An Image Forensic Technique Based on 2D Lighting Estimation Using Spherical Harmonic Frames

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Abstract. In this paper, a novel approach for exposing digital image tampering based on the theory of spherical harmonic frames is presented. We describe a robust technique for exposing digital forgeries that we utilize the information along a 2D occluding contour and estimate the lighting feature using spherical harmonic frames. Spherical harmonic frames are generated by the rotation along the symmetry axes of a symmetry group. The lighting-based digital forensic technique using spherical harmonic frames inherits the robust property of frames and improve the statistical results compared with spherical harmonic bases. Experimental results performed using spherical harmonic frames prove the robust measurements and discriminability of the complex lighting environments from synthetic data and real data. The application of identifying the tampered images reveals the improvement of our method.

Keywords: Spherical harmonic frames · Digital forensic technique · Lighting

1 Introduction

A major effort of the research community has been devoted to the digital forensic technique of exposing image tampering[1–5]. As the recent advances in computational photography, computer vision, and computer graphic, the development of friendly and easy-to-use manipulation tools has made the community into a crisis of confidence, which is caused by pervasive use of digital fakes in legal certification, the media, advertising, entertainment industry, national security, and more. In this new environment, the demand for efficient forensic tools that can accurately and trustfully expose the digital fakes is emerging.

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In the area of image forensic, researchers have successfully developed a variety of image authentication tools according to different situations. When utilizing multiple images to generate a tampered image, since the image targets are captured under different lighting conditions, it is difficult to keep lighting consistency between different targets. Using lighting inconsistency between the different targets of one image to identify image authenticity is one technology of image forensics. In previous work, Johnson and Farid [6] use lighting information extracted from 2D occluding contour to identify the authenticity of the image. In order to extract 3D lighting information in a single image, and they take advantage of the spot position of the human eye to estimate the direction of light [7]. Johnson, Farid [8], Stork [9] and Kee [10], utilize spherical harmonic lighting model to estimate complex lighting environment. However, due to the degradation effects of noise contamination and data incompletion on obtained 2D information, the lighting-based forensic tool using spherical harmonics model can not distinguish illumination characteristics robustly.

Actually, the lighting-based forensic tool using spherical harmonic basis to identify tampered images will be trapped in the imprecise 2D-information extraction from a single image. Lighting measurements and discrimination using basis functions may be affected by many factors in real scenes, such as the difference of tested objects, the limitation of the available data and the error of recovered 2D information. In this paper, to conquer these noise contamination and data incompletion of 2D information, we present a robust diffuse lighting model using spherical harmonic frames in 2D space. In the novel 2D lighting model, we improve the detective ability of the lighting-based forensic tool compared with spherical harmonic basis. To the best of our knowledge, our method is the first that proposes a diffuse lighting model using spherical harmonic frames to be applied in 2D space and presents a robust forensic tool which can resist the noise contamination and data incompletion caused by the capture of 2D information.

The rest of this paper is organized as follows. We briefly introduce related works on the irradiance expressions for a convex Lambertian object in real 3D complex lighting environments in Sect.2. In Sect.3, we analyze lighting estimation using the 2D achievable data. In Sect.4, experiments which are performed using synthetic and real data reveal the comparisons between bases and frames lighting models. The forensic applications are also presented using different lighting models. In the end, the conclusion is given.

2 Lighting Model Using Bases and Frames

The irradiance for a convex Lambertian object can be expressed in terms of spherical harmonic bases and spherical harmonic frames. Next, we will describe the lighting model in terms of these two expansions.

In terms of spherical harmonic bases $Y_{l,k}$ with order l and degree k, the irradiance of a convex diffuse object can be described as

$$E(\boldsymbol{n}) = \sum_{l=0}^{2} \sum_{-l \le k \le l} \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,k} Y_{l,k} \tag{1}$$

The corresponding image intensity is

$$I(\boldsymbol{n}) = \sum_{l=0}^{2} \sum_{-l \leq k \leq l} \rho \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,k} Y_{l,k} \tag{2}$$

where $\boldsymbol{n}$ is the normal vector of 3D object, ρ is the surface albedo, A_l is the coefficient of transfer function in order l, the product $\rho\left(\frac{4\pi}{2l+1}\right)^{1/2} A_l$ is always treated as a constant to compute the nine lighting coefficients $L_{l,k}$ in the least square method.

In the work [11], the authors derive a similar formation of lighting model in terms of spherical harmonic frames. The irradiance in terms of spherical harmonic frames is expressed as

$$E(\boldsymbol{n}) = \sum_{l=0}^{2} \sum_{t=0}^{n(l)-1} \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,t} Y_{l,t}^{d} \tag{3}$$

The corresponding image intensity is

$$I(\boldsymbol{n}) = \sum_{l=0}^{2} \sum_{t=0}^{n(l)-1} \rho \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,t} Y_{l,t}^{d} \tag{4}$$

where $n(l)$ is the number of frame elements in subspace H_l. The number of elements of frames is determined by the redundancy of frames which is integer n multiples of spherical harmonics. Compared with the lighting expression in spherical harmonics which are only described by 9 coefficients, the redundant information provided by spherical harmonic frames can describe not only along the original perpendicular axes, but also along the the symmetry axes of a subgroup of $SO(3)$. An element of spherical harmonic frame is generated by the rotation of spherical harmonics,

$$Y_{l,m}^{s} = \sum_{m=d(s),|k| \leq l} M_{m,k}^{s} Y_{l,k}(\theta, \phi) \tag{5}$$

where $\boldsymbol{M}$ (denoted as a Wigner-D matrix D^l) indexed by s is the s-th rotation representation for subspaces H_l. It represents a $(2l+1) \times (2l+1)$ rotation matrix between a symmetry axis of a symmetry group and original z-axis.

3 Lighting Estimation

At present, it is still a tough problem to recover 3D geometry from a single image. For an object in a single image, there is no known 3D geometry information to be provided for the solution of equations (2) and (4). However, the occlusion contour of an object remains the 2D geometric information, which simplifies the estimation of lighting field from a single image. Under the orthogonal projection, the surface normal along the occluding contour of an object is $\boldsymbol{n}_{z=0} = (x, y, 0)$.

The character of its lighting field can be described by five coefficients of spherical harmonics, since there is no geometric information about z-component of the surface normal. In the lighting model described by spherical harmonic frames, the redundant lighting coefficients which are more than five basis coefficients provide a robust character from the 2D geometric information. The property of frame offers a robustness against noise and incomplete data [11].

In terms of spherical harmonic frames, the image intensity of one geometric point along 2D contour can be expressed as

$$I(\boldsymbol{n}_{z=0}) = \sum_{l=0}^{2} \sum_{t=0}^{n(l)-1} \rho \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,t} Y_{l,t}^{d}(\boldsymbol{n}_{z=0}) \tag{6}$$

Correspondingly, in terms of spherical harmonic bases, the image intensity is

$$I(\boldsymbol{n}_{z=0}) = \sum_{l=0}^{2} \sum_{-l \le k \le l} \rho \left(\frac{4\pi}{2l+1} \right)^{1/2} A_l L_{l,k} Y_{l,k}(\boldsymbol{n}_{z=0}) \tag{7}$$

In Eq. (6) and (7), the lighting coefficients of a diffuse object with a constant albedo ρ can be solved using the least square procedure.

3.1 2D Information Extraction

In order to analyze the lighting characteristics of a diffuse object in one image, we should get information from 2D occluding contour of the object, including the normal vector and the intensity. The related process of information extraction along the 2D contour is illustrated in Fig. 1.

For the image information extracting along the 2D contour, the article [12] has pointed out that simply using the intensity close to the border is often sufficient. Then, the 2D contour intensity can be extracted from the pixels in the opposite direction to the surface normal. The z-component of normal vector along the 2D contour is zero due to the orthogonal projection. Then, the x, y components of normal vector can be obtained by fitting curve of the contour. Thus, the intensity of the 2D contour can be determined by the following formula,

$$I(\boldsymbol{n}_{z=0}) = I(\boldsymbol{p} + \alpha \boldsymbol{n}_{z=0}) \tag{8}$$

where $\alpha > 0$ is an offset value along the normal $\boldsymbol{n}_{z=0}$ at the boundary point $\boldsymbol{p}$.

4 Experiments

The proposed approach using spherical harmonic frames has been evaluated for the robust performance using two sets of images. One is Lambertian spheres rendered by the ten light probes [11] and the other set is the real natural images which are photogrphed by ourselves or collected from Flickr website, etc. Results of both show advantages in the measurement of image consistency

(a) (b)

Fig. 1. (a) 3D information extraction from a sphere (b) 2D information extraction along the boundary of a sphere. L denotes the light direction, N denotes the surface normal; N_1 and N_2 are the normal vectors along the occluding contour.

and discrimination using spherical harmonic frames compared with orthogonal spherical harmonic bases. We also present the identification results of two tampered images. The lighting coefficients are only computed in the green channel of all test images.

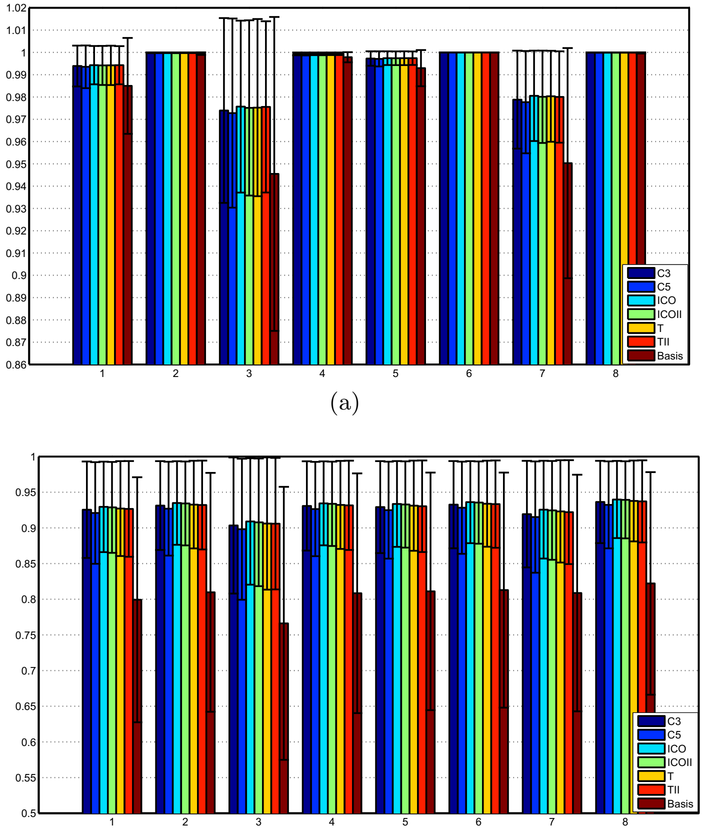
4.1 Synthetic Data

In a single image, we need to use the 2D information along the occluding contours to estimate lighting coefficients. The available information of geometry and intensity is always restricted in a limited range. Many factors may affect the final results of estimation, such as the shape differences of objects, the limitation of the available data, the error of the derived 2D information and the effects of highlights and cast shadows. Considering the above factors, we simulate the disturbed data of surface normals and intensities.

First, we divide the tests into two groups: a unit circle and a unit semicircle. The data of circle and semicircle are tested to show the sensitivity of the estimation to surface normal extent. Second, considering the differences of the available data from different objects, we randomly sample in the semicircle group. That is to say, the starting point of the semicircle is randomly selected on the $z = 0$ circle of unit sphere. Third, to simulate the error of the recovered signal and the effects of highlights and cast shadows, we add Gaussian noise to the surface normal or intensity of the 2D information.

We construct two classes of spherical harmonic frames to estimate lighting from 2D occluding boundaries, total spherical harmonic frames and partial spherical harmonic frames [11]. For comparison, we also present the results of orthogonal spherical harmonic basis functions. Six frames are constructed: **T**, **ICO** (two total frames are generated by tetrahedron and icosahedron, respectively), **Tii**, **ICOii** (two partial frames are generated by tetrahedron and icosahedron, respectively), and two other frames through cyclic group **C3**, **C5**.

The lighting environments are characterized by the coefficients of spherical harmonic basis functions, **C3** frame, **C5** frame, **T** frame, **ICO** frame, **Tii** frame and **ICOii** frame, correspondingly. These coefficients are computed using the



(a)

(b)

Fig. 2. (a) diagram of consistency of different samples in the identical lighting environments; (b) diagram of inconsistency of different samples in the different lighting environments. The grouped bars (1, 3, 5, 7) and (2, 4, 6, 8) exhibit statistical results of lighting correlation of unit semicirle data and unit circle data, respectively. The grouped bars (1, 2), (3, 4), (5, 6) and (7, 8) display the results of contaminated noise, 15% normal plus 15% intensity, 15% normal plus 30% intensity, 15% normal, and 30% normal, respectively. The color bars represent the means of statistical measurement computed by frames and basis; the error bars represent the standard deviations correspondingly. Each color bar and error bar reveal the statistical result from all 100 groups noise data of one class.

least square procedure. For analyzing the consistency of the identical lighting environment, statistical results of the lighting consistency from synthetic data are considered. A correlation indicates the consistent degree of different samples in an identical lighting environment. Fig. 2(a) illustrates the correlation of different samples in the identical lighting environment. Fig. 2(b) illustrates the inconsistent measurement of different lighting. Lower mean and greater standard

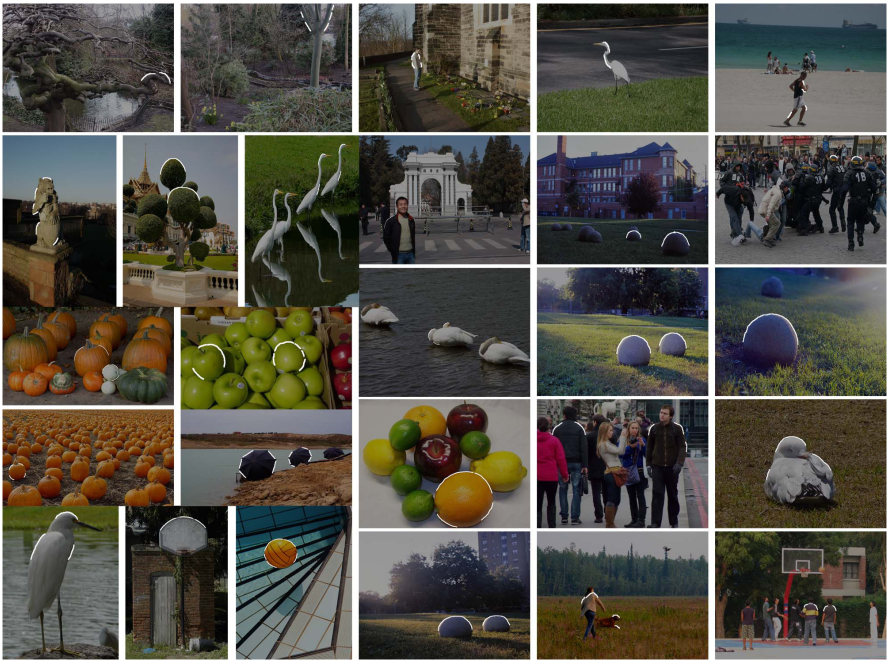


Fig. 3. Twenty-seven natural images with a light dark cover to show the analyzed boundaries.

derivation indicate that the consistency measurement is less robust. The robustness of the lighting estimation characterized by different approaches is evaluated by the corresponding mean value and standard derivation. When only small noise of the surface normal is added, the consistency measurements of frames and basis have approximate results. When both normal and intensity noise are added, the correlation of identical lighting measured by frames exhibits more robustness than basis, particularly in the semicircle group. Moreover, the lighting consistency in the semicircle group reduces more rapidly. As the noise-resistant property, the variation of frame coefficients is less than the variation of basis coefficients. Thus, the consistency of lighting characterized by frame coefficients is superior to the result characterized by basis coefficients. Moreover, as shown in (b), the inconsistency of lighting characterized by frame coefficients is suppressed in a limited extent.

4.2 Real Images

To test the noise-resistant property of our lighting model, we select 27 natural images of multiple objects in natural lighting environments from Flickr, USC-SIPI database and the others photographed by ourselves. To ensure the forensic application in the real complex situation, various objects in images including people, plants, animals and sculptures are considered. The 2D occluding contours in one image are captured using the painting tool of Adobe Photoshop by painting along the boundaries of objects, which are shown in Fig. 3.

Table 1. The statistical results estimated using spherical harmonic frames

	T	**Tii**	**ICO**	**ICOii**	Basis
mean	0.9105	0.9112	0.9064	0.9041	0.9048
var	0.0628	0.0621	0.0677	0.0717	0.0664

There are 12 pairs of objects from the same scene and 351 pairs of objects from different scenes in all tested images. The lighting coefficients of objects are computed using spherical harmonic basis lighting model and spherical harmonic frames lighting model, respectively. For the pairs in the identical scene, the mean and derivation of lighting correlation computed using spherical harmonic basis lighting model are 0.9048 and 0.0664, respectively. For comparison, the mean and derivation of lighting correlation computed in spherical harmonic frames lighting model (**T**, **ICO**, **Tii**, **ICOii**) are listed in Table 1. The listed results of real images confirm to the ones of synthetic data, the correlation evaluated by spherical harmonic frames can keep better similarity measurements as the redundancy of frames. As the product moment correlation which represents the lighting similarity is sensitive to extreme magnitudes [13], the absolute values of frame coefficients will be decreased with the increase of the redundancy. The higher redundancy of frames will reduce the evaluation of the similarity. The redundancy of frames will be considered properly to keep the advantage of consistency measurements.

4.3 Tampered Images

Two tampered images are generated using the Adobe Photoshop, shown in Fig. 4. The operated images are from Fig. 3. The rendered sphere of a tested object which reflects the lighting information of one environment is shown correspondingly [14]. The consistency and inconsistency of lighting coefficients estimated from the objects in the tampered images are listed in Table 2 and Table 3. The similarity measurements are given using spherical harmonic basis, spherical harmonic frames **T**, **Tii**, **ICO** and **ICOii**. The consistency of objects in the identical environment (2VS3) reveals that the lighting similarity measurements using spherical harmonic frames have a better evaluation than spherical harmonic basis. In addition, the inconsistency of objects in the different environments (1VS2, 1VS3) measured by the correlation reveals that the dissimilarity evaluated by spherical harmonic frames can be suppressed effectively, compared with spherical harmonic basis. Thus, for the forensic application in the real scenes, the lighting model based on spherical harmonic frames can possess a robust measurement and discrimination compared with spherical harmonic basis, which can provide an assistance in identifying the tampered images.

(a) Tampered image 1

(b) Tampered image 2

Fig. 4. Two tampered images. The rendered spheres which reflect the lighting environments are shown correspondingly.

Table 2. The consistency of tampered image 1

	Basis	T	Tii	ICO	ICOii
1VS2	0.3627	0.3330	0.2790	0.3068	0.3100
1VS3	-.1544	-.0794	-.1296	-.1224	-.1145
2VS3	0.8458	0.8941	0.8970	0.8881	0.8891

Table 3. The consistency of tampered image 2

	Basis	T	Tii	ICO	ICOii
1VS2	0.4660	0.4716	0.5160	0.4869	0.4332
1VS3	0.3514	0.3751	0.4281	0.3922	0.3341
2VS3	0.9675	0.9789	0.9815	0.9770	0.9784

5 Conclusion

In this paper, we propose a novel robust lighting model using spherical harmonic frames to characterize the lighting of diffuse objects in different complex environments. The available 2D information is trapped in the limit and noise of occluding contours. The redundancy of frames provides a robust property to estimate the 2D lighting information. The related statistical results in experiments demonstrate the robust measurements and discrimination using the lighting model in terms of spherical harmonic frames in 2D space. Further more, we improve the forensic technology through spherical harmonic frames lighting model compared with spherical harmonic bases lighting model, which is shown in the tampered cases.

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