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High dynamic range infrared thermography by pixelwise radiometric self calibration

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ABSTRACT

A procedure is described where the response function of each pixel of an InSb detector is determined by radiometric self-calibration. With the present approach no knowledge of the spectral characteristics of the IR system is required to recover a quantity which is linear with the incident irradiance of the object. The inherent detector non-uniformity is corrected on the basis of self-calibrated scaled irradiance. Compared to the standard two-point non-uniformity correction procedure – performed with the detector signal – only two NUC-tables are required for arbitrary integration times. Images obtained at various exposures are fused to a single high dynamic range image. The procedure is validated with synthetic data and its performance is demonstrated by measurements performed with a high resolution InSb FPA.

1. Introduction

Applying infrared cameras to capture scenes with high radiometric dynamics can be challenging, especially in scientific applications where an accurate quantitative analysis is required. Under-exposure or saturation of the detector limits the dynamics of the resolvable incident irradiance. Since in most cases temperature is the quantity of interest, the spectral integration range also needs to be considered. Cooled InSb detectors for example work in the 3–5 μm range, where the sensitivity of irradiance to temperature is high and so the resolvable temperature span is small.

To overcome this restriction and to be able to capture scenes over a higher dynamic range, images obtained at different exposures are fused to one of high dynamic range (HDR). To the authors' knowledge, the state-of-the-art commercially available technique is based on a radiometric calibration with a blackbody, modelling the spectral characteristics of the emitter, lenses, filters, and detector responsivity. The calibration is performed with different integration times, mapping the respective non-uniformity corrected detector output to the modelled irradiance [1].

Compared to the procedure described earlier, the present approach does not require radiometric modelling. Accounting for differences in response, the individual pixel response functions are determined by pixelwise radiometric self-calibration. On the basis of self-calibrated scaled irradiance a non-uniformity correction (NUC) is performed. This approach has the major advantage that the NUC is valid for arbitrary integration times, giving the user the freedom to optimize the detector output to the current scenery. At the same time, the non-uniformity corrected quantity is linear with incident irradiance and a high dynamic range image can be created by fusing images obtained at different exposures.

2. Infrared thermography

The basic principle of an infrared thermography system is to determine temperatures by measuring the IR radiance emitted from the object. For an ideal blackbody, the spectral radiant emittance W_b can be described by Planck's law:

$$W_b(\lambda, T_{obj}) = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT_{obj}} - 1)} \tag{1}$$

where h is Planck's constant, c, the velocity of light, k, Boltzmann's constant, λ, the wavelength, and T_{obj} is the absolute temperature of the object.

Depending on the spectral emissivity ε_{obj}, the spectral radiant emittance of the object W_{obj} is defined as:

$$W_{obj}(\lambda, T_{obj}) = \varepsilon_{obj}(\lambda) \cdot W_b(\lambda, T_{obj}) \tag{2}$$

The radiation from the object W_{obj} is attenuated by various IR transmitting media, e.g. gas, windows, camera lenses and filters. The incident spectral irradiance from the object onto the detector of the camera E_{obj} is:

$$E_{obj}(\lambda, T_{obj}) \propto \tau_{total}(\lambda) \cdot W_{obj}(\lambda, T_{obj}) \tag{3}$$

where τ_{total} represents all transmissivities in the optical path.

Furthermore, the radiation of the same media and radiation of the surroundings, which is being reflected at the test surface, are superimposed with the radiation of the object. Thus, the total incident spectral irradiance onto the detector E_D is:

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Nomenclature

a	scaling of incident irradiance (–)
c	velocity of light (m s^{-1})
c	polynomial coefficient
E	incident spectral irradiance (W m^{-2} μm^{-1})
h	Planck's constant (J s)
I^*	incident irradiance (spectrally weighted with normalized detector responsivity) (A.U.)
I	scaled incident irradiance (spectrally weighted with normalized detector responsivity) (A.U.)
k	Boltzmann's constant (J K^{-1})
N	polynomial order (–)
P	number of pixels (–)
Q	number of images (–)
r	normalized spectral detector responsivity (–)
r, b, f	temperature calibration parameters
R	ratio of integration times (–)
t	integration time (s)
T	temperature (K)
U	detector signal (A.U.)
W	spectral radiant emittance (W m^{-2} μm^{-1})
x	coordinate (pixel)
z	coordinate (pixel)
ε	emissivity (–)
λ	wavelength (m)
τ	transmissivity (–)

Subscripts

b	blackbody
D	detector
k	kth image
n	nth polynomial coefficient
NUC	non-uniformity corrected
obj	object of interest
offset	offset
p	pth pixel
q	qth image
total	total

Abbreviations

FPA	focal plane array
HDR	high dynamic range
InSb	indium antimonide
IR	infrared
NUC	non-uniformity correction
RMS	root mean square

$$E_D(\lambda) = E_{obj}(\lambda, T_{obj}) + E_{offset}(\lambda) \tag{4}$$

where E_{offset} represents the sum of all superimposed radiation.

A detector which is exposed to the spectral irradiance E_D will produce an output signal U which is dependent on its normalized spectral responsivity r and integration time t:

$$U = g\left\{t \cdot \int_0^\infty r(\lambda) \cdot E_D(\lambda) \cdot d\lambda\right\} = g\{t \cdot I^*\} \tag{5}$$

In the following, the term irradiance is used for I^*, although it is weighted by the normalized spectral detector responsivity. The product $t \cdot I^*$ is called exposure.

The function g is a non-linear function and recovering a quantity proportional to the incident irradiance amounts to finding the inverse function f.

$$t \cdot I^* = f\{U\} \tag{6}$$

$$f = g^{-1} \tag{7}$$

3. Common procedures to correct for non-uniformities

IR focal plane arrays (IR FPA) are known to show differences in the response of the individual pixels. In addition, inhomogeneities introduced by the optics lead to non-uniform illumination of the detector. Fig. 1 shows a characteristic distribution of the raw signal of a high resolution InSb FPA (SC6000, FLIR systems) normalized by its dynamic range (14 bit). Although the optics point at a flat-field source of constant temperature, a strong non-uniformity can be observed.

There are mainly two different techniques to correct for this non-uniformity: calibration-based and scene-based techniques. The calibration-based method which is most common is the two-point NUC [2,3], where a flat-field blackbody is heated to two temperatures and the raw signals of the pixels are corrected by individual gains and offsets to the respective mean values. This approach can be further improved, accounting for the non-linear response of the detector by a piecewise linear approximation, polynomials [3] or analytical functions which approximate the physics of the detector [4]. Alternatively, the integration time can be changed instead of varying the temperature of the source to perform a NUC [5].

Scene-based correction techniques follow a statistical approach on the basis of a sequence of images [6]. The assumption is made that, over a certain period of time, all pixels will be equally exposed to a mean irradiance, presuming that the scene changes over time (either by motion of objects or by movement of the camera). From statistical values, pixel gains and offsets can be derived for a linear correction. Scene-based correction techniques provide a convenient way of compensating for non-uniformities, since they do not require special one-time calibration set-ups. However, they depend on moving objects which is not the case in scientific applications with static scenes.

4. Common procedures to recover high dynamic scenes

4.1. HDR imaging for infrared cameras

IR HDR scenes can be recovered by using detector signals from different integrations times, assuming that the object of interest

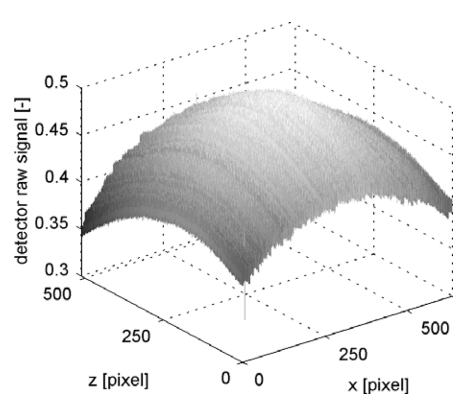

Fig. 1. Detector raw signal of an object at constant temperature of 401 K.