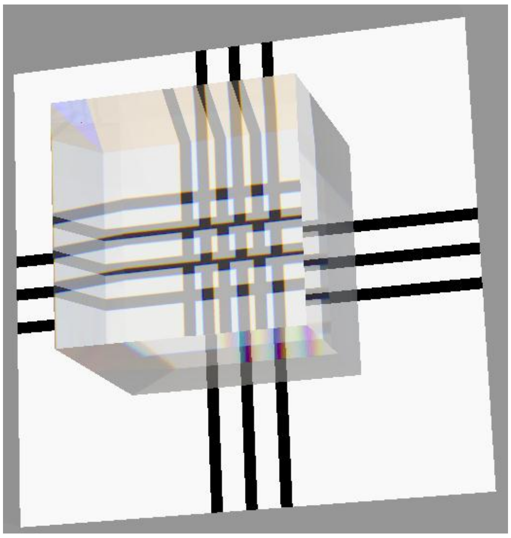

Figure 8. Computed image of a biaxial cube.

Various virtual scenes are created during the debugging process. In Fig.8, Fig.9, and Fig.10 three typical examples are shown. For the tests the repository includes:

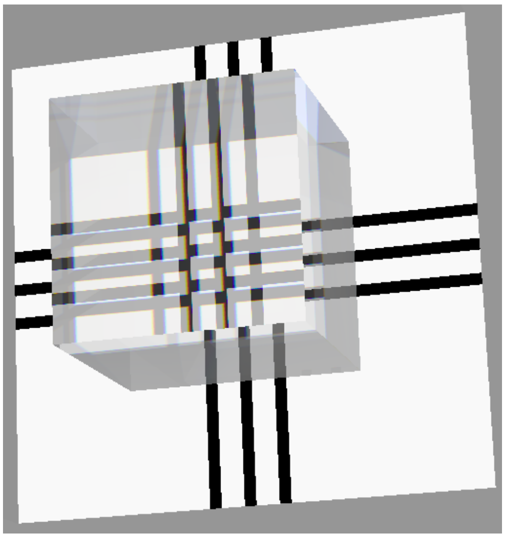

Figure 9. Computed image of a uniaxial cube.

- An image of a test scene rendered with OpenGL. It is used to comment the scene geometry and simplify the understanding.
- Coordinates of cube vertices.
- Coordinates of a square axes-aligned textured plate.
- Texture image.
- Light environment.
- Ray tracing depth in bounces.
- Pin-hole camera parameters: focus length, aperture point, view direction.
- Image plane sizes.
- Image resolution.

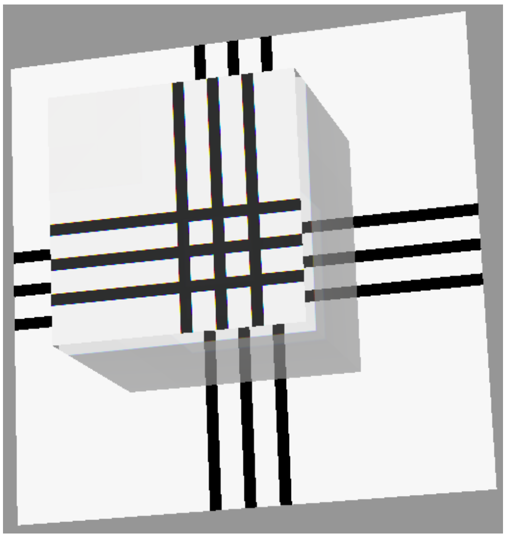

Figure 10. Computed image of an isotropic cube.

- Optical type of the scene filler: isotropic, uniaxial, biaxial. In our case it is isotropic.
- Refractive index of the filler.
- Optical type of the specimen: biaxial (Fig.8), uniaxial (Fig.9), or isotropic (Fig.10).
- Representation of the spectra: number of samples from 380nm to 780nm.
- Main refractive indices for each sample.
- Calculated image.
- Several copies of the calculated image with appropriate comments (optional).

It is now possible to calculate the image of the specified scene and provide its per pixel comparison with the image from the repository.

7. RENDERING

The repository may include several calculated images for a single virtual scene. They can be different because of the following rendering parameters:

- Image resolution.
- Number of wavelengths used (e.g., one for monochromatic light). All the optical parameters (see previous section) should be represented by spectra of equal length to represent the smooth part of the spectrum and the set of separate peaks to represent the another part.
- Depth of ray tracing. A recursive ray tracing is very time consuming, since at each bounce the ray is split into up to four generated rays. For example, if the data are: depth=20, spectra of 21 samples the rendering took several hours of calculation on a 8-processor cluster.

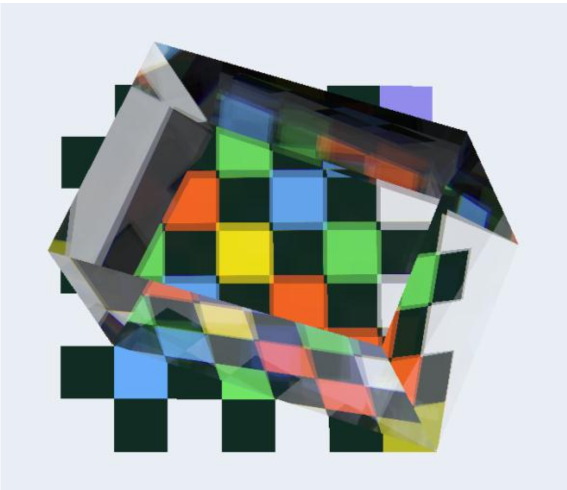

Figure 11. Calculated image corresponding to the photograph in Fig.2.

- Camera parameters given in the scene coordinate system. For example, we used pin-hole camera in the algorithm.

Each image is specified by its computer platform and the computational time. This will facilitate in comparing the performance of the algorithms.

A result of rendering our virtual scene is shown in Fig.11.

8. OTHER TESTS

Virtual Scenes Illustrating Some Well-Known Facts From Optics

Internal conical refraction is a phenomenon observed in biaxial crystals. The conoscopic images of anisotropic crystals are a practical means in petrography; see [Bor80] for a theoretical foundation. In [Deb10] corresponding virtual scenes are described. These tests can help in debugging and comparing the rendering algorithms.

Additional Tests

This group of tests is targeted to help in the debugging of separate program blocks. The description may be reduced to a minimum. We suggest that the authors contributing to the repository may only name a fact and refer to a proper source from the well known literature. For example, "Brewster Angle Test", see [xx, page yyy]. A better way is a detailed description of a test including the specifications of: a) the optical characteristics of two media; b) the ray incident onto the boundary between the media; c) polarization of the ray; d) the resulting rays (reflected and refracted) with their polarization states.

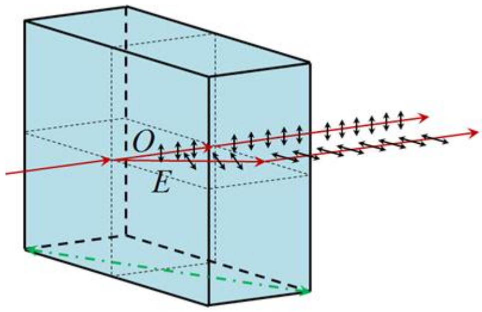

Figure 12. Birefringence test, arrows show polarization state.

In [Deb10] several examples are given: Snell's law, Brewster's angle, and a birefringence test. Consider the last one. In Fig.12 a typical scene is presented. Not only the ray directions be verified, but the polarization state of the generated rays as well. This can be useful if the repository includes several examples of optical media with incident rays and derived rays of different polarization states and intensities.

The problem of numerical stability may arise in debugging, e.g., when the directions of the ray, the optical axis, and the normal are almost the same. We believe that such situations must be put into the repository too, especially, the problem has been solved.

9. CONCLUSIONS

We did not intend to cover every possible situation in the rendering of crystals. In this paper we have presented our approach. The repository must not have a certain predefined format. Tests of any complexity delivered by any developers are welcome. The contributing developer may deliver his/her information in any convenient format. Nevertheless, we have remarks: a) lossless image formats like BMP, PNG should be used; b) the spectra should be used wherever it is possible. In case other formats are used they should be transformed to the BMP or spectra formats explicitly. This will help in avoiding possible uncertainties.

Additional information of any kind will be very useful, for example: an OpenGL image of the recovered geometry (see Fig.7), references to the relevant papers and reports, images with comments, a photograph or a scheme of a real scene (Fig.1), and appropriate unpublished comments.

We suggest separating all tests in the repository into the following groups:

- A photograph of a real scene,
- Virtual scenes,
- Virtual scenes of optic phenomena,
- Tests of particular features,
- Other tests.

Additionally, a set of keywords should be supported; each keyword refers to the relevant tests. The set of keywords contains: real scene photographs; recovery of specimen's geometries; definitions of illumination, transparent media, absorbing media, isotropic media, uniaxial media, biaxial media, camera calibration, etc.

We do not believe that we have found a complete solution. This paper was caused by the present time situation with accessible tests.

An Internet site, [Crt], was developed initially as a support for the paper [Deb10]. At the present time it is under reconstruction. Nevertheless, the reader can find a detailed description of the tests corresponding to Fig.8-11.

The problem of creating test scenes based on real scene photographs is not an easy task. Experts on a wide variety of research have to be involved: crystallographers, specimen cutters, etc. Also a wide range of specific devices have to be used: spectrometers, etc.

We hope that this paper will help in creating a repository with the specifications described above. The inclusion of any test into our website is welcome.

10. ACKNOWLEDGMENTS

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