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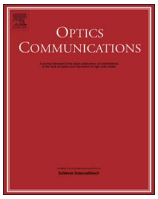

A novel calibration method of focused light field camera for 3-D reconstruction of flame temperature

Jun Sun[a], Md. Moinul Hossain[b], Chuan-Long Xu[a,*], Biao Zhang[a], Shi-Min Wang[a]

[a] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, China
[b] School of Engineering and Digital Arts, University of Kent, Canterbury, Kent CT2 7NT, UK

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ABSTRACT

This paper presents a novel geometric calibration method for focused light field camera to trace the rays of flame radiance and to reconstruct the three-dimensional (3-D) temperature distribution of a flame. A calibration model is developed to calculate the corner points and their projections of the focused light field camera. The characteristics of matching main lens and microlens f-numbers are used as an additional constrains for the calibration. Geometric parameters of the focused light field camera are then achieved using Levenberg-Marquardt algorithm. Total focused images in which all the points are in focus, are utilized to validate the proposed calibration method. Calibration results are presented and discussed in details. The maximum mean relative error of the calibration is found less than 0.13%, indicating that the proposed method is capable of calibrating the focused light field camera successfully. The parameters obtained by the calibration are then utilized to trace the rays of flame radiance. A least square QR-factorization algorithm with Plank's radiation law is used to reconstruct the 3-D temperature distribution of a flame. Experiments were carried out on an ethylene air fired combustion test rig to reconstruct the temperature distribution of flames. The flame temperature obtained by the proposed method is then compared with that obtained by using high-precision thermocouple. The difference between the two measurements was found no greater than 6.7%. Experimental results demonstrated that the proposed calibration method and the applied measurement technique perform well in the reconstruction of the flame temperature.

1. Introduction

Flame is a 3-D medium with sparse density, particle participation and self-illumination. It plays an essential role in various industrial processes such as combustion in power plant and rocket engine. Where temperature is one of the most important characteristic parameters of the flame and closely linked to the performance of the combustion process. In the process of combustion diagnostics, the quantitative characterization of flame temperature can be used for informing the operators or the control system to diagnose the state of the flame or to optimize the process [1]. However, the 3-D temperature measurement is then crucial for improving the combustion efficiency and controlling the product such as NO_x [2–4]. Besides, to achieve an in-depth understanding of combustion processes, the spatial and temporal measurement of the flame temperature in a combustion system is also necessary and an effective means for the 3-D measurement of flame temperature remains a challenge for combustion engineers and researchers [5,6]. Over the past few years various measurement techniques were developed to reconstruct the temperature distribution of a flame, such as laser based diagnostics techniques [7–10], single camera [11–13] and multi-cameras based diagnostics techniques [5,6,14–16]. For example, Doi et al. [8] reconstructed the 3-D temperature distribution of turbulent flame using multi-directional holographic interferograms. Ma et al. [9] proposed a novel technique to obtain simultaneous tomographic images of flame temperature and species concentration based on hyperspectral absorption spectroscopy. Yang et al. [10] presented the water vapour multiplexed tunable diode-laser absorption spectroscopy (TDLAS) technique to obtain the 3-D flame temperature. However, laser based diagnostics techniques require more complex system and unsuitable for industrial furnaces due to the complex setup, high cost of the system. A single CCD (charge-coupled device) camera or multi-cameras based tomographic techniques [5,6,11–16] are also used for the 3-D temperature measurements. For instance, Huang et al. [11] proposed a method to reconstruct the soot temperature and volume fraction of the flame sections. LSQR (least square QR-factorization algorithm) algorithm and two-color

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[*] Corresponding author.
E-mail address: chuanlongxu@seu.edu.cn (C.-L. Xu).

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technique with a single camera based stereoscopic image system were used. Brisley et al. [13] developed a prototype instrumentation system based on two-color pyrometry and image processing techniques to reconstruct the 3-D flame temperature using a single CCD camera. Those techniques are simple in structure and thus being easy to install on a practical furnace but they can only be used under strict condition such as a high level of rotational symmetry and stable flames. Recently, Hossain et al. [5] developed an optical tomographic algorithm incorporating logical filtered back-projection and simultaneous algebraic reconstruction techniques to reconstruct the grey-level intensities of flame sections using optical imaging fiber bundles and multi-cameras based imaging system. The flame temperature is determined from the reconstructed grey-level intensities based on the two-color principle. Gong et al. [14] proposed a new combination of optical sectioning tomography (OST) and two-color method to reconstruct the 3-D temperature distribution of impinging flames in an opposed multi-burner gasifier. Though a more reliable and accurate 3-D temperature reconstruction of flames can be achieved using the multi-cameras systems compared to single camera systems. But they are in high system cost, complexity in system setup and installation. Besides, Li et al. [16] proposed a radiative imaging model and Tikhonov regularization method to reconstruct the 3-D flame temperature field. However, these techniques (single camera or multi-cameras based techniques) utilized the conventional CCD camera which is unable to distinguish the direction of flame radiance and hence the radiance of flame captured by a conventional camera is limited to two-dimensional (2-D). Whereas the light field camera is capable of recording the direction of each ray with corresponding intensity and 3-D radiance field of the flames through a single exposure [17–20]. And the cone angle of the flame radiance captured by a single pixel of a light field camera is much smaller than that of a conventional camera [21].

In recent years, the application of the light field camera is increasing with the maturing of the manufacturing technique of microlens array [22–28]. To determine the 3-D position of the object, the geometric calibration of the focused light field camera is important. It is also crucial to obtain the intrinsic parameters (such as separation between the main lens and the CCD sensor) of the light field camera for related applications like ray tracing. However, very limited research can be found on the geometric calibration of the focused light field camera, particularly for the 3-D temperature reconstruction of a flame [21,29]. Jeffrey et al. [29] preliminary investigated the 3-D measurement of flames with a light field camera using image refocusing, 3-D deconvolution and tomographic reconstruction techniques. However, feasible methods were not proposed to reconstruct the flame temperature or to calibrate the focused light field camera. Sun et al. [21] also preliminary reconstructed the 3-D temperature distributions of the flame using a single light field camera where the geometric calibration of the focused light field camera was not considered. Usually, the relationship between the 3-D point on calibration board and the image point on the sensor plane for main lens is utilized to calibrate the conventional camera [30–32]. Because the corner points are imaged twice by the main lens and microlenses in the focused light field camera, these methods for conventional camera [30–32] cannot be employed directly to calibrate the focused light field camera. Yunsu et al. [33] developed an efficient geometric calibration method for traditional light field camera (i.e. lytro light field camera) using line features technique. Basically distance between the sensor plane and the microlens array in the lytro light field camera is equal to the focal length of each microlens. Hence the 3-D point on calibration board is not imaged directly on the sensor [33]. It is therefore difficult to extract precise locations of the corner points from raw images captured by the lytro light field camera. To capture the positional information of the light field more densely, the microlenses are focused on the image produced by the main lens in the focused light field camera [34–37]. In the focused light field camera the corner points are imaged on virtual image plane by main lens and then re-imaged on the CCD sensor by the microlenses. The points are thus recognizable on the raw image captured by a focused light field camera while there are no recognizable corner points in the raw image captured by a traditional light field camera. The recognized corner points can then be used for the calibration process. So the line features are not necessary for the geometric calibration of the focused light field camera. The calibration model proposed in [33] is not applicable for the focused light field camera since the CCD sensor deviates from the focal plane of the microlenses. Ole et al. [34] proposed a calibration method for the focused light field camera and the parameters are estimated by minimizing the residual between the projected model points and the measured points of calibration pattern. A sequential quadratic programming (SQP) algorithm was employed to optimize the residual. However, a good initialization of the unknown parameters is required for the accurate optimization, or the algorithm may be converged to local optima. Klaus et al. [35] employed the total focused images to calibrate the focused light field camera. The total focused image is the image which is rendered from the raw image captured by the light field camera and each point in the total focused image is on focus. Generally, a clear total focused image relies on a series of reliable algorithms (e.g., refocusing algorithm). The calibration method described in [35] is then capable of calibrating the focused light field camera with high accuracy. However, the relationship between the virtual image points and their projections for microlenses is not included in their calibration model. The preliminary geometric calibration of the focused light field camera using raw light field images was presented in [37]. But the method was performed very poor and the high reprojection errors was found up to 1.8%. The overall optimization was also not considered in the calibration procedures.

This paper presents a novel geometric calibration method of focused light field camera with overall optimization in the calibration procedures and the evaluation of the 3-D reconstruction of flame temperature. The developed geometric calibration model is solved by incorporating the Levenberg-Marquardt algorithm. To establish the calibrations, the same f-numbers of main lens and microlens are applied. The calibrations of a focused light field camera are performed by using a bespoke calibration board. Results obtained from the calibration are presented and analyzed. Experiments were carried out on a lab-scale ethylene air fired combustion test rig to reconstruct the 3-D temperature distribution of a flame. The results obtained from the experiments are presented and discussed. Flame temperature was also measured by thermocouple and compared with the reconstructed temperature of the flame and their results are described.

2. Methodology

2.1. Proposed geometric calibration model

Fig. 1 illustrates the schematic diagram of radiative imaging model of the flame based on a single focused light field camera. In this model,

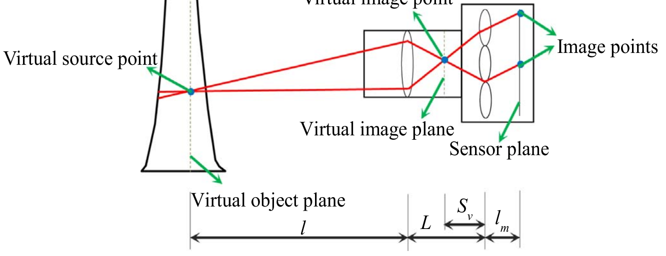

Fig. 1. Schematic diagram of the radiative imaging model of the focused light field camera.