REPRODUCIBLE REPRODUCTIONS

Color, light, and digital images

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1 Introduction

We believe that our perception of an object reveals its true nature. However, the image is the result of particular lighting conditions, and the physiology of the eye. In this paper we investigate how to characterize an object independent of its environment. Such that two independent measurements yield the same answer, independent of the lighting and the camera.

At the most basic level this problem deals with the scattering of light. Light with a particular wavelength and polarization hits and object at a particular point under a given angle. Part of the light is absorbed, part is scattered over a wide range of scattering angles. The smallest unit in which this problem can be decomposed is the chance of scattered light at a certain angle and polarization, given the incident light at a certain angle and polarization. The wavelength of the scattered light can be different from the wavelength of the incident light, however, for all practical purposes we can assume that both are the same.

Once these core features are known, we can reconstruct the appearance of an object under all lighting conditions, for different observers. This requires us to move away from the human as the ultimate gauge, as the humans are unable to distinguish separate wavelengths, except in the crudest manner of red, green, and blue averaged color luminances. Much of color theory is devoted to this particular, more or less physiological aspect, of image reproduction.

Gloss and structure are usually considered unwanted features in image reproduction, however, they are as much features of an object as the color that remains when the lighting conditions are optimized in the sense that the apparent gloss and structure is minimized. Rather than seeking the lighting conditions that minimize the surface effects, we seek to characterize the scattering, such that the analysis of the image can extend beyond the color features of the original, and problems of surface structure and gloss are documented for future study.

We already mentioned the degrees of freedom which characterize the scattering process from which the more complex situations of lighting and imaging can be reconstructed. Note that these do not depend on any model for the lighting, the object, or the camera or observer. These are basic physical and reproducible processes. They involve the wavelength, polarization, and the angle of both the incident light and the reflected light. Gloss, and specular reflections, are usually associated incident and reflective angles which are close together, and a small wavelength dependence such that the color associated with gloss is the color of the lighting.

The core measurement would involve hitting the object with monochromatic light from a given angle and measuring the reflected light at another angle. The measured light, given the amount of incident light would be an invariant and reproducible observation. However, generally, in different experiments different angles, and different wavelengths might be used, which makes a direct, one-to-one comparison impossible. Therefore it is a common procedure to use the scattering data to generate smooth functions for all angles and wavelengths, such that different experiments yield the same basic quantities. These are often referred to as multipole expansions. Another feature of making this fitting part of the experimental analysis is that integrated quantities, such as our physiological eye characteristics are easily determined.

For a given class of objects, such as paintings, the first task is to find out how many, and which independent measurements are required to characterize the object sufficiently. It might well be that a substantial number of measurements are required under small angles to characterize the detailed structure of gloss. It might also be that a precise angular-spatial correlation is necessary to disentangle all the features that resulted from the structure of the surface. A priori, there is little else than preliminary measurements that can tell us how detailed the actual measurements should be.

2 Digital formats

Single device digital camera's for color images usually have a pattern of color filters (like green-red-green-blue) painted on the photo-sensitive cells. Therefore the digital color image is reconstructed in two ways: using (large-scale) spatial information to recover, for example, the green pixel value on a cell that received only the red-filtered light. Second, correcting for the deficiencies of both the filter and the semi-conductor characteristics. Last year a new technique emerged that sidestepped the color filter method, using the penetration depth of different colors light to recover the color information in a single cell using multiple read-outs. However, still, one should be aware that digital camera's do not record objective images, but depend largely on the manufacturer's choices of reconstructing digital information from the electronic signals.

Eventually, color charts photographed together with the object should set the standard. Using these charts should allow one to make transformation in color space to the agreed standard color representation. However, as color space is three dimensional, and, as it appears, the distortions are highly nonlinear, determining the proper transformations might be a complex task, which should be automated.

Once this digital image exists it can be stored in many different ways, often using compression methods because the raw data is large. This compression can be loss-less or lossy. The most famous loss-less data format is GIF, which is based on the patented LZW compression algorithm. However, often the number of colors of an object exceeds the capabilities of the GIF algorithm, leading to a breakdown, or a poorly compressed image. On the other hand the most common lossy compression JPEG does not infringe any patents. The JPEG group wants to cover also the loss-less and more elaborate digital information formats, and came up with a new standard, which is called JPEG2000, or JP2. Whether this will be the new standard remains to be seen. But it certainly has the versatility and the potential.

For actual computation, conversion, and comparison PPM is the internal standard. Most shareware programs, such as in the GNU project, convert internally to PPM format, since each pixel can be handled separately, with minimal references to certain settings, such as color resolution and image size.

3 Positioning

Central to comparison of two images is the ability of overlay them properly, which might be harder than one expect. First, the images have to be scaled to the same size. Second, the central axis might be different, so one image might appear skewed or tilted with respect to the other. Third, spherical aberrations might occur that lead to distortions in which the sides of a square can appear curved, inward or outward.

Altogether, there are five or six parameters that determine the geometrical transformation which allow one to overlay two images. In order to determine the values of these parameters accurately, one best resort to a numerical routine that maximizes the correlations between the two images.

4 Global structure and small angles

If the light hits the object under small or shearing angles, small deviations in these angles might generate large differences. It is possible that some differences remain unresolved. For example, the canvas will position itself differently if it is lying flat or hanging vertically. The tension in the canvas and the global curvatures might even depend temperature and humidity.

Eventually, it might turn out that small angle lighting yield a non-reproducible image. The practice should determine the smallest angles, and possibly the combination of angles that is invariant under different mechanical and physical conditions. One can for example imagine that combinations of the difference and sum between left and right shearing lighting depend much less on the state of the canvas, that each separately.

5 Observer angles

The most complete information of an object is obtained if the observer, or the camera, is positioned at a number of angles. However, this is not very practical since images from different angles are hard to compare, or even combine. Therefore a single setting perpendicular to the object, on the central axis, at a reasonable distance might be appropriate. In this way we do lose some information of structure and polarization.

The distance of the camera and the lighting from the object is important. If either of them is too close, a substantial angular variation of the incident and reflected light will occur across the object. Better still, the record of each image should contain this information, or it should be possible to recover this information from standard cones or sticks parallel to the lens axis in the far corners photographed together with the object.

6 Specular angles

Gloss and glare occurs at angles close to the angles of specular reflection. It can be seen as a surface effect, which depends solely on the geometry and properties of the surface layer. One common model to describe such phenomena consists of an ensemble of small flat mirrors with a distribution in orientation and reflectivity. However, that ignores the fact that the surface structure might be at the size of the wavelength and essential interference might occur. Even though the wavelength dependence of specular effects might be small; say a factor of two over the visible range, it is important to obtain this information as it gives crucial insight in the microscopic structure of the surface.

As the wavelength dependence reveals the microscopic information, the angular dependence reveals the macroscopic information; the roughness and the deformation which is associated, for example, with surface cracks. In order to proper characterize these angular dependencies, many close spaced measurements might be required.

7 Lighting, color and intensity

Lighting is the key to creating a reproducible image. If there is not enough light, or only a particular color, or a restricted angle, it is impossible the reconstruct the true object information from the images under the restricted set of lighting conditions. Apart from the quality of the light source and its position and, possibly, its polarization, it is also important to know the intensity. The effect on the object will be minimal, if the duration is restricted, but both film cameras and digital cameras have a complex response depending on the amount of light reaching the light sensitive element. It affects both the registration of color and contrast. Furthermore, not all lamps have a constant light color through its life time.

Ideally, one would hope that standard color and gray scale charts would allow one to reconstruct the nature of the light source. However, it requires a detailed investigation to ensure all the color and contrast information of an object is present in a particular lighting-camera setup.

Eventually not many of the state-of-the-art setups will be available. Therefore, it is also important to invest into a generalized chart, with color and angular information, that gives us full access to the particulars of the lighting-camera responses, such that at least the information and lack of information for full reproducibility can be quantified. An automatic chart information interpreter would be important in this line of pursuit.

Although, a full chromatic resolution of the image, say in 10 or 20 nanometer steps might be complicated to achieve. On the other hand, that might be the standard that is actually worth having. This requires most likely a complex lighting scheme as well as a more complicated camera setup. Furthermore with the present CCD standard, a single object would require a few Gb storage capabilities, with the current CD-RW prices is not a problem, however, accessing and combining such among of data will require specialized software and hardware.

8 Polarization

Since the human eye cannot perceive polarization, there is the common misconception that polarization does not tell us much. Except for the Polaroid company which advertises with polarization filter sunglasses to reduce glare. Indeed for glare and gloss, polarization is an important aspect. For example, the Brewster angle, is the angle of the reflected light which is fully polarized, which is again related to the refractive index, an important characteristic of the surface.

For the study of paintings this seems to be a more or less unscathed field of research, which might give us important clues about varnish and other surface treatments. Furthermore, the surface structure might be much more apparent under polarized light and with a polarization filter before the camera lens.