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Time calibration of thermal rolling shutter infrared cameras

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HIGHLIGHTS

- Rolling shutter blur prevents accurate defect detection using microbolometer cameras.
- A time delay compensation method is designed for thermal cameras.
- Inter-frame delays are compensated by properly chosen trigger properties.
- Intra-frame delays are estimated with an accuracy of 16 μs using low cost equipment.

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ABSTRACT

The working principle of nearly all uncooled microbolometer thermal imaging systems is based on the rolling shutter principle. This results in time delays between rows giving rise to distorted and blurred images which are difficult to correlate with, for example instantaneous numerical simulation results for nondestructive evaluation. Until today high-end and high-cost thermal cameras need to be used for instantaneous measurements. Furthermore, quantitative defect evaluation on average conductive materials is difficult to perform as a result of the rolling shutter blur of the uncooled cameras. In this contribution, a time delay compensation method is designed. The developed algorithm is described and a measurement routine is elaborated to measure the inter- and intra-frame delays between two pixels. Finally, an artificial global shutter image sequence is developed using linear interpolation between the original fluctuating frames. We will show that by applying our proposed method, the intra-frame delay can be predicted and compensated with an accuracy of 16 μs. Besides, there is only made use of low-cost equipment to provide a straight-forward methodology which makes it applicable for the further integration of low-cost microbolometers in industry. This means that we have made the application of low-cost microbolometers feasible for instantaneous measurements.

1. Introduction

In the past 20 years, non-destructive research is increasing with the rise of the carbon fabricated composite structures [1]. One of the mostly performed measurement techniques for quantitative detection is an ultrasonic inspection. However, recent research goes further than defect detection and monitoring. Methods are investigated to quantitatively estimate failure size, failure location, and material properties using finite element (FE) model updating [2,3] which results in large and time-consuming complex calculations [4]. Active thermography is a fast surface inspection method which is used extensively for qualitative purposes or initial inspections of high-risk spots for material failure [5,6]. For quantitative purposes, this method poses several difficulties in comparison to other techniques. Some of the difficulties are for example the estimation of the defect size and depth out of a thermal image sequence, the synchronisation and timing of the image sequence and the choice of the most efficient excitation position, amplitude and duration according to the inspected material [3,5,6]. The use of FE model updating can resolve the majority of these problems to make it a fast, reliable, and accurate structural health monitoring and evaluation technique [3]. Thus, it is essential to have a global integration time and a fixed frame rate to compare the results with a numerical analysis. This is only one feasible application area where the described methodology is necessary. All application domains, where accurate timing or an instantaneous frame recording is necessary, can use the described method. In general, low-budget thermal cameras are working according to the rolling

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shutter principle [5,6]. This makes it nearly impossible to use low-budget thermal imaging cameras for FE updating unless we can find a method to resolve both the timing inaccuracy between two frames and within a single frame.

The rolling shutter principle is a broadly described working principle for CMOS sensors [7–9] with well-known deblurring techniques for position estimation of objects and moving imaging techniques [7,8,10]. In most cases in the field of active thermography, the position of the camera and the object remains constant during the measurements, but the microbolometer read-out temperature is related to the history of the sensor which results in a similar rolling shutter blur. The difference with the well-known movement blurring for CMOS sensors is that the blurring is not spatially dependent but time dependent. This results in different absolute time instances captured between the first pixel and the last pixel in one single frame. The timing issue is however extremely important for the comparison of the temperature evolution between the different pixels and the updating routines used in FE updating for spatially distributed measurement points [3]. When using pulsed heat sources, it is important that all compared pixel locations are captured at the same time with a stable time sample rate [5].

The contribution of this work is twofold. Firstly, the described algorithm compensates the time delays for the full frame imaging sequence. In order to achieve this goal, the algorithm makes use of a time delay estimation for each pixel. The measurement technique applied in this contribution makes use of a threshold value which is statistically evaluated using the 29/29 method [11] for finding an accurate delayed flash signal on an aluminium plate with high thermal conductivity. Secondly, the algorithm redefines an equidistantly time-sampled imaging sequence using a linear interpolation between two consecutive frames.

2. Materials & methods

Initially, this section describes briefly the working principle of the microbolometer camera and the rolling shutter principle. We proceed with the explanation of the fluctuating delay between two consecutive frames and a description of the used measurement set-up and method. Afterwards, this section will continue with the delay between two pixels in the same frame separated in row dependent delays and delays from the transition between two successive rows. This section will end with a subsection discussing the developed algorithms.

2.1. Working principle microbolometer & the rolling shutter principle

Microbolometer sensors convert the absorbed electromagnetic radiation into thermal energy causing a rise of the detector temperature which is converted into an electric signal using the thermally dependent resistivity of the microbolometers. Thereby it is important that the measured signal is dependent on the short history of the microbolometer pixel. For a square-wave pulse of radiation, the change in detector temperature δT exhibits an exponential response with a time constant τ for each pixel of 7–10 ms for a-Si sensors [6,12]. This time constant is equal for each pixel of the sensor as the irradiation of the sensor occurs globally. This delivers a fixed delay for each pixel and provides a static delay between the process and the measurement of that process: $T_{view}(t) = T_{object}(t - \tau)$.

The read-out of this microbolometer array is done sequentially pixel by pixel, row by row similar to the read-out of CMOS sensors [13]. The sequential read-out delivers a time delay κ_i between two consecutive pixels in the same row and an additional delay κ_j between the last pixel of row $j-1$ and the first pixel of row j. These delays cause an increasing time shift between the pixels from the top left to the bottom right of the image. The time shift for the read-out of a 640×480 resolution camera results in a delay between the registration of the excitation pulse for the first and last pixel of 42.2 ms which is significantly more than 4 times time constant τ. This will be further explained in Sections 2.4 and 2.5 but is not related to the frame rate of the camera. This means that fast changing thermal scenes as thermal pulses on high conductive materials are read out more than two frames in advance on the last pixel than on the first pixel as the absolute time measured in the last pixel is delayed with respect to the first pixel. This will result in stable offsets for the bottom region of the image by updating of numerical simulations with experimental results. The maximum temperature rise in the bottom area of the inspected surface on the numerical model will be compared with values which are measured 42.2 ms subsequent due to the intra-frame delay. For high conductive materials, these values are already cooling down, which results in a stable temperature offset and which limits the achievable convergence of the numerical updating.

2.2. Inter-frame distortion

The rolling shutter camera has a fixed image capturing frequency, the free running frequency f_{fr} on which it operates for its full field spatial resolution when triggering is not used. This frequency is in state-of-the-art camera systems around 50 Hz, which results in a time step around 20 ms. For the Xenics Gobi640-gige camera used in this work the free running frequency with standard deviation is $50.5820\ \text{Hz} \pm 0.0005$ Hz as measured from the output trigger channel. This frequency depends on the internal temperature of the camera. For active thermography measurements of low conductive materials, the frequency on which the images are captured can be reduced and controlled using the triggered mode instead of the free running mode.

Inter-frame distortions are defined as the error between the measured temperature and the instant real temperature due to the time offset resulting from the inter-frame delay. Two essential conditions are important to eliminate inter-frame distortions. First, f_{fr} is stable or has a tractable shifting as which is fulfilled for the Xenics camera after achieving regime temperature. Second, the used frame rate controlled by a trigger signal is an exact divisor of f_{fr}. If one or both conditions are not met, an inter-frame delay occurs with an accuracy bandwidth, within which the frame is captured, with the size of the time step of f_{fr}, in this case, 19.77 ms. This is also represented in Fig. 1. At 15 Hz, the first following free running frame will be captured. This results in an inter-frame delay of $1/f_{fr}$. For the second condition, namely the triggered mode, two different solutions exist. First, almost all cameras provide the option to remain running at the optimal free running frequency. This has the disadvantage that the chosen frequency of the trigger signal, further called the trigger frequency (f_{trig}), should be a denominator of f_{fr} as shown in Fig. 1. In general cases, this is the best method for low triggered frequencies.

For triggered frequencies above 10 Hz it is acceptable to use a truly triggered mode (custom trigger) where the camera only starts capturing a frame after a trigger signal with a certain delay is received. The drawback of this method is that the absolute temperature accuracy decreases as the microbolometer sensor cools down more than what he have been calibrated for, between two read-outs. This results in a practical use of custom trigger only for frequencies close to the free running frequency or for relative measurements where the absolute temperature is not important.

2.3. Measurement method

To measure the inter-frame distortion between two consecutive frames and intra-frame distortions within one frame, we