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Compensating the Size-of-Source Effect: Relationship between the MTF and a Data-Driven Convolution Filter Approach

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Abstract

The size-of-source effect (SSE) describes the dependency of the measured object temperature on the object geometry. Since thermography cameras are radiometrically calibrated with a single calibrator geometry, the calibration uncertainty applies only to objects with the same relative dimensions. In optics, the modulation transfer function (MTF) is used to describe the spatial frequency-dependent response of a system. A data-driven filter exists to compensate the SSE. In this work, the relationship between the MTF and the SSE filter is investigated. Due to the differing results, it is demonstrated that the step response measurement is not sufficient to fully describe the SSE.

1. Introduction

Thermal cameras are established optical measuring devices for the measurement of object surface temperatures. Emissivity, interfering radiation or the thermal instability (drift) of uncooled detectors are often considered as influential factors for the measurement quality. Another, typically neglected problem is the dependence of the measurement output on the object size, the so-called size-of-source effect (SSE). Even for objects considerably above the minimum object size specified by camera manufacturers (often > 2 of a single detector's field of view IFOV, due to Shannon's sampling theorem), the SSE can lead to measurement results significantly outside the manufacturer's specified uncertainty range [1, 2, 3].

According to [3], Fraunhofer diffraction is the main cause for the SSE in the manufacturer specified object size ranges. There, the mathematical representation of the effect is described by the modulation transfer function (MTF) from linear optics. In [1], a data-driven method based on classical image processing methods (convolutional filter) is presented, which reduces the SSE by $\approx 70\,\%$. The main drawbacks for the practical application of the method are the time-consuming data acquisition (requires varying temperatures and aperture sizes), as well as the computationally expensive implementation of the filter. Linking MTF and SSE could be a way to overcome these limitations in the future.

2. Comparison between MTF and SSE Filter

The local distribution matrix of radiance $\boldsymbol{L}_{\mathrm{Out}} \in \mathbb{R}^{m\times n}$ at the output of an optical system depends on the convolution of the input radiance matrix $\boldsymbol{L}_{\mathrm{In}}$ with the discrete point spread function $\boldsymbol{PSF}$ of the optical system:

$$\boldsymbol{L}_{\mathrm{Out}} = \boldsymbol{PSF} * \boldsymbol{L}_{\mathrm{In}} \tag{1}$$

By means of the 2D discrete Fourier transform $\mathcal{F}$ (DFT) the convolution can be replaced by a multiplication:

$$\mathcal{F}\left\{\boldsymbol{L}_{\mathrm{Out}}\right\} = \mathcal{F}\left\{\boldsymbol{PSF}\right\} \cdot \mathcal{F}\left\{\boldsymbol{L}_{\mathrm{In}}\right\} \tag{2}$$

The complex spatial frequency-dependent DFT of the $\boldsymbol{PSF}$ is called optical transfer function $\boldsymbol{OTF}$:

$$\boldsymbol{OTF} := \mathcal{F}\left\{\boldsymbol{PSF}\right\} \tag{3}$$

with the magnitude *modulation transfer function* $\boldsymbol{MTF} = |\boldsymbol{OTF}|$ and the phase *phase transfer function* $\boldsymbol{PTF} = \sphericalangle(\boldsymbol{OTF})$ (which is neglected due to the rotational symmetry of an optical system). The goal is to obtain an undisturbed scene representation from the disturbed image at the output of the optical system (e. g., the actual temperature radiation distribution on the object surface from a blurred, geometry-dependent thermogram):

$$\mathcal{F}\left\{\boldsymbol{L}_{\mathrm{In}}\right\} = \boldsymbol{MTF}^{-1} \cdot \mathcal{F}\left\{\boldsymbol{L}_{\mathrm{Out}}\right\} \tag{4}$$

However, this deconvolution is practically not possible, since the $\boldsymbol{MTF}$ tends to be 0 at the boundaries. The SSE filter of [1] uses data-driven methods and a physically motivated modeling approach. Since the $\boldsymbol{MTF}$ is based on the radiance proportional readings, here also the SSE filter is trained and applied to radiance values rather than temperature readings:

$$\boldsymbol{L}' = \boldsymbol{H} * \boldsymbol{L} + d \tag{5}$$

with the measured radiance of the camera $\boldsymbol{L}$ $(= \boldsymbol{L}_{\mathrm{Out}})$, the filter matrix $\boldsymbol{H}$, the corrected radiance $\boldsymbol{L}'$ $(= \boldsymbol{L}_{\mathrm{In}})$ as well as an affine factor d. It is thus apparent that there is a mathematical similarity between (1–4) and (5) ($\boldsymbol{H} \approx \mathcal{F}^{-1}\left\{\boldsymbol{MTF}^{-1}\right\} = \boldsymbol{PSF}^{-1}$). Since the $\boldsymbol{MTF}$ is mathematically not invertible, the SSE filter and the $\boldsymbol{PSF}$ should be compared experimentally.

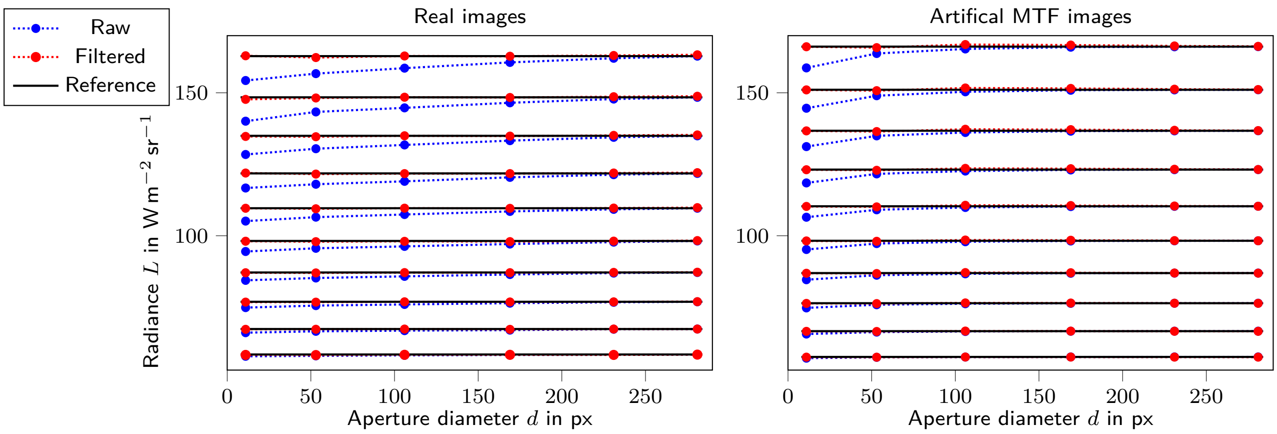

Fig. 1. *Exemplary results at the third measuring distance ($= 182\,\text{mm}$). The graph shows the filtering of real captured images (left) and the filtering of ideal, artificial images, which were convolved with the measured $\boldsymbol{MTF}$ (right). The points are the radiance values at the midpoint of the infrared calibrator over the different aperture diameters and calibrator temperatures.*

3. Experiments

The used camera is an uncooled LWIR camera with a wide-angle lens ($53° \times 28°$) and a detector element array of $382\,\text{px} \times 288\,\text{px}$. By means of an IR calibrator as well as different cardboard apertures, the $\boldsymbol{MTF}$ (according to [4]) as well as the SSE filter parameters (according to [1]) are determined at three different distances $d_{\text{cam}} = [108; 143; 182]\,\text{mm}$. The filter apertures were sized to achieve similar relative calibrator diameters in the image at all three distances. In addition, the $\boldsymbol{PSF}$ of the $\boldsymbol{MTF}$ is applied (convoluted) to perfect artificial images (T_{cal} if calibrator area, T_{amb} else) and these images are then also used as data sets for filtering. The full paper will also show the consequences of an only $\boldsymbol{MTF}$ based filter parameterization.

4. Results

A first, exemplary analysis of the data is shown in Figure 1. It can be seen that the data-driven filter approach can be used to improve both the real images and the images with $\boldsymbol{MTF}$ applied. The mean difference between the reference and the measured values are $\overline{L_{\text{Real raw}}} = -1.82\,\text{W m}^{-2}\,\text{sr}^{-1}$, $\overline{L_{\text{Real filter}}} = -0.04\,\text{W m}^{-2}\,\text{sr}^{-1}$, $\overline{L_{\text{MTF raw}}} = -0.88\,\text{W m}^{-2}\,\text{sr}^{-1}$ and $\overline{L_{\text{MTF filter}}} = 0.06\,\text{W m}^{-2}\,\text{sr}^{-1}$. However, differences between the size-dependent measured temperature curve and the results of the $\boldsymbol{MTF}$ convolution are visible (comparison between blue curves on the right and left) for the middle sized apertures.

5. Conclusion

It is shown that the data-driven SSE filter can approximate the inverse of the PSF by compensating its impact on thermal images. Nevertheless, it is visible that besides the measured spatial frequency-dependent MTF, other effects exist which have an influence on the SSE, since the results of SSE and MTF differ. These could be, for example, errors in the nonlinearity correction (NUC) or internal housing reflections, which do not directly affect an MTF measurement. Accordingly, understanding of and compensating for the influence of these individual phenomena will be important for the SSE reduction.

References

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