Multispectral Infrared Thermography through Quantitative Image Fusion

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Abstract

In thermography measurements, unknown target emissivity is a critical source of uncertainty. Multispectral methods aim to overcome this problem by measuring the target exitance at different channels having different spectral characteristics, then applying an emissivity model and solving a system of equations to yield the target temperature and the model parameters. Although several accurate temperature and/or emissivity results have been reported, the exact processing techniques and models depend strongly on the characteristics of a particular target. Towards developing a universally applicable multi-spectral thermography technique, the present research focuses on reducing uncertainty of infrared measurements through novel data acquisition and image fusion procedures based on the photoresponse of an IR camera. Preliminary results based on numerical simulations backed by experimental data indicate that the proposed acquisition method inherently eliminates parasitic signals as well as fix-pattern noise, without requiring repeated calibration or corrections for temporal drift. Furthermore, the employed technique improves measurement accuracy by fusing raw digital counts from several integration time images in steady targets of all emissivities and/or large spatial emissivity variations, with no target-specific adjustments. Present efforts are focused on mapping of the intermediate photoquantity into temperature, as well as reduction of error bands in temperature estimations.

1. Introduction

Infrared (IR) radiometry is a nondestructive, noncontact evaluation technique used increasingly in diagnostics and monitoring. Thermal imaging cameras, which can resolve surface details and radiance gradients, are utilized in many applications such as remote sensing, medicine, gas detection, metallurgy, etc. [1-3]. *Multispectral radiation thermometry* (MRT) is a general name for optical measurement and data processing techniques for obtaining temperature based on radiometric measurements performed in several spectral bands. The independent band-intensity datasets are then used alongside an emissivity model to obtain the temperature and apparent emissivity of the target. Thermography based on MRT may allow the acquisition of 2D surface temperature distributions using very weak assumptions on the target's emissivity [4-6].

The signal detected by an IR camera corresponds mostly to the received radiant intensity, which consists of factors including: the target, the atmosphere, the surrounding objects and the optics. As a result of noise and parasitic signals, a target of perfectly homogenous radiative exitance does not induce a uniform response across all pixels. Consequently, distinguishing solely the object's exitance from the aggregate signal is not a trivial task [7]. Very often, scenes contain a collection of different targets, and inevitably, under certain acquisition settings, some radiance values might suffer from low resolution or lie outside the measurement range entirely. The choice of integration time prescribes the detectable radiation range (dynamic range) and its resolution. A detector's dynamic range can be manipulated via the setting of its *integration time* (IT), which acts as "gain". A higher-sensitivity detector is able to measure weaker radiations at an acceptable SNR, but on the other hand, it saturates for a lower radiation. Conversely, at a shorter IT, the dynamic range shifts to higher flux levels – thus allowing to measure previously saturated signals. This is commonly encountered in conventional photography under the name of *high dynamic range* (HDR) imaging, where each final pixel value results from blending (or "fusion") of multiple differently-exposed frames.

For accurate thermography to be possible, the measurement procedure and data interpretation scheme must both be carefully considered. The former relates mostly to the configuration of the measurement system (such as selection of optical filters, integration times, averaging settings etc.), which define the dynamic range, the resolution and the *signal-to-noise ratio* (SNR) of the outcome. The latter relates mostly to post-processing of the measurements, including image processing of flux maps, fusion of data from different measurement conditions (e.g. dynamic ranges or spectral bands), and conversion of apparent flux into brightness temperature via calibration [1]. Some commonly encountered issues include: optical drivetrain re-radiation [8]; image pixel misalignment upon changing filters [9]; and ambiguity in the optical system characteristics [10, 11].

Photo-response nonlinearity is an often-neglected source of error in quantitative measurements [12]. This is a common premise for the well-known *non-uniformity correction* (NUC), where several "reference points" serving as interpolation anchors are obtained by modifying the total exposure of the image [13]. A linear (or a piecewise-linear) relation between the radiant power input and the detector output signal is commonly assumed, and in following, all pixels are brought to a "consensus" via the introduction of per-pixel correction parameters. Thereby, the different response curves of all pixels ideally collapse onto a single function. As reported in a recent paper by the authors, the implicit linearity assumption of detector response (which forms the so-called "reciprocity law") is not satisfactory from a quantitative perspective [14].

2. Methods

2.1. Image fusion

A camera imaging sensor, or focal plane array (FPA), consists of a multitude of light-sensing pixels. It is possible to described each pixel's response function as the sum of several contributors,

$$DL - BF = R \cdot IT^{P(R)}, \tag{1}$$

where DL represents the pixel's raw output signal, R is a quantity that represents the incident radiation (including the object, optics and stray) and BF is the pixel's offset non-uniformity (spatially varying over the FPA) [14]. In (1), the LHS contains only measurable quantities; and the RHS contains the chosen IT, and the unknowns R and P.

Improving the range, resolution, and SNR of the resulting data is possible by increasing the amount of available information to be used for radiation estimates, via acquisition conducted using multiple ITs. The fusion technique employed herein is a parametric fitting of DL values obtained at different IT settings [12], in order to resolve radiation flux and integration-time-nonlinearity of each pixel (R and P in Eq. (1)). The photoquantity R can be estimated by solving a log-linear optimization problem of the form:

$$\log(DL) = \log(R) + P \cdot \log(IT). \tag{2}$$

For a set of ITs $(IT_1, \dots, IT_N)$ and the corresponding DLs $(DL_1, \dots, DL_N)$, the following system of equations is formed:

$$\begin{bmatrix} \log(DL_1) \\ \vdots \\ \log(DL_N) \end{bmatrix} = \begin{bmatrix} 1 & \log(IT_1) \\ \vdots & \vdots \\ 1 & \log(IT_N) \end{bmatrix} \begin{bmatrix} \log(R) \\ P \end{bmatrix}. \tag{3}$$

The solution of such an optimization problem yields the estimates $\hat{R}$ and $\hat{P}$. In this study, the system is solved by a weighted least squares method:

$$\hat{\theta}_{WLS} = (X^T W X)^{-1}\, X^T W y. \tag{4}$$

This formulation allows specifying different weights (W) for measurements via left-multiplication of both sides of Eq. (3) by a diagonal NxN matrix.

2.2. Filter design

The transmittance of narrow bandpass IR filters cannot be considered monochromatic, given the employed detector's spectral sensitivity. The typical half-width of the transmittance curve of manufactured filters varies from about 10 to 200 nm. The choice of filter spectral locations, which reflects the investigated temperature range, is nontrivial. There is an obvious tradeoff inherent to choosing filters: the smoothness assumption of the emissivity model is more accurate the closer the wavelengths are to each other, but at the same time, the difference between the two spectral radiations and, consequently, the sensitivity to temperature, is reduced. Ultimately, the optimal choice of the filters depends on the range of the measured temperatures and the required temperature resolution.

It is often considered that the radiation transmitted by a filter is limited to its pass-band. Indeed, the majority of the radiation is contributed within the filter central lobe, however, it turns out that the blocking regions contribute a non-negligible amount as well. The radiation transmittance in the blocking regions is about 0.2%-0.3%. Yet due to their wide spectral width, their integral transmittance amounts to 5-10% of the total signal. Numerically-simulated system response using published transmittance data for the employed optical elements (filters, detector, lens) showed that ignoring the contribution of the blocking regions introduces a potentially large error into the estimated temperature. Thus, the application of optical elements' spectral transmittance curves, provided by different manufacturers, to the simulation of a whole optical drivetrain is of limited use.

2.3. Black-body calibration

Relating measured signals to physical quantities requires performing of radiometric calibration using well-defined radiations source. This is commonly done using a blackbody radiator whose temperature relates to spectral exitance via the Planck equation:

$$B_\lambda(\lambda, T) = \frac{c_1}{\lambda^5} \frac{1}{\exp(c_2/\lambda T) - 1} \tag{5}$$

where c_1, c_2, T, λ are the 1st and 2nd radiation constants, temperature and wavelength, respectively. However, eq. (5) cannot be used directly, as the detected radiation constitutes but a limited part of the incoming blackbody irradiation. Not only do optical elements have a wavelength-dependent transmittance (associated with the finite spectral width of the filter and the transmission of the lens), and the quantum efficiency of the detector is uneven, but there also exists uncertainty in these optical properties that does not allow accurate evaluation of the integral. Instead, it is possible to describe the photoresponse using approximate interpolation equations, such as the Sakuma-Hattori equations [16, 17] or subsequent models [18]. After comparing several interpolation formulae that mimic Planck's formula (5), a three parameter model was chosen based on minimal fitting errors across a wide range of temperatures and filters. The adjustable parameters a_i take into account the detector response, the spectral transmittance of the optical drivetrain and the form factor in the experiment [9]:

$$R_{BB} \approx \frac{a_0}{exp\left(\frac{a_1}{T} + \frac{a_2}{T^2}\right) - 1} \tag{6}$$

Equation (6) prescribes the changes of R with respect to T. The parameters a_i are found during the fitting process separately for every optical configuration.

2.4. Multispectral thermometry

Combining information from several wavelength bands requires obtaining filter-specific photoquantities, a way to account for emissivity, a conversion method between photoquantities and temperature, and finally, a measure of "confidence" to weight overdetermined measurements.

Assuming that emissivity follows a linear trend (that is, defined by two coefficients: m, n), then for filter k, one gets the following measurement equation (based on (6)):

$$R_k = (m \cdot \lambda_k + n) \cdot \frac{a_0}{exp\left(a_1/T + a_2/T^2\right) - 1}, \quad (7)$$

where a_i are calibrated constants; λ_k is a characteristic wavelength (typically CWL); m and n are unknowns related to the emissivity model; and T is the unknown temperature. Thus, a minimum of 3 measurements at different wavelengths is required for the system to be fully determined.

3. Results

Choosing the right filter combination has a significant impact on the usefulness of MRT. A filter design tool was developed to study tradeoffs related to filter selection, affecting an MRT system's robustness, sensitivity, temperature-range of operation and the validity of assumptions regarding emissivity. Using this tool, the transfer function of various optical configurations was simulated, and potential pitfalls were identified. Although complete target-independent thermometry remains out of reach, the analysis of synthetic radiometric data indicated a significant possibility to obtain useful thermometric results on metals. As part of the future work, these findings shall undergo experimental validation.

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