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Close range radiometry for quantifying the spatial distribution of illumination on flat surfaces

Ahmad Mojiri, Cameron Stanley, Gary Rosengarten *

School of Aerospace, Mechanical, and Manufacturing Engineering, RMIT University, Melbourne, VIC 3001, Australia

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Abstract

Measuring the spatial distribution of irradiance on surfaces has extensive applications in various fields of heat transfer such as concentrating solar energy. In this paper, we have introduced a close range radiometry measurement method for flat surfaces employing camera calibration to extract illumination distribution data with high accuracy and resolution. The equations for quantifying the illumination profile on the target using the measured geometrical parameters have been introduced. The method developed in this work was experimentally demonstrated to have an accuracy of ±10% with additional improvement opportunities identified and discussed.

Keywords: Radiometry; Digital image; Flux distribution; Solar; Concentrated

1. Introduction

Measuring the spatial distribution of irradiance is highly desirable in heat transfer engineering. For example, in the field of concentrating solar energy high levels of irradiance are found in photovoltaic, thermal, thermoelectric, thermochemical, and hybrid receivers. Parameters such as collection efficiency and flux uniformity (especially in photovoltaic receivers) play a vital role in maximising the overall performance of such systems (Antón et al., 2003). For this reason, there is a need for accurate methods for measuring the illumination profile. So far, different methods such as radiometric flux mapping and light scanning have been introduced to measure the irradiance. A combination of photogrammetry and ray tracing is also used to predict the illumination profile of concentrators (Lüpfert et al., 2007).

Radiometric flux mapping uses photographic pixelated images to extract the illumination pattern on surfaces. The advantage of this method is that it requires simple hardware and allows the irradiance distribution to be determined in a more straight-forward manner compared to photogrammetry-ray tracing and light scanning techniques. In this method the flux pattern on a diffuse reflector target is photographed using a digital camera. The greyscale value of the image pixels is associated with the irradiance of light impinging upon the corresponding points on the reflector. Rectification to correct for optical and perspective distortions allows the distribution of the irradiance to be mapped from the image to the real world coordinates system and vice versa. However, the accuracy of this method is dependent on proper calibration of the camera setup. A diffuse reflector as the target is necessary to record the illumination data, but a Lambertian diffuse reflector can simplify the data analysis significantly.

Radiometric flux mapping has been developed and tested for long range applications where either the camera

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* Corresponding author. Tel.: +61 3 9925 8020.
E-mail address: gary.rosengarten@rmit.edu.au (G. Rosengarten).

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Nomenclature

α	angle between pupil normal and r (rad)	I	irradiance (W/m^2)
γ	angle between r and R (rad)	M	lens magnification
ϕ	angle between R and pupil surface normal (rad)	n	number of pixels on dS'
ψ	sensor response function	P	proximity factor
ρ	surface reflectivity	PV	pixel grey value
θ	angle between r and object normal (rad)	R	object-camera distance (m)
a	scanned area half width (m)	r	surface element to pupil element distance (m)
A_{EnP}	entrance pupil area (m^2)	R_m	rotation matrix
B	radiance (W/m^2/sr)	s	standard deviation
b	scanned area half height (m)	SE	standard error
C	Lambertianness correction coefficient	t	t-distribution coverage factor
CI	confidence interval	T_m	translation matrix
$d\Omega$	solid angle subtended by dS_{en} (sr)	X, Y, Z	image space coordinates (pixels)
dS	surface element on the object (m^2)	x, y, z	object space coordinates (m)
dS'	image element area (m^2)	x_c, y_c, z_c	camera location vector
dS_{en}	surface element on the entrance pupil (m^2)	x_n, y_n, z_n	camera orientation vector
F	radiant flux (W)	Z	camera-target distance (m)
f	lens focal length (m)		

is far away from the target such as solar power towers or the spot size is small such as dish concentrators. Blackmon (1985) outlined the design and operational characteristics of a long range radiometry system for monitoring the performance of heliostat mirrors. He used a video camera to capture an analogue image which was digitised in a post-processing stage. Johnston (1998) employed a CCD camera and a video recorder to analyse the illumination pattern of a dish concentrator. He used uniform irradiance on a white reflector to calibrate the camera. Antón et al. (2003) used a similar method to characterise the spatial distribution of the illumination at the focal region of dish and parabolic trough concentrators where the spot size was small compared to the camera distance.

Significant research work has been carried out using these methods in the German Aerospace Center (DLR) to study point focusing and linear concentrators (Lüpfert et al., 2004; Schiricke et al., 2009). Ulmer et al. (2002) used a photographic flux mapping method to quantify the illumination profile at the focus of a dish concentrator. Sarwar et al. (2014) used the same method to analyse the performance of a solar simulator. Lee et al. (2014) studied the optical performance of a solar furnace with a spot size of 300 mm by 300 mm from a camera to target distance of about 5 m. Neumann and Groer (1996) employed the photographic method to study the performance of a solar furnace with a spot size of about 100 mm on a diffuse target area of about 500 mm by 500 mm from a distance of 1500 mm. In order to circumvent the excessive heat at high levels of illumination, such as in solar furnaces, Schubnell et al. (1991) used lunar light to illuminate the target and study the illumination profile of a solar furnace.

In these cases, due to the long distance of the camera from the target, the effect of camera objective effects such as the $\cos^4$ law may be negligible depending on the spot size, which simplifies the required calculations and technical challenges. However in some cases, due to spatial constraints or a requirement for higher resolution, close range radiometry measurements are desirable. In this paper, we present a photographic radiometry method to perform close range flux mapping where the spatial size of the illuminated area is in the order of the camera-target distance. This requires accommodation for the effect of lens distortion and a precise method to extract the geometrical configuration of the setup. The lens distortion effects are addressed by the radiometry theory that is explained in the next section. We have reconsidered the required radiometry equations and have applied a camera calibration method to extract the necessary geometrical data for close range radiometry.

2. Radiometry theory

A digital camera sensor, CMOS or CCD type, comprises of a dense array of tiny pixels that convert the radiant energy (J) on each pixel into a digital number in a grey scale image. In case of using an RGB camera, the image should be converted into a grey scale image in order to account for all radiant energy on a pixel over the total spectral band of the sensor sensitivity. The energy received by a pixel is proportional to the product of the radiant flux (W) and the exposure time (s). Since the exposure time for all pixels is almost the same (i.e. we ignore the transient motion of the physical shutter in front of the sensor) we can say that the sensor pixel response is a function of the radiant flux as $PV = \psi(F_{px})$, where, PV is the pixel grey value in a greyscale digital image and F_{px} is the radiant flux (W) on the pixel. By comparing the PV corresponding to