Infrared camera NUC and calibration: comparison of advanced methods
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ABSTRACT
Image uniformity and accurate radiometric calibration are key features of state-of-the-art infrared cameras. Over the past years several non-uniformity correction and radiometric calibration techniques have been developed. In this paper we present and compare different techniques: 2-point calibration, CNUC™/multi-point’s calibration and Telops’ Real-Time Image Processing (patent-pending). For each method we assess the performances, the ease of use, the advantages and drawbacks as well as the most important operational limitations considering a broad range of exposure times, ambient and scene temperatures.

Keywords: infrared camera, radiometric calibration, real-time calibration, radiometric temperature, in-band radiance, non-uniformity correction, high-speed camera, thermal imaging

1. INTRODUCTION
The use of infrared (IR) cameras is becoming more widespread as the price of IR technology is decreasing. Infrared imagery enables to meet the requirements of specialized applications that cannot be met by a standard visible camera such as night vision, thermography and non-destructive testing. Another factor helping the dissemination of the IR technology is the ease of use that is featured by new cameras being introduced to the market, enabling non-expert users to easily access high performances without requiring strong experience in neither radiometry nor thermography.

One difficulty with infrared cameras stems from the fact that the semiconductor materials used in the infrared focal plane arrays (FPA) is less mature and much less uniform than the Silicon used in visible range cameras. Spatial non-uniformities in the photo-response of individual pixels can lead to unusable images in their untreated state. Non-uniformity correction (NUC) have been devised to address this limitation and to produce corrected images that provide more valuable and useable information. Modern IR cameras feature built-in hardware and automation to allow NUC to be performed with little user intervention.

High-end and scientific thermal infrared cameras are usually required to produce absolutely calibrated images in units of temperature or radiance, rather than just non-uniformity corrected images. Ideally this calibration correction is performed in real-time and also with as little user intervention as possible.

This paper presents a description of the needs for calibration in any infrared camera acquisition. Following a classification of the aspects governing any calibration method, 2-point, multi-point and Telops “infinite” -point methods are described and analyzed.

2. WHY CALIBRATION

2.1 Needs for calibration

At first the following question has to be asked: why do we require calibration when using infrared cameras? To answer this question it is essential to study further what is inside an infrared camera and to go over the various processes involved to produce the image of an infrared scene.
Each physical process involved in an infrared camera, starting from the infrared radiation emitted from a scene up to a displayed clean image, may leave a signature on the data that has ideally to be removed by calibration. If not removed, each aspect may eventually result in artifacts, distorting the image and providing false estimates of the radiation level incident from the scene. To determine a proper calibration method, one has ideally to know the impact of these processes on the data, in order to sort out their importance and to identify the most important ones. Design of a good calibration approach is governed by this selection of aspects to be corrected.

2.2 What is to be corrected

As stated above, it is important to look at the physical processes involved into the transformation of the received infrared radiation into an image.

Let first start with the optical part where photons coming from the scene are directed towards the FPA. The lens system of the camera transmits part of the energy, while its absorption counterpart results in self-emission at its own temperature. Geometry of the optical system defines the collecting throughput, thus the subtended solid angle and the absorbing area. These are determined by the optical system $f/\#$, the pixel size (defining its area), and the obliquity of the off-axis pixels, the latter resulting in the well-known $\cos^2\theta$ effect.

Part of the incident photons on the FPA are transmitted to the semiconductor material. Most photons are then absorbed and they are converted into photo-electrons, which are next collected and accumulated in wells having a limited capacity during a given integration time. Once the integration is stopped, the Read-Out Integrated Circuit (ROIC), mounted nearby the detecting semiconductor, ensures the charge transfer and the conversion of the resulting photocurrent into a convenient voltage. Proper conditioning of this voltage finally enables the conversion of the detected signal into a digital word by the Analog-to-Digital Converters (ADC).

2.3 Camera parameters governing calibration

From the operator point of view, many operating parameters of an infrared camera impact the observed image.

The first obvious observation on any raw infrared image, particularly when looking at a uniform scene like a blackbody source, is the fact that all pixels show different levels, even under a similar infrared signal. One is thus at first convinced that calibration of an infrared camera must be pixel-wise. However the observed non-uniformities have many distinct causes, meaning that non-uniformities may be efficiently corrected only if their source is well understood. Many operating parameters of the camera changes the way the pixels are related to the infrared flux: the integration time is the most important one, but under some conditions, the frame rate and the selected sub-window changes the raw image. The read-out process as well as the electronics channels carrying the pixel signals may also distort the detected level.

Considering the level of maturity of the semiconductor technology, all FPA exhibit pixels that are very “different” from their neighbors: the so-called bad pixels. These pixels may lack gain; they may have too large offsets; or they may continuously flicker. A good calibration algorithm should include methods to efficiently detect bad pixels.

Finally it is also observed that each optical lens leaves its own signature on the acquired data. Its transmittance is not necessarily uniform, and corner pixels may suffer more than the central ones from lens emission if vignetting is present. The addition of any neutral optical filter (or spectral optical filter) has also strong impact on the detected image. Aside their nominal impact, they are usually sensitive to ambient temperature variations, which may add to the effects to be considered.
3. CALIBRATION METHODS

3.1 Classification of calibration methods

When considering calibration methods, one may identify 3 main categories governing their characteristics. For each category, different possibilities are offered. Any calibration method is based on a selection of a given possibility for each of the following 3 categories.

The first category is related to the number of blackbody acquisitions performed at different temperatures. The selected temperatures should be in the vicinity of the scene radiance temperatures. The possibilities are:

- 1-point calibration, where data is acquired for a single blackbody temperature;
- 2-point calibration, where data is acquired for a pair of blackbody temperatures;
- Multi-point (in fact multi 2-point) calibration, whose extracted data is taken at any pair of consecutive blackbody temperatures;
- Multi-point (continuum) calibration, whose extracted data is interpolated for any blackbody temperatures.

The second category is related to the integration time support.

- Single integration time;
- Multi-integration time (discrete), where a set of preselected integration times are supported;
- Multi-integration time (continuum), whose extracted data is interpolated for any integration time.

The last category sets the calibrated physical quantity. Any calibration method has the choice between 2 very different possibilities:

- Measured blackbody temperature;
- Calculated “in-band” radiance, in units of W/(m\(^2\)· sr).

The latter possibilities have opposite characteristics. While the first is based directly on a temperature measurement, the second relies on a calculated quantity from the same temperature, which requires knowledge of the blackbody emissivity (generally assumed as grey body) and the pixel spectral response (generally assumed uniform over the entire array). Even if the 2 assumptions stated in the last sentence are not exact, the calculation of in-band radiance represents a non-linear transform from the blackbody temperature. While the relation between digital counts and blackbody temperature is intrinsically non-linear, its calculated counterpart exhibits a much more linear relation since it is expected that in-band radiance directly relates to absorbed flux.

In order to give an insight on the variability of the spectral response across the entire array, Figure 1(a) illustrates the spectral response for a few randomly selected pixels. Figure 1(b) shows the extent of the distribution by presenting the percentiles along wavelength.
3.2 Calibration environmental conditions

Any calibration method is affected by the experimental conditions present during the measurements. There are 2 main reasons causing the environment to influence the calibration results: the ambient atmosphere and the infrared radiation emitted by the blackbody surroundings.

The ambient air contains molecules that are active in the infrared region, namely the carbon dioxide (very strong lines in the MW, weak lines in the LW) and water (strong lines on edges of both LW and MW bands). These molecules absorb the incoming blackbody radiation, and emits accordingly at their own temperature. The contribution of the air layers thus depends on its thickness, its temperature and its content.

Practical blackbody sources have obviously non-unitary emissivity. As stated above, the calculation of the in-band radiance may consider the emissivity of the source; however a non-unitary emissivity means a non-zero reflectivity. Since the blackbody surface mostly exhibits diffuse reflection, it means that infrared radiation incoming form all directions facing the surface make the global radiation reflected from the surface. Controlling the amplitude and the spectral content of this contribution may be challenging; it is thus often assumed as a uniform blackbody at laboratory temperature.

3.3 “Local” vs. “Global”

Calibration methods globally fall in either one of 2 groups. Some methods are more “local”, in a sense that they apply to a very limited set of operating parameters (e.g. integration time, scene temperature range, ambient conditions). They often produce excellent results under these restricted conditions, but poor results otherwise. Such calibration data is often called “volatile”, since it has to be acquired again if any change in operating conditions happens. At the opposite “global” methods are designed to provide very good results and to support a much wider range of operating parameters. They thus implicitly involve compromises to support all operating conditions. For example, a global method may deal a decrease in image quality to gain better accuracy, thus exhibiting more uncorrelated spatial “noise”. A global method involves inherently more “permanent” calibration data.
3.4 2-point calibration

This simple method needs 2 blackbody acquisitions (2 distinct temperatures) for a single integration time. Either temperature or in-band radiance may be used as the calibrated quantity. Calibration is done by applying pixel-wise gain and offset, which corresponds to a simple linear interpolation. The main characteristics of this method are given here:

- Simple local method, resulting in excellent image quality;
- Providing quantitative estimates;
- Applicable to low-contrast scenes;
- Valid for a single integration time;
- Valid for a single ambient temperature;
- No compensation for analog data acquisition non-linearity.

Figure 2 illustrates 2-point calibration method using either (a) measured blackbody temperature or (b) calculated in-band radiance. The in-band radiance is here calculated using the manufacturer’s specification about the spectral range covered by the detectors. The blackbody emissivity is here assumed unitary.

Even if the temperature difference between the 2 reference points is rather small (i.e. 10 °C), one can easily see the intrinsic non-linearity of the digital counts to temperature relation, shown in Figure 2(a), and its impact on correction accuracy. Interpolation error may be kept at an acceptable level, by keeping small the difference between the 2 reference temperatures, but extrapolation errors become very large. The non-linearity present in Figure 2(b) is much smaller, making the interpolation error about 10 times smaller.

In order to appreciate the capability of applying a transformation to linearize the digital counts to temperature relation, Figure 3 shows typical variations for randomly selected pixels across the array. Figure 3(b) particularly shows that the different pixels exhibit different curvatures that a single non-linear transformation cannot correct. This is mainly caused by the variations in the spectral response across pixels (as shown in Figure 1) and by non-linearity of the analog channels.

![Figure 2. 2-point calibration of a typical MW camera about room temperature. Reference points are taken at 20 °C and 30 °C. (a) Measured blackbody temperature. (b) Calculated in-band radiance.](image)
Figure 3. 2-point calibration of randomly selected pixels for a MW camera about room temperature. Reference points are taken at 20 °C and 30 °C. (a) Measured blackbody temperature. (b) Calculated in-band radiance.

3.5 Multi-point calibration

This method has the advantage of representing how the pixel digital levels evolve with blackbody temperature, for selected integration times. The method may be called multi-2-point because the very same approach of linear interpolation is used (with the same limitation due to the spacing of the measured blackbody temperatures). However since many blackbody temperatures are characterized, the appropriate pair of temperatures has to be selected in order to apply the matching gain and offset parameters. In order to cover a wider range of blackbody temperatures, a set of integration times is preselected. This method provides good performances if the number of measured blackbody temperatures is sufficiently large, which results in numerous acquisitions to build the calibration dataset.

As for the 2-point method, either temperature or in-band radiance may be used as the calibrated quantity. Similarly, multi-point calibration also involves calculating a NUC with gain and offset, thus using piecewise linear interpolation. The main characteristics of this method are given here:

- Global method;
- Moderate to large complexity;
- Providing quantitative estimates;
- Applicable to contrasted scenes;
- Valid for all preselected integration times;
- Though (non-linear) interpolation may be used to create NUC data for intermediate integration times included in the preselected range;
- Valid for a single ambient temperature;
- Though compensation may be added by taking another dataset at a different ambient temperature (and apply interpolation);
- Partial compensation for analog data acquisition non-linearity;
- Separate pixel-wise NUC and single global radiometric calibration.
Figure 4 shows typical multi-point calibration data for a MW camera over 3 integration times.

Figure 4. Multi-point calibration of a typical MW camera. (a) Measured blackbody temperature. (b) Calculated in-band radiance.

3.6 Telops calibration

Telops innovative calibration has been designed to closely match the camera physics in order to apply correction in the very same reference domain where the effect to be removed is applied [1]. Rather than relying on the observation of the variations of digital counts as a function of blackbody temperature or in-band radiance, it is based on the characterization of fluxes (representing the slope of the digital counts to integration time linear relation). Here follows a short description of the method and its principles.

Figure 5(a) presents the typical variation of the measured digital counts as a function of the exposure time. Ideally, the number of accumulated electrons linearly increases with exposure time. It is observed that the detected electron flux (slope) increases with blackbody temperature, but the intercept is always the same since it relies more on the offset level of the ROIC.

In Figure 5(b), the increase of the slope with measured blackbody temperature is depicted. Strong similarity between curves corresponding to various pixels is first noticed, meaning that they may be represented by an affine transformation based on a representative nominal curve and gain and offset parameters for each pixel. Figure 5(c) finally illustrates the effect of increasing ambient temperature, which simply adds a given flux, independent from the scene.
Figure 5. Telops calibration of a typical MW camera. (a) Change in digital counts as a function of integration time for increasing blackbody temperatures, for a given pixel. (b) Slopes (flux) as a function of blackbody temperature for a few randomly selected pixels. (c) Expected increase in slope (flux) when the ambient temperature is increased.

As with the previous calibration methods, Telops method may be applied to either temperature or in-band radiance. Telops calibration approach fundamentally performs non-linear interpolation for both digital counts and flux domains; domains matching detectors’ physics. It has the important advantage of being an integrated pixel-wise NUC and pixel-wise radiometric calibration. The main characteristics of this method are given here:

- Global method;
- Moderate complexity;
- Provide quantitative estimates;
- Applicable to contrasted scenes;
- Valid for any integration time supported by the FPA;
- Valid for any ambient temperature;
- Full compensation of analog data acquisition non-linearity;
- Permanent calibration.

3.7 Unique capabilities of Telops calibration

Due to its distinctive way of processing the data, Telops calibration presents unique features that are not possible with other calibration schemes.
At first it is important to point out that Telops calibration is a global and permanent, which means that calibration parameters are acquired in factory and that the user no more need to perform demanding blackbody measurements under field conditions to ensure accurate infrared calibration. With Telops Real-Time Processing (RTP) hardware, the infrared camera is ready to provide calibrated images once FPA has cooled down to its operating temperature.

A second important advantage of Telops calibration method is that once a full calibration dataset is determined in factory, the user may easily create a different data set to support a different lens. A very limited number of blackbody acquisitions under controlled conditions are required to perform this task.

The final, and most important, feature enabled by Telops calibration method, is the operation of the infrared camera in Automatic Exposure Control (AEC) mode where the camera autonomously and dynamically adjusts its integration time to the scene radiance level, while always providing uniform and calibrated images in real-time. Figure 6 introduces the temperature accuracy when looking at a 25°C blackbody scene while changing the exposure time.

![Figure 6: Automatic Exposure Control (AEC) example](image)

4. CONCLUSION

Proper calibration of infrared camera data is the key to enable the user to extract valid information from its measurements. Due to the many diverse sources of effects altering the acquired data, it is essential to analyze the strengths and weaknesses of the calibration approaches (removing the impact or leaving artifacts).

Through a classification of infrared camera calibration methods, various approaches are compared in the present paper: 2-point, multi-point, and Telops “infinite”-point. The 2-point method, being characterized by a very limited scope, enables excellent performances related to image quality if the operating conditions are kept constant. Otherwise one must rely on a more global method such as multi-point or Telops method. Multi-point approaches have a much broader coverage, but have still limited operating conditions due to their implicit separate consideration of NUC and radiometry. Telops method relying more on camera physics provide a permanent solution to camera calibration. Factory acquired calibration data ensures the user to get valid measurements under any integration time or ambient temperature. Telops innovative calibration offers simplicity of temperature calibration with radiometric advantages of in-band radiance methods.
REFERENCES