This item is the archived peer-reviewed author-version of:

Time calibration of thermal rolling shutter infrared cameras

Reference:

Peeters Jeroen, Louarroudi Ebrahim, De Greef Daniël, Vanlanduit Steve, Dirckx Joris, Steenackers Gunther.- Time calibration of thermal rolling shutter infrared cameras

Infrared physics and technology - ISSN 1350-4495 - 80(2017), p. 145-152

Full text (Publisher's DOI): <https://doi.org/10.1016/J.INFRARED.2016.12.001>

To cite this reference: <https://hdl.handle.net/10067/1385880151162165141>

Time calibration of thermal rolling shutter infrared cameras

J. Peeters^{a,*}, E. Louarroudi^a, D. De Greef^b, S. Vanlanduit^{a,c}, J.J.J. Dirckx^b, G. Steenackers^{a,c}

^a*University of Antwerp, Op3Mech, Groenenborgerlaan 171, B-2020 Antwerp, Belgium. Tel.: +32-3-2051938*

^b*University of Antwerp, Laboratory of Biomedical Physics, Groenenborgerlaan 171, B-2020 Antwerp, Belgium.*

^c*Vrije Universiteit Brussel, Acoustics & Vibration Research Group, Pleinlaan 2, B-1050, Brussels, Belgium.*

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 $16\mu\text{sec}$. 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.

Keywords: thermography, rolling shutter correction, finite element updating, microbolometer camera, time distortion, error quantification

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

*Ing. Jeroen Peeters

Email address: jeroen.peeters2@uantwerpen.be (J. Peeters)

URL: www.op3mech.be (J. Peeters)

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 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, 8, 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 640x480 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 $50.5820 \text{ Hz} \pm 0.0005 \text{ Hz}$ 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 Figure 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 Figure 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 readouts. 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.

Figure 1: Representation of the theoretical frame triggering for free running (50 Hz), an integer subdivision (10 Hz) and a rational subdivision (15 Hz).

2.3. Measurement method

To measure the inter-frame distortion between two consecutive frames and intra-frame distortions within one frame, we developed a measurement set-up consisting of the following components:

- A thermal front in the long infrared spectrum assumed to produce homogeneous flashes at a synchronised rate with the frequency on which the images are captured: f_{fr} or f_{trig} .
- A repetitive flashing flash lamp with a focused heat spot on the aluminium plate. The amplitude of the heat flash should remain low to ensure that the test sample cools down sufficiently fast.
- A thin aluminium plate which is dimensioned to fill the full field of view of the microbolometer camera and has a black acrylic coating to absorb the heat flash.
- A Xenics gobi640 gig-e camera with a Noise Equivalent Temperature Difference (NETD) of 50 mK and a resolution of 640x480 pixels.

A representation of the used measurement set-up is shown in Figure 2.

Figure 2: In this figure the experimental set-up is shown.

The heat source delivers a continuously repeated fast disappearing illumination on the aluminium plate with a frequency which is a common denominator of the frame rate. A convex glass lens is used to filter the IR spectrum out of the signal and focus the remaining energy on the aluminium plate. The plate is mainly excited with the visible and UV energy

emitted by the flash lamp. It is the energy of this spectrum which is used to heat the aluminium test sample. The test sample emits in the IR spectrum due to the absorbed energy. A photodiode is used to measure the visible and UV peak value of the pulse signal. If the signal is periodic, there could only be a fixed offset between the time registration of the photodiode and the microbolometers due to the thermal inertia of the aluminium plate. As the delay will remain the same for each pulse and for each pixel, this produces no additional uncertainty in the measurements. The periodicity of the pulses is investigated in the frequency domain. And as shown in Figure 3, the energy peaks have a signal of more than 40dB above the noise level and the inclination of the peak values are steep.

Figure 3: The Fourier transformed pulse signal shows the accuracy of the used excitation source.

The pulse length of 35 ms is chosen to illuminate at least for the duration of one frame. Due to the working principle of the flash lamp, this results in an exponentially rising temperature monitoring by the thermal camera as long as the flash lamp is exciting. Due to the homogeneous illumination of the aluminium plate in the field of view of the camera, we can define that each microbolometer pixel receives the same exponential signal instantly. By delaying the triggering of the heat source we can synchronise the appearance of the heat spot with the frame rate of the camera as the camera readout has a fixed delay between its trigger and the readout. By accurately measuring the delay of the peak of the exponential peak value between the first pixel and the regular flashing heat source, using the delay between the flash trigger and the camera output trigger, we are able to measure the inter-frame delay by searching the frame of each pixel where the maximal illumination occurs using the well-known triggered frequency of the camera. This method is used to verify the frequency of the trigger output on which is read out. Both trigger modes provide similar results.

For measuring the intra-frame distortions we use a cycle of $N = 10$ heat pulses. Between each heat pulse, the material has more than 5τ cooling time to avoid cumulative heat effects. From these 10 periods, a single period of the model is constructed with an improved SNR, which filters the noise out of the system using the standard uncertainty of the synchronized measurements according to Eq.1 with N the amount of periods and $x(t)^{[i]}$ the specific period of the heat pulse cycle which is the investigated signal. The delay between the heat source triggering and the camera triggering is handled using synchronised function generators with a relative delay accuracy of 1 ps, which is more than sufficient for this application.

$$Noise(t) = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^N \left(x(t)^{[i]} - \bar{x}(t) \right)^2}, \quad \text{where } \bar{x}(t) = \frac{1}{N} \sum_{i=1}^N x(t)^{[i]} \quad (1)$$

2.4. Intra-frame Distortion

We now focus on the scenario where the camera monitors a thermal scene. The scene commence with a thermal stable steady state situation that is subject to a thermal distortion from a heat pulse and should be monitored as is often the case in active pulse thermography measurements.

Without additional post-processing, the four corners and the centre of the thermal image as defined in Eq. (2) provide a qualitative representation of the delays as shown in Figure 4 by the shift of the peak values over the image. The peak is registered earlier for pixels in the bottom of the frame as for pixels at the first rows. The Y-axis of Figures 4 and 5 show the relative temperature difference for each pixel where the spatial map on the first frame, before the thermal pulse, is used as reference temperature.

$$M = \begin{bmatrix} p1 & - & - & - & p2 \\ | & \diagdown & & \diagup & \\ | & & p3 & & \\ | & \diagup & & \diagdown & \\ p4 & - & - & - & p5 \end{bmatrix} \quad (2)$$

Theoretically, three considered pixels should be sufficient to measure the delay plane and differentiate the noise and the noise-free signal model. However, since the signal magnitude is only twice the noise level all pixels are used to increase the signal-to-noise ratio (SNR). The SNR of the noise reduced modelled period is increased by factor $\sqrt{N}$, as shown in Figure 5. It is noticeable that the SNR is strongly increased for each pixel using the single model based on the ten-period measurement cycles. This results in a sufficient SNR for quantitative determination of the pulse peak timing for each pixel.

Since the sensor is read out row after row it results in an intra-frame delay between two consecutive rows. This delay is calculated for different frame rates starting from a modelled period for each different frame rate for 10 measurement periods. For each pixel, the peak of the thermal pulse is searched on sub-pixel level and is averaged for each line to calculate a continuous variation between two consecutive frames. Sub-pixel level means that due to

Figure 4: A qualitative representation of the intra-frame delay with the shift of the pulse peak.

Figure 5: A modelled period with the filtered noise level for the custom triggered measurements at 50 Hz.

Table 1: Calculated row delays at different frame rate frequencies for different trigger modes.

Trigger mode	Frame rate [Hz]	Pulse freq [Hz]	Row delay [μsec]
Free running synced	50.5820	0.202328	66.225
Optim Trigger	50.0	0.200	80.3
Custom Trigger	50.0	0.200	80.6
Optim Trigger	40.0	0.200	90.6
Custom Trigger	40.0	0.200	80.4
Optim Trigger	30.0	0.200	107
Custom Trigger	30.0	0.200	110
Mean $\pm$ std			87.9 ± 15.8

a polynomial fit of the measured temperature evolution during the pulse, the real peak value is estimated between two frames, which improves the accuracy. This methodology is a time-derivated version of the computer vision sub-pixel technique [14]. Afterwards, the row on which the mean of the frame number where the peak occurs is traced. All previous plus current row is the highest possible number of rows which can be read out with respect to the particular frame rate. By that, the time necessary for the number of rows can be calculated. After performing the calculation for different frame rates the delay for each row can be predicted with a certain probability. As shown in Table 1, the 'optimal' triggered measurements are performed with the camera running on his free running frequency (50.5820 Hz) and sending the first frame after the trigger signal is received. The 'custom' triggered measurements are performed with the camera running on the triggered frequency and frame capturing starts 343 ns after the trigger signal has been received [15]. In Table 1 all measured intra-frame delays are shown and the mean intra-frame delay is calculated with its standard uncertainty. From those results can be seen that the average delay for the specific Xenics Gobi camera is around $87.9 \mu sec$ with an estimation accuracy of $15.8 \mu sec$.

2.5. Time-distortion Correction Algorithm and instant frame estimation

An algorithm for the distortion due to spatial motion of CMOS rolling shutter cameras with scanline integration is presented in [7] which resolves a similar problem. In this contribution, an algorithm is designed for thermal decaying non-moving scenarios for focal plane arrays where each line is sequentially processed. In the following, $s_1 = (s_{1,x}, s_{1,y})$ denotes the coordinates of a pixel in the distorted image, and $p_1 = (p_{1,x}, p_{1,y})$ denotes the coordinates of a pixel in the normal image. $T(t)$ is the temperature in $[\text{°C}]$ at time instant t , $\eta(t)$ is the inter-frame dependent distortion and $s_{.,T}$ is the line dependent intra-frame delay. The distortion in one frame is described by Eq.(3) to (5) where i is the column index, κ_i the time delay between two consecutive pixels in one row, j is the row index and κ_j the time delay between the last pixel of the previous line and the first pixel of the calculated line.

$$p_2 = p_1 + s_2 - s_1 + T(s_{2,T} + d \cdot \eta(t)) - T(s_{1,T}), \text{ with } \begin{cases} d = 0 & \text{if pixels in one frame} \\ d = 1 & \text{if pixels not in one frame} \end{cases} \quad (3)$$

With:

$$s_{1,T} = \kappa_i \cdot (s_{1,x} + (s_{1,y} - 1) \cdot i) + s_{1,y} \cdot \kappa_j \quad (4)$$

And:

$$s_{2,T} = \kappa_i \cdot (s_{2,x} + (s_{2,y} - 1) \cdot i) + s_{2,y} \cdot \kappa_j \quad (5)$$

This results in a two parameter formula (κ_i and κ_j). Special cases are $\kappa_i = 0$ and $\kappa_j = 0$. If $\kappa_i = 0$ this represents a line scanning camera or linewise reading FPA camera as used in this contribution. If also $\kappa_j = 0$ this represents a global integrating camera with no rolling shutter effect. This clearly indicates that if we can measure the $\eta(t)$ parameter for the inter-frame distortion and the κ parameter of the intra-frame distortion, we can determine the time instant for each pixel.

The time-distortion correction algorithm as shown in Figure 6, from which a result is shown in Figure 8:

1. Determine the intra-frame distortions κ_i and κ_j as solving the set of equations Eq.(3-5) for the delay between two consecutive measurement points as explained in the previous section.
2. From the intra-frame distortion coefficients we obtain the delay array for the full image which will be used as input for the inter-frame distortion calculation.
 - (a) We first search the centre of the heated spot in the image sequence and set the threshold for the 29/29 method to $5 \cdot \tau$.
 - (b) The inter-frame delay can be determined by calculating the difference between the heat pulse frame rate and the triggered camera frame rate.

The calculated values of the intra-frame and inter-frame delays are used to build an artificial image sequence with instantaneous frame estimation of $n - 1$ frames with a stable frame rate. Thus, the intra-frame distortion coefficients are used to linear interpolate the

Figure 6: Flowchart of the developed methodology with above the main chart and below the subchart to calculate the intra-frame distortions.

(a) Original data: the points in the right bottom corner are already cooled down further at the registration time. (b) Corrected data: the temperature is more homogeneous distributed.

Figure 7: Comparison of the surfaces of the Aluminium plate during cooling down after flash excitation.

values starting from the second frame of the original image sequence. The inter-frame distortion coefficient is used to define the offset between two consecutive frames. The algorithm is validated with artificially defined inter-frame and intra-frame distortions with a time measurement noise of 5 nanoseconds on the input data and with the measurement data shown in previous sections. A flowchart of the algorithm to calculate a time rectified image, so without inter-frame distortions is shown in Figure 6 for better understanding. The results are shown in Figure 7 for the cooling profile of the Aluminium plate after the homogeneous pulse as described in section 2.3. In Figure 7a can be seen that the corner at the bottom right is already significantly cooler than the top left which is the result of the delay in image capturing due to the rolling shutter principle. By comparing Figure 7a and Figure 7b it is shown that after the correction the temperature distribution over the plate cools down more homogeneously than before the correction. The qualitative results are shown in Figure 8, which can be compared with the results before rectification in Figure 4. For the measurements of the acrylic coated aluminium plate the temperature difference between the measured pixel value and the actual estimated temperature of instantaneous measurements is 120.94 mK which is more than 2 times the noise level and delivers a significant difference for accurate measurements. The corrected time distortion is 42.2 ms for the full image. A representation of the time shifted temperature data is shown in Figure 9. By comparing the steep thermal signal used with pulsed thermography as shown in Figure 5 with the time distortion of 42.2 ms it can clearly be seen that it is not possible to perform accurate pulsed thermography measurements on high conductive materials using microbolometer cameras based on the thermal rolling shutter principle due to the intra-frame distortion. The time rectification of the image sequence opens new perspectives for time accurate measurements with microbolometers.

Figure 8: A qualitative representation of the corrected intra-frame delay without the shift of the pulse peak.

Figure 9: Temporal delay and temperature distortions plotted for a frame of the pulsed thermography measurement at 50 Hz.

3. Conclusions

In this manuscript, the working principle of the rolling shutter of microbolometers is initially described. It is also described how to perform time-critical measurements with different constraints. Next, the inter-frame and intra-frame delays were described and quantified. It is clearly demonstrated that the choice of the used frame rate and trigger mode are essential to perform stable measurements. Subsequently, the intra-frame delays are theoretically explained and proven by experimental measurements using pulsed thermography. This results in a time-distortion correction algorithm to calculate instant frame estimations from microbolometer measurements and ultimately compensate for the corresponding time delay for each pixel. As a consequence, it will be possible to use microbolometer cameras for more time critical triggered measurements in future measurement campaigns.

Acknowledgements

This research has been funded by the University of Antwerp and the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) by the support to the TETRA project 'Smart data clouds' with project number 140336. Furthermore, the research leading to these results has received funding from Industrial Research Fund FWO Krediet aan navorsers 1.5.240.13N and funding for a research stay: V401016N. The authors also acknowledge the Flemish government (GOA-Optimech) and the research councils of the Vrije Universiteit Brussel (OZR) and University of Antwerp (fti-OZC) for their funding.

Bibliography

- [1] M. Rao, Review of nondestructive evaluation techniques for FRP composite structural components, Ph.D. thesis, College of Engineering and Mineral Resources at West Virginia University (2007).

- [2] T. Marwala, Finite-element-model Updating Using Computational Intelligence Techniques, 2010.
- [3] J. Peeters, G. Arroud, B. Ribbens, J. Dirckx, G. Steenackers, Updating a finite element model to the real experimental setup by thermographic measurements and adaptive regression optimization, Mechanical Systems and Signal Processing 64-65 (2015) 428–440. doi:10.1016/j.ymssp.2015.04.010.
- [4] V. Vavilov, Thermal NDT Historical milestones , state -of-the-art and trends, 2014, p. 1.
- [5] X. Maldague, Theory and practice of infrared thermography for nondestructive testing, Wiley, Quebec, 2001.
- [6] M. Vollmer, K. Möllmann, Infrared thermal imaging: fundamentals, research and applications, 2010.
- [7] C. K. Liang, L. W. Chang, H. H. Chen, Analysis and compensation of rolling shutter effect, IEEE Transactions on Image Processing 17 (8) (2008) 1323–1330. doi:10.1109/TIP.2008.925384.
- [8] L. Oth, P. Furgale, L. Kneip, R. Siegwart, Rolling shutter camera calibration, Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (2013) 1360–1367doi:10.1109/CVPR.2013.179.
- [9] M. Li, B. H. Kim, A. I. Mourikis, Real-time motion tracking on a cellphone using inertial sensing and a rolling-shutter camera, Proceedings - IEEE International Conference on Robotics and Automation (2013) 4712–4719doi:10.1109/ICRA.2013.6631248.
- [10] P. E. Forssén, E. Ringaby, Rectifying rolling shutter video from hand-held devices, Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (2010) 507–514doi:10.1109/CVPR.2010.5540173.
- [11] E. R. Generazio, Binomial Test Method for Determining Probability of Detection Capability for Fracture Critical Applications, Tech. Rep. September (2011).
- [12] D. Uwaerts, Xenics Gobi 384 1471 user manual (2010).
- [13] R. K. Bhan, R. S. Saxena, C. R. Jalwania, S. K. Lomash, Uncooled infrared microbolometer arrays and their characterisation techniques, Defence Science Journal 59 (6) (2009) 580–589.
- [14] K. Ikeuchi, Computer Vision: A Reference Guide, Springer Publishing Company, Incorporated, 2014.
- [15] JDS, CDU, User Manual Gobi-640-17m GigE / CL / CXP Camera and Gobi-384-25m GigE / CL Camera (2014).