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Data acquisition and simulation of dynamic flame with temperature distribution

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ABSTRACT

Data acquisition and reuse of dynamic flame provides a new way for realistic flame simulation. The virtual model has a comparable physical data support while reconstructing the realistic flame. In this paper, we focus on the acquisition and simulation of dynamic flame with temperature distribution. Firstly, a synthesis 2D dynamic flame texture method is proposed to simulate and edit the high frequency detail of dynamic flame based on temperature distribution. Secondly, a 3D flame reconstruction method is put forward to reconstruct and edit temperature field from the captured multi-view flame images based on pyrometry and fluid dynamics. The simulated flame has the constraints and support of the physical temperature data; and the dynamic flame can be edited based on the temperature distribution intuitively. Different flame scenes were tested and the experimental results show that our method is effective in flame temperature data acquisition and simulation.

1. Introduction

Fire/Flame is an essential element of nature, and the realistic flame simulation is an important part of the virtual environment. However, fire simulation with physical properties has been slow to progress for the characters of spare density, diverse velocities, uneven particle distribution and self-illumination. Data acquisition and reuse of dynamic flame provides a new idea for realistic flame simulation. The physical properties such as the temperature, particle velocity, and density of the flame are captured while the flame visual model is being reconstructed based on the data sampling of the real flame, so as to provide the virtual model with comparable physical data support.

Data acquisition and simulation of dynamic flame has achieved good results in many areas, including three-dimensional flame reconstruction, dynamic flame texture synthesis, temperature field reconstruction, et al. However, there are still some problems that need to be solved. Firstly, visual flames lack support for physical attribute data. Secondly, the reconstructed flame is difficult to edit.

According to the principle of radiation thermometry and Planck's law, there is a one-to-one mapping between temperature and color of a flame. A novel acquisition and simulation method of dynamic flame is presented with temperature distribution in this paper. Firstly, a multi-view data acquisition device is designed to capture the multi-angle images of dynamic flame. Secondly, we put forward the dynamic flame texture synthesis method to simulate the high frequency detail of dynamic flame which is based on temperature distribution. This method compresses the model data from RGB three dimensions to temperature one dimension. Thirdly, a method to reconstruct and edit 3D temperature filed is put forward for dynamic flame based on a two-color method. In order to check our method's effectiveness, we test several kinds of flame scenes.

The main contributions of this paper include: firstly, this simulated flame has the constraints and support of the physical temperature data. Secondly, the reconstructed 3D flame can be edited intuitively which relies on the temperature field.

2. Related work

Dynamic textures are the sequences of pictures in moving scenes, which show properties with certain stability in time. Nelson and Polana [1] were the first ones who put forward the problem of modeling dynamic textures. After that, De Bonet [2] published the time-varying texture synthesis algorithms. Following that, Soatto and Doretto [3, 4] introduced an ARMA model to perform learning and synthesis of

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sequences from the training data. Doretto et al. [5, 6] modeled the statistics of data segments that exhibited temporal stationarity by using conditional linear processes for shape, motion, and appearance. Vasconcelos and Chang [7] proposed the model of layered dynamic textures demonstrating the picture sequence. As a set of random layers of different appearances and dynamics, every layer was simulated as a temporal texture sampled from different linear dynamical systems.

Image is one of the important ways to obtain flame data. More and more researchers began to focus on the data acquisition and reuse of flame images. Bheemul et al. [8] designed an instrumentation system to quantitatively characterize the flame geometry, including the surface area, volume, length, orientation and circularity et al. Atcheson et al. [9] developed the first time-resolved schlieren tomography system to capture and reconstruct 3D refractive index values of dynamic flames. Ishino et al. [10]applied a forty-lens camera to further restore the distribution of local burning rate of a turbulent flame. Ohiwa and Ishino [11] designed a custom-made camera system, with forty lenses. This system is used to capture the flame images from different views at the same time, after which the 3D emission distributions of dynamic flame will instantly be rebuilt from the captured images. Kutulakos and Hasinoff [12] put forward a photo-consistent rebuilding method. This method slashes fire rebuilding to the convex combination of sheet-like density fields. Afterwards, Magnor and Ihrke [13] proposed a tomographic method to rebuild the volumetric model from multiple-color images of flames, using the visual hull to limit the solution.

Optical radiation pyrometry, which is based on the Planck's radiation law, establishes a relationship between flame temperatures and image pixels. On the basis of the reference temperatures, H. C. Zhou et al. [14] captured the monochromatic images to measure the temperature of combustion flame in the boiler. Utilizing a single monochromatic CCD camera and two narrow band-pass filters Y. Yan and Y. Huang [15] designed a beam-spilt optical system for capturing the images of a flame at two different wavelengths concurrently. In order to determine the flame's temperature distribution, Phillip M. Brisley et al. [16] rebuilt band-limited grayscale expressions of the flame. As the flame structure is rotational symmetry during the rebuilding process, this method is not considered by the authors a true 3D method. In an attempt to rebuild the laboratory-scale 3D flame temperature and emissivity distributions, Md. Moinul Hossain et al. [17] investigated an optical fiber imaging. During the process, they used the reconstructed gray-level intensities of the red and green components and two-color pyrometric technique. This is a real method of 3D temperature field rebuilding.

In this paper, the focus is on the acquisition and reuse of flame temperature distribution. Temperature-based dynamic flame simulation and editing are achieved from both two-dimensional and three-dimensional aspects.

3. Method overview

Based on the principle of Planck's radiation law and color pyrometry, the integral of radiant energy of the small radiators with different temperatures along viewing ray determines the intensity of a pixel. For 3D flame temperature field reconstruction, the process of flame imaging is shown in Fig. 1(a). The reconstruction of 3D radiant existence field can be viewed as a computer tomography problem in terms of multi-view irradiance images [18]. Fig. 1(a) displays the process of calculating the 3D temperature distribution of flame from the captured multi-view images. The three-dimensional space is divided into voxels, with only one temperature for each voxel. Suppose the irradiance of the ith pixel as E_i and that the radiant existence of the jth voxel as M_j. Then the relationship between E_i and M_j can be formulated as

$$E_i = \sum w_{ij} M_j, \tag{1}$$

where w_{ij} represents the weight of pixel i intercepted by the total energy released by voxel j. The monochromatic emissive power $M(\lambda, T)$ of a radiation object with temperature T(K) can be calculated by the Planck's radiation law.

$$M(\lambda, T) = \varepsilon_\lambda \cdot \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}, \tag{2}$$

where C_1 and C_2 are known as the Planck constants,ε_λ is the monochromatic emissivity which is inversely proportional to the wavelength λ in this paper.

For 2D dynamic flame synthesis, it's assumed that the accumulated radiant existence equals to the radiant existence of an ideal surface radiator with temperature T; then the same irradiance on the image planes will be received for an ideal surface radiator and a volume flame, and the CCD will output the same pixel intensity. The volume flame can be approximated by an ideal surface radiator in viewing direction according to the radiation thermometry principle, as shown in Fig. 1(b). Therefore, the distribution of a flame image color can be converted into a temperature field for 2D dynamic texture synthesis [19,20].

In this paper, a multi-view imaging system is designed for precise capture of the flame images. A novel method is put forward to simulate and edit dynamic based on temperature distribution. The framework of our method is shown in Fig. 2. Firstly, the color images of combustion flames are captured by multi-view CCD cameras. Secondly, temperature-based dynamic textures method is presented to simulate and edit 2D dynamic flames. Thirdly, temperature-based reconstruction and edit method is exhibited to simulate and edit 3D dynamic flame with temperature field distributions. Different flame scenes have been tested to prove the effectiveness of our method.

4. Data acquisition

In order to acquire different directions of synchronous 2D flame images, we design a multi-view digital imaging system, which is composed of four color CCD cameras. The color camera's model is pointgray Flea 2 series 08S2C, with a frame rate of 30 frames/s at a maximum resolution of 1032 × 776. The central wavelengths of the camera are 650, 530, and 455 nm , which are respectively corresponding to the R, G, and B components. The physical equipment of our system is shown in Fig. 3.

In Fig. 3, the four cameras are on a 45-degree auxiliary ring. The target flame is placed in the center of the ring at the same distance from each camera. Eight-pin (General Purpose Input/Output) connectors are used to trigger these cameras simultaneously. In order to avoid the effect of other light sources, the flame images are shot in a completely dark environment. The standard techniques serve to calibrate the internal and external parameters of all cameras. The target furnaces are used to produce flames of laboratory-scale. The flames' heights are about 150 mm. From four different directions, 100 frames images for each flame scene were caught at the same time, and the frame rate was 12 frames per second. To ensure that the pixels were not saturated in any spectral channel for flames, the exposure time was set to 80 ms. This blackbody furnace (LumaSense M330) has a 100 mm long blackbody cavity with an internal diameter of 40 mm and an emissivity of about 0.996 (300 ºC-1700 ºC). The alcohol, candle and butane flame scenes were captured to prove the effectiveness of our method. In addition, some of the datasets in Reel Fire 2 [21] was used to test the proposed dynamic texture method. 100 images with a resolution of 352*288 were chosen for each dataset.

5. Dynamic flame texture synthesis and editing with temperature distribution

A temperature-based dynamic flame texture synthesis method is proposed in this section with the data processing shown in Fig. 4. According to Planck's law of radiation [22] and the color pyrometry

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