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Technical Section

Star-effect simulation for photography ☆

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A R T I C L E I N F O

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A B S T R A C T

This paper discusses the creation of star effects in captured night-time photos based on using depth information available by stereo vision. Star effects are an important design factor for night-time photos. Modern imaging technologies support that night-time photos can be taken free-hand, but star effects are not achievable for such camera settings. Self-calibration is an important feature of the presented star-effect simulation method. A photographer is assumed to take just an uncalibrated stereo image pair (i.e. a base and a match image), for example by taking two photos subsequently (e.g. by a mobile phone at about the same pose). For self-calibration we apply the following routine: extract a family of pairs of feature points, calibrate the stereo image pair by using those feature points, and calculate depth data by stereo matching. For creating the star effects, first we detect highlight regions in the base image. Second, we estimate the luminance according to available depth information. Third, we render star patterns with a chosen input texture. Basically we provide a complete tool which is easy to apply for the generation of a user-selected star texture. Minor variations can be introduced in star pattern rendering in order to achieve more natural and vivid looking star effects. By extensive experiments we verified that our rendering results are potentially similar to real-world star effect photos. We demonstrate some of our results, also for illustrating that they appear more natural than results achieved by existing commercial applications. We also illustrate that our method allows us to render more artistic star patterns not available in recorded photographs. In brief, this paper reports research on automatically simulating both photorealistic and non-photorealistic star effects.

1. Introduction

Star patterns around highlights, known as *star effect* in photography (see Fig. 1), are often essential for defining the esthetic meaning of night-time photographs. The appearance of star patterns in night-time photographs depends on scene characteristics (e.g. distribution of lighting) and camera recording (e.g. chosen camera setting). Altogether, the creation of particular star patterns defines a challenge for any photographer.

Photos are taken increasingly with compact cameras or mobile phones. The technological progress (e.g. large aperture lenses or high-sensitivity image sensors) also makes it possible to shoot night-time photos free-hand. To obtain a star effect, a photo has to be shot normally with a small aperture (e.g., f22). Such an aperture setting is unfit for free-hand shooting because it requires several seconds of exposure time; the photo would be largely blurred by hand shake.

Star effects can be achieved with a *star filter* in front of the lens. But this is not really appropriate for casual shooting with compact cameras or mobile phones because special equipment is needed.

In this paper we provide an answer to the question: How to obtain a star effect in case of casual hand-held photography? Generating star effects by post-processing is a possible way, for example by adding star effects manually using available photo-editing applications. This might be a time-consuming process for a complex scene because the size and color of each star should be carefully set, one by one. Professional skills are also needed. Dedicated applications such as *Topaz Star Effects plugins*, or instructions given in some online tutorial videos [8,19], draw uniform-sized star patterns to all the overexposed regions of a photo. Though it may also look beautiful, such effects typically look unnatural and different to the star effect generated by a small aperture. Our contribution aims at having an automatic star-effect generator which corresponds to the actual content of a photo.

Computational photography [18] became a very active field of research and applications in recent times. For example, exploring

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0097-8493/

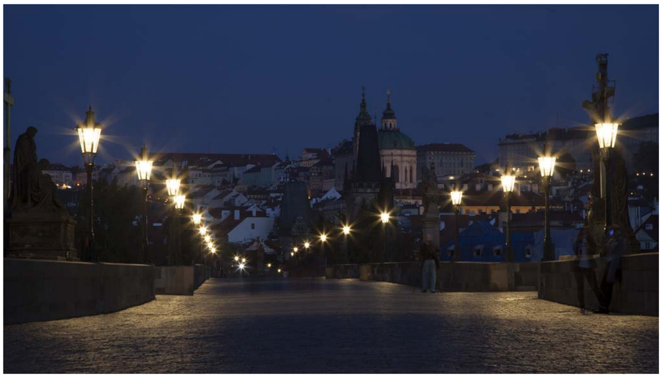

Fig. 1. A night-time photo with star effect.

the simulation of various photo effects such as fog [13], bokeh [14], glare [21] or high dynamic range photos [26]. This paper presents for the first-time[1] a way for automatically simulating photo-realistic or non-photorealistic star effects. Self-calibrated stereo vision is at the core of our automatic method for adding star effects to a photo, to be presented in this paper.

Consider a given uncalibrated stereo pair, for example two pictures of the same scene taken subsequently with a mobile phone at about "near-parallel" poses. First we detect a family of feature point-pairs and do a self-calibration. By stereo matching we estimate depth information of the scene. Next, "star-capable" highlights are detected, and luminance and color information (clipped by overexposure) is recovered according to the available depth information. Finally, we render star patterns considering the luminance and color of the highlights using an input star model. See Fig. 2 for a brief workflow of the proposed method.

Compared to the conference version [15], we introduce in this paper also an interface for generating star models, and a mechanism offering variations of stars during rendering. In this altogether more detailed paper we also added several new experiment results illustrating the flexibility in achieving star effects.

The rest of the paper is structured as follows. Section 2 briefly recalls theories and techniques related to our work. In Section 3 we provide details for our self-calibrated depth estimation method. Section 4 discusses our method for the detection of highlights and the estimation of luminance and color of highlights. Then, Section 5 discusses our star effect rendering method. Experimental results are shown in Section 6. Section 7 concludes.

2. Basic and notation

This section lists notation and techniques used. RGB color images I are defined on a rectangular set Ω of pixel locations, with $I(p) = (R(p), G(p), B(p))$ for $p \in \Omega$ and

$$0 \le R(p), G(p), B(p) \le G_{\max} \quad (1)$$

Let N_{cols} and N_{rows} be the width and the height of Ω, respectively. Position O be the center of Ω (as an approximation of the principle point). We suppose that lens distortion has been corrected in cameras, otherwise we can correct it by using the lens profile provided by the manufacturer. Altogether, we consider input image I as being generated by undistorted central projection. In the following, a *star-effect photo* refers to a photo taken of a night scene with a very small aperture, in which star patterns appear around highlights.

[1] Not counting our brief report about photorealistic star effects presented at the Pacific-Rim Symposium on Image and Video Technology, November 2015, at Auckland [15].

2.1. Star effects in photography

A star effect is normally caused by *Fraunhofer diffraction*; see [2]. Such a phenomenon is most visible when bright light from a "nearly infinite" distance passes through a narrow slit, causing the light to spread perpendicular to the slit. This spreads a point-like beam of light into a pair of arms (i.e. streaks). Suppose a rectangular aperture A with width w_1 and height w_2, located in an x_1x_2 plane having its origin at the centroid of A; axes x_1 and x_2 are parallel to the edges with width w_1 and w_2, respectively. Suppose an axis y perpendicular to the x_1x_2 plane. When A is illuminated by a monochromatic plane wave of wavelength λ, the intensity $I(\theta_1, \theta_2)$ of the light through A forms a pattern that is described by

$$I(\theta_1, \theta_2) \propto \mathrm{sinc}^2\left(\frac{\pi w_1 \sin\theta_1}{\lambda}\right) \cdot \mathrm{sinc}^2\left(\frac{\pi w_2 \sin\theta_2}{\lambda}\right)$$

$$\text{where } \mathrm{sinc}(x) = \frac{\sin(x)}{x} \quad (2)$$

with $\tan\theta_1 = x_1/y$ and $\tan\theta_2 = x_2/y$. Similarly, for a parallelepiped aperture with edge lengths w_1, w_1, and w_1, we have a pattern defined by

$$I(\theta_1, \theta_2, \theta_3) \propto \mathrm{sinc}^2\left(\frac{\pi w_1 \sin\theta_1}{\lambda}\right) \cdot \mathrm{sinc}^2\left(\frac{\pi w_2 \sin\theta_2}{\lambda}\right) \cdot \mathrm{sinc}^2\left(\frac{\pi w_3 \sin\theta_3}{\lambda}\right) \quad (3)$$

Fig. 3 shows some real-world star patterns shot with different aperture shapes. It can be seen that each blade of the aperture contributes a pair of arms to the star pattern. Due to overlapping, in case of a lens with an even number a of blades, generated star patterns have the same number a of arms.

In fact, every beam of light that goes to the image sensor through a small aperture spreads a star pattern to its neighboring region due to diffraction. In normal-contrast regions of an image, the star pattern is very slight and not visible (it only causes a reduction of local sharpness). Only in very high-contrast cases, such as highlights in a night-time photo, the star pattern is noticeable.

As described above, the shape of the star pattern depends on the shape of the aperture, which is not a user-controllable parameter. A modern-designed lens normally uses a near-circular aperture (in order to obtain good *bokeh* quality [14]), which generates only weak and scattered star arms. Our method provides controllable star pattern styles, which is convenient for photo-art creation.

A *star filter* can be used to simulate a star effect as introduced by small aperture (see Fig. 3, right). Such filter embeds a very fine diffraction grating or some prisms. A star effect can be obtained even at large aperture when using such a filter in front of the lens. The star pattern generated by a star filter is visually a little different from that one generated by a small aperture. Our method can simulate both styles by introducing different templates.

2.2. Stereo vision

For stereo vision, we take a *stereo pair* (i.e. a *base image* I_b and a *match image* I_m) as input, and estimate depth information for a scene by searching for corresponding pixels in the stereo pair [10]. For reducing the complexity, the given stereo pair is normally geometrically rectified into *canonical stereo geometry* [10], in which I_b and I_m are as taken by identical cameras, only differing by translation distance b along the *base line* on the X-axis of the camera coordinate system of I_b. Rectification transform matrices $\mathbf{R}_b$ and $\mathbf{R}_m$ can be calculated in a stereo calibration process. Our proposed method is not very sensitive to accuracy of available depth values. For convenience, we use a self-calibration method with only a few assumed camera parameters. After rectification, a stereo matching method such as belief-propagation [4], or semi-global matching

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