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Image based temperature field reconstruction for combustion flame

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ABSTRACT

We present a novel solution to accurately reconstruct three-dimensional temperature field for combustion flame. Traditional flame temperature field reconstruction methods ignore the effects of flame refraction. However, flame is a kind of inhomogeneous medium, traveling inside which the light rays will be bent. The neglect of refraction will lead to poor accuracy of the reconstructed results. In this paper, we propose a new model to establish the relationship between the flame radiation and the radiance field, which fully considers the refractive effect of the refraction index changing. We use high dynamic range (HDR) cameras to take flame images, calculate temperature from radiance with a lookup table between them, and put forward an algorithm to reconstruct the flame temperature field. The experimental results on real flame accord with the physical facts, which demonstrate the validation of our solution.

1. Introduction

The computational modeling of flame is given significant attention in industrial monitor and control [1–3] as well as in other fields of experimental science [4,5]. Since temperature is one of the most essential physical parameters to flame, the reconstructing of flame temperature field becomes a hotspot, and is significantly valuable to related industries [6–8]. In the fossil-fired power plant, accurate temperature field is one of the basic factors to save energy, reduce emission and operate safely. In computer graphics, flame simulation based on real physical parameters, e.g. temperature field, possesses an apparent advantage over the traditional methods, for it is able to show the special behaviors of combustion flame, to be more exact, the physically plausible as a whole, but complex and chaotic behaviors in local area.

Flame is considered to be the luminous reaction products of fire [9]. Due to complex physical mechanism and random behaviors of the flame, to model the combustion flame and reconstruct its temperature field becomes a tough nut to crack.

Temperature field measurements can be divided into two categories, i.e. intrusive measurements and non-intrusive ones. Early methods, e.g. thermocouple based and thermal resistance based temperature measurement, belong to the former category. They are easy to implement, but only can measure one single point temperature each time, besides, the flame may be disturbed when being measured. Thus the scope of application is quite limited. Non-intrusive measurements can be further divided into two subcategories, i.e. active methods and passive ones. The active methods are based on the fact that some physical parameters may change when the original signal such as sound wave or laser travels through the flame. Flame temperature field is able to be calculated from the changed physical parameters. Some technologies such as acoustic thermometry [10,11] and laser spectroscopy [12] are of this kind. The demands of costly facilities limit its application. Passive methods rely on the radiation of the flame. The radiation from flame is captured by sensors and shown by images. Then the temperature field is reconstructed based on those flame images. Shimoda et al. [13] introduced a flame temperature field measurement method, namely two-color method, which is only suitable for two dimensional cases. Wu [14] investigated the relationship between flame image brightness and flame temperature. Wang et al. [15] made an intensive study of reconstruction of flame temperature field as well as concentration field. Wang and Zhao [16] made important contribution to flame image process and 3D flame temperature field reconstruction. Based on reference temperature, Zhou et al. [17] measured the temperature distribution of combustion flame in the boiler through monochromatic flame images. Zhang et al. [18] studied the quantitative relation model between temperature and flame radiation. Gilabert et al. [19] developed a prototype instrumentation system on the basis of digital imaging process and tomographic techniques for 3D luminous reconstruction of combustion flames.

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Hossain et al. [20] designed an optical fiber imaging based tomographic system to reconstruct the luminosity of a burner flame. Wang et al. [21] takes flame images with high dynamic range cameras and reconstructs the radiance field on camera band for the flame, then obtains the flame temperature field through the lookup table between radiance and temperature.

There exist two drawbacks of the passive methods mentioned above. First, all the methods ignore the refraction of the flame and assume that light rays travel through the flame along straight lines. Since flame is a kind of inhomogeneous medium, it bends the light rays internally. Sometimes, the bending is significant, and ignoring the refraction effects will lead to poor reconstruction results. Second, except for the work proposed by Wang et al. [21], other works do not take into account the fact that the dynamic range of the flame emission is larger than that of general industrial cameras. Thus, the accuracy of the reconstruction results cannot be guaranteed.

Our approach belongs to the passive methods. In our work, we offer three contributions over the existing state of the art. First, a new model, which establishes the relation between the flame radiation accepted by cameras and radiance field produced by flame, is put forward. This model not only includes the effect of the absorption, but also takes account refraction caused by refraction index changing. Second, integral operation for radiance on camera response band is performed. Lookup table between temperature and radiance is established to effectively reduce the computational complexity when calculating flame temperature field. Third, an algorithm that reconstructs the temperature field based on the consistency between temperature and refractive index is proposed. The algorithm starts with the initial temperature field calculated through traditional methods, and terminates when temperature and refractive index field physically consistent with each other. Experimental results indicate that our improvements are successful.

The remainder of this paper is organized as follows. In Section 2, we present the model that establishes the relationship between flame radiation and radiance field, and show how the solution of the model is affected by the refractive index field. In Section 3, we show in detail how to calculate temperature from radiance. In Section 4, we provide a brief description of calibrating camera response function as well as getting irradiance from flame images. We will propose the algorithm that reconstructs temperature field and discuss the details of this algorithm in Section 5. In Section 6, we will show the experimental setting and results. Section 7 concludes this paper.

2. Optical model of flame

Fire is typically defined as an oxygen-fueled chemical decomposition that releases heat to the environment, and flame is the visible luminous reaction products of fire [9]. When the radiation from flame arrives at the sensor (CCD or CMOS), it is converted into electrical signals by a photoelectric converter. The electrical signals are then digitized and formed images on the image processor. Before reaching the sensor, radiant energy inevitably undergoes several kinds of attenuation, including reflection, refraction and absorption.

The radiant energy $E(p)$, a pixel p in a flame image received, consists of two parts (as shown in Fig. 1): The radiant energy emitted from flame along curve c and background's contribution $E_{bg}(p)$. Curve c is the path, which light rays travel along, before reaching pixel p. The reason why light rays travel through the flame along a curve path lies that, flame is inhomogeneous, the density of fire products varies in different areas of the flame. As a result, light rays are bent inside the flame. The bending effect of the flame is illustrated in Fig. 2.

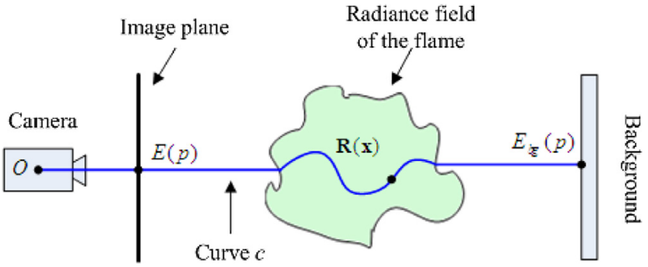

Fig. 1. Optical model of flame. The radiant energy $E(p)$ that a pixel p received depends on the integral of radiance field along curve c. Curve c is the path that light rays travel along before reaching pixel p. The radiant energy $E_{bg}(p)$ from background also contributes to $E(p)$.

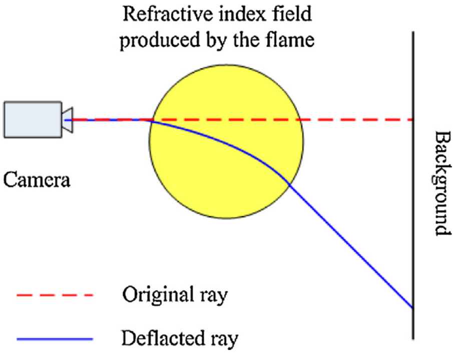

Fig. 2. Light rays travel along a curve path inside the flame due to refraction.

Thus, $E(p)$ can be expressed as

$$E(p) = \int_c \tau(x)\alpha(x)\mathbf{R}(x)dx + E_{bg}(p) \tag{1}$$

where $\alpha(x)$ is the view factor from x, a point locating on curve c, to pixel p (shown in Fig. 3). For the description, the distance from x to pixel p is denoted as d, the area of the pixel element is denoted as s_0. ψ denotes the angle between the image plane and the tangent line of curve c at pixel p. So $\alpha(x)$ is formulated as

$$\alpha(x) = \frac{s_0 \ \cos\psi}{2\pi d^2} \tag{2}$$

here, we make an assumption on the structure of the radiance field $\mathbf{R}(x)$, we do this by assuming that $\mathbf{R}(x)$ can be represented by a linear combination of base functions $R_t(x)$:

$$\mathbf{R}(x) = \sum_i a_i R_i(x) \tag{3}$$

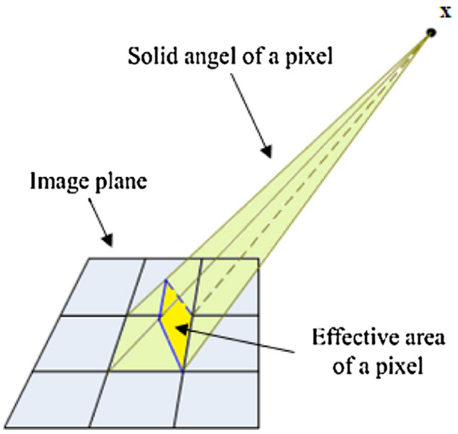

Fig. 3. The radiant energy that one pixel received from x.