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Real Time Non-uniformity Correction Algorithm and Implementation in Reconfigurable Architecture for Infra-red Imaging Systems

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ABSTRACT

In modern electro-optical systems, infra-red (IR) imaging system is an essential sensor used for day and night surveillance. In recent years, advancements in IR sensor technology resulted the detectors having smaller pitch, better thermal sensitivity with large format like 640×512, 1024×768 and 1280×1024. Large format IR detectors enables realisation of high resolution compact thermal imager having wide field-of view coverage. However, the performance of these infrared imaging systems gets limited by non uniformity produced by sensing element, which is temporal in nature and present in spatial domain. This non uniformity results the fixed pattern noise, which arises due to variation in gain and offset components of the each pixel of the sensor even when exposed to a uniform scene. This fixed pattern noise limits the temperature resolution capability of the IR imaging system thereby causing the degradation in system performance. Therefore, it is necessary to correct the non-uniformities in real time. In this paper, non uniformity correction algorithm and its implementation in reconfigurable architectures have been presented and results on real time data have been described.

Keywords: Thermal imaging; Infra-red; Fixed pattern noise; Non uniformity; FPGA

1. INTRODUCTION

Present day electro-optical systems comprises of infra-red imaging systems which are primarily used for both day and night surveillance and have wide applications in military, remote data sensing, coastal surveillance, medical, fire and detection of mines. These infra-red imaging systems are designed based upon 2-D array of IR detectors[1-3]. Advancement in IR detector technology has resulted in the realisation of large detector formats such as 640×512, 1024×768 etc. which are having narrower pitch and improved noise equivalent temperature difference (NETD) or thermal sensitivity. There are several factors which contribute in the performance of a Thermal Imager. They can be enumerated as blurred image due to improper selection of lens diameter, detector's inherent unequal response to incoming photons, improper sampling of scene information due to Nyquist criterion, image distortion due to shot, thermal and photon noise. However, most prominent problem is due to random variations in the detector response to incoming photon flux in an IR detector. Since there are large individual detector elements in the detector matrix and they provide different output to uniform scene irradiance, which results non-uniformities in the image[4]. The random variations in between individual detector elements lead to degradation in detector response viz. low frequency noise (1/f noise), nonlinear detector output via readout circuit, and the variation in FPA responsivity. This non uniformity varies nonlinearly with time and cannot be estimated accurately. This causes a variable pattern superimposed on the scene information known as fixed pattern noise (FPN) which resulting in degradation of thermal resolving capability of the infra-red sensor. A suitable mechanism by mitigating this FPN through non uniformity correction (NUC) algorithms is required for better target detection. NUC algorithms assume a linear model for the Infrared detector, thus the objective of NUC is to find responsivity and offset.

2. BASIC OPERATION OF NON UNIFORMITY CORRECTION

A substantial change in the responsivity (gain) and offset (dark current) in each individual detector elements when exposed to a uniform scene causes non-uniformities in the image. The amount of gain and offset variations depend on:

(i) The photosensitive part of the infrared focal plane array and
(ii) Fabrication inaccuracies of focal plane array.

It can be readily understood that no two detector elements of the infra-red imaging system can have same output for same input. They show some output even when there is no input available. So, it is known as offset. Gain or responsivity is the ratio of detector output for given scene irradiance and it is not linear. So, gain and offset vary with time and also different for individual detector elements. This gain and offset correction has to be done in real time as enumerated in Fig. 1.

The photo response of each individual detector element

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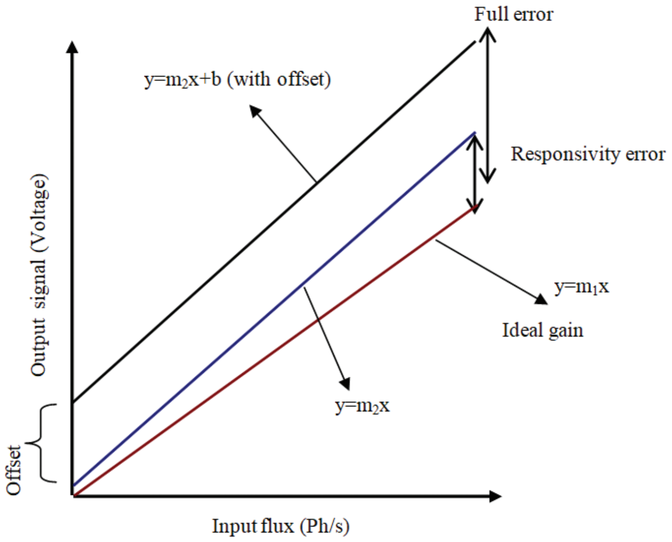


Figure 1. Fixed pattern noise errors.

can be plotted as a line in this curve. In the Fig. 1, the slope of this line represents gain of individual detector elements. If it is 1, then this is ideal case and non uniformity gain correction need not be applied. But if it is more or less than 1, then the gain correction should be applied by multiplying (1/gain) with incoming sensor data. The y-axis value at origin for each line corresponding to individual detector elements gives the offset. In order to do offset correction, this value should be added or subtracted from corresponding sensor data. Hence, non uniformity correction includes both gain and offset correction.

Several techniques are reported in the literature to correct the image through NUC techniques. These techniques can be broadly classified into: (i) Blackbody calibration method based[4,5] (ii) Scene information based[6,7,8].

2.1 Calibration-based non uniformity Correction Techniques

To correct for non uniformities, simplest and most accurate methods is calibration-based method. Single point correction (SPC), two point correction (TPC) and multiple point correction (MPC) methods are common method which fall under calibration based techniques. Parameters like gain and the offset are estimated by exposing FPA to a uniform IR radiation source at one or more temperatures.

In staring IR focal plane arrays, each detector will have different gain and offset coefficient and this variation produces fixed pattern noise. Fig. 2 shows signal output of each detector elements plotted as separate lines for the incident photon flux before NUC. These lines have different offsets and slopes which collectively cause non uniformity in image. Fig. 3 shows the output signal at two points T_1 and T_2 after NUC. All the detector elements tend to overlap after NUC and their offsets are nullified. There is still some residual FPN that remains at operating temperature T.

Calibration method based techniques employ a blackbody based test setup in laboratory environment to correct the non uniformities. It is off line process and easy to implement in hardware.

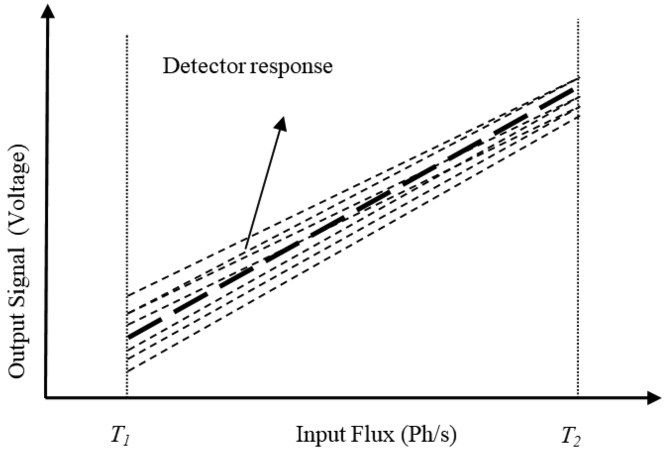


Figure 2. Output signal before NUC.

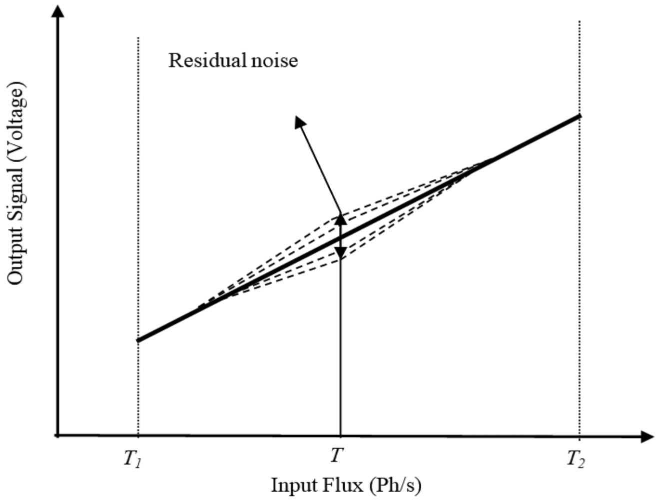


Figure 3. Output signal after NUC.

2.2 Scene based non uniformity Correction Techniques

The scene-based non uniformities compensation uses different image processing algorithms by exploiting change in the actual scene related features or the motion in order to compute coefficients of scene temperature per detector. The true image from the fixed-pattern noise-affected scene is generated by compensating these scene based coefficients. In scene based method, scene parameter mean and variance of the pixels do not vary from one frame to another. It corrects both additive and multiplicative types of fixed pattern noise. Also, the scene based NUC techniques estimate the global translation between several adjacent frames and computes the errors by various methods such as multi frame registration and neural network techniques. Neural network based methods adopt spatial filters and sparse representation theory[9]. These algorithms are difficult to implement in real time and they do not provide the required radiometric accuracy. Since, the scene-based NUC algorithms normally use motion as one of the criteria for separating the true image from the FPN, hence these algorithms usually leave artifacts in the image due to presence of non moving objects, which are required to be corrected algorithmically. However, scene based techniques employ some robust algorithm to correct the non uniformities in real time.

Since infrared imaging systems are used in target acquisition, engagement and missile guidance, therefore, real-time performance is mandatory. The scene based NUC methods are computationally complex and real-time performance is difficult to achieve in defined constrains e.g. size and power consumption. Computational complexity of calibration based methods is moderate in nature. The polynomial based NUC algorithm[10] can be implemented in FPGA, with near real-time performance. Two point calibration method having coverage of operating range from - 20 °C to + 55 °C have been analysed and suitable implementation on reconfigurable architecture for real-time performance has been presented in subsequent sections.

3. MATHEMATICAL MODEL OF BLACKBODY BASED CALIBRATION TECHNIQUE

A mathematical model of Blackbody based calibration technique[11] is developed and presented in this section.

A two-point (two different temperature/ integration time) NUC technique[12,13] corrects each individual detector element (incoming raw data) by multiplying it by corresponding gain value and adding it by the corresponding offset value. Let the output signal be represented as O_{xy} for $(x,y)^{th}$ individual detector at time t:

$$O_{xy}(t) = m_{xy}(t) \times I_{xy}(t) + d_{xy}(t) \tag{1}$$

where $m_{xy}(t)$ and $d_{xy}(t)$ are the responsibility and offset coefficients of the $(x,y)^{\text{th}}$ individual detector and $I_{xy}(t)$ is the true irradiance received by each detector element.

From Eqn. (1), the true irradiance is given by:

$$I_{xy}(t) = \frac{O_{xy}(t) - d_{xy}(t)}{m_{xy}(t)} \tag{2}$$

To compute the gain and offset coefficient, the infra-red imaging system is kept in front of a Blackbody source and by using a standard frame grabber electronics card, it captures image frames at two different temperatures (catering to dynamic range of temperature). Then using the following formulae the gain and offset parameters are calculated offline and applied in real time on the incoming raw sensor data.

Defining $m_{xy}(t)$ which is gain coefficient as:-

$$m_{xy}(t) = \frac{P_{2xy}(t) - P_{1xy}(t)}{M_2 - M_1} \tag{3}$$

$$d_{xy}(t) = M_1 - \frac{\mathrm{P}_{1xy}(t)}{m_{xy}(t)} \tag{4}$$

where

$$M_1 = \frac{1}{m.n}\sum_{x=1}^{m}\sum_{y=1}^{n} P_{1xy} \tag{5}$$

$$M_2 = \frac{1}{m.n}\sum_{x=1}^{m}\sum_{y=1}^{n} P_{2xy} \tag{6}$$

For each pixel I, the two point corrected output level is computed according to the following formula:

$$\mathit{Corrected\ Output\ Level} = \frac{\mathit{Output\ Level}}{m_{xy}(t)} + d_{xy}(t) \tag{7}$$

where $P_{1xy}(t)$ and $P_{2xy}(t)$ are $(x,y)^{\text{th}}$ individual detector intensities at two temperatures[4]. M_1 and M_2 are the collective average intensities corresponding to the two frames captured at T_1 (lower) and T_2 (higher) blackbody temperatures respectively. Using the Eqns. (1), (3), and (4), the non uniformity corrected output can be calculated using Eqn. (7).

4. NUC IMPLEMENTATION ON AN LWIR IMAGING SYSTEM

Due to a combination of significant improvements in both MBE and GaSb substrate technology, and substantial difficulties encountered in developing a viable large area substrate technology for Mercury Cadmium Telluride (MCT) or alternatives, type two super lattice (T2SL) technology is now viewed in many countries as a promising and realistic technology for affordable and high performance MWIR and LWIR large array detectors. T2SL technology is based on III-V compound semiconductors and was proposed over 20 years ago for IR detection applications as an alternative to the II-VI material MCT. A T2SL structure contains numerous repetitions of ultra-thin layers (~40 Å each) of InAs and GaInSb (or GaSb). NUC scheme has been implemented in an LWIR thermal Imager based on 640 x 512 T2SL[3] based IR focal plane array (IRFPA). The Thermal Imager senses radiation in 8-12 µm band with F-number (*f#* = Effective Focal Length/ Aperture Diameter) of 2.7 and aperture diameter of 90 mm. The incoming infrared photons are focused onto the IRFPA which converts them into electrons. Associated proximity electronics changes them into measurable voltage signal and further digitize them. The Video processing electronics generates IRFPA interface signals, implements 2-point NUC and bad pixel replacement and generates CCIR-B/PAL standard video output which can be displayed on any monitor. Various set of image data have been captured during day and night. For 2-point NUC, two sets of image data have been acquired at lower temperature 12 ºC and at higher temperature 33 ºC respectively. To reduce the temporal noise, 64 image frames have been captured and averaged. Collected data is used to calculate the gain and offset coefficient which is stored in flash memories of video processing board.

In this research work, residual noise[13,14] is used as a quantitative measure to determine the NUC capability of proposed method.

$$\mathit{Residual\ noise\ (RN)} = \frac{\mathit{Output\ Standard\ Deviation\ (SD)}}{\mathit{Output\ Mean\ (M)}} \tag{8}$$

$$RN = \frac{SD}{M} = \frac{1}{m.n}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(x_{ij} - y_{ij}\right)^2} \tag{9}$$

where x_{ij} is corrected image, y_{ij} is calibrated image, and (m,n) are number of rows and columns in image.

5. NON UNIFORMITY SCHEME HARDWARE IMPLEMENTATION: EXPERIMENTS AND RESULTS

Two point calibration based NUC algorithm was implemented in reconfigurable hardware unit[16] as shown in Fig. 4. The infrared detector is 640 × 512 element based on T2SL LWIR FPA is interfaced with this hardware unit. The unit is exposed to blackbody in two temperature ranges i.e. -20 °C to +15 °C and +15 °C to +55 °C. The collected data is stored in SRAM memories (CY7C1061). The non uniformity correction scheme to calculate offset & gain data was realised on Xilinx field programmable gate array (FPGA) based video card[17,18]. Flash memories are used to store the calculated coefficients. The images (frame by frame) are stored in SRAM memories in ping-pong fashion. A required correction to remove non uniformity correction is applied on incoming 14-bit digital data for real-time correction. The image data is fetched and multiplied by corresponding gain coefficients which is further added from offset coefficients. The core processing unit is designed around XC5VLX110 FPGA having other requisite peripheral devices such as Flash memory (SST39VF3202), encoder (TVP5146) etc. The system clock is 80 MHz. This non uniformity corrected data is processed through an encoder which converts it into CCIR/PAL compatible video output. The video is displayed on a CRT/ LCD display. The NUC algorithm requires the addition and multiplication function. The module for multiplication and floating point correction has been optimised for real-time operation. The resource utilised in implementing the two point calibration based NUC algorithm on FPGA is as shown in Table 1. 18 per cent resources of FPGA are utilised for NUC alone. The remaining resources are being used in standard video/ image processing module being used in thermal imaging systems.

Figure 5(a) shows the image of uncorrected Blackbody source and Fig. 5(b) shows the image of non uniformity corrected blackbody source. Figures 6(a) and 6(b) show the 3-D representation of uncorrected and corrected blackbody source. Figures 7(a) and 7(b) illustrate the uncorrected and corrected target 1 image. Figures 8(a) and 8(b) illustrate the result of uncorrected and corrected target 2 image.

Table 1. Hardware (FPGA) resource allocation

Resource name	Allocated	Total	(%) used
Slice flip flops	5150	69,120	7
Occupied slices	3156	17,280	18
Slices LUTs	6920	69,120	10
BUFG/BUFGCTRLs	9	128	7
BlockRAM/FIFO	22	200	11
DSP48Es	12	64	18
DCM ADVs	2	12	16

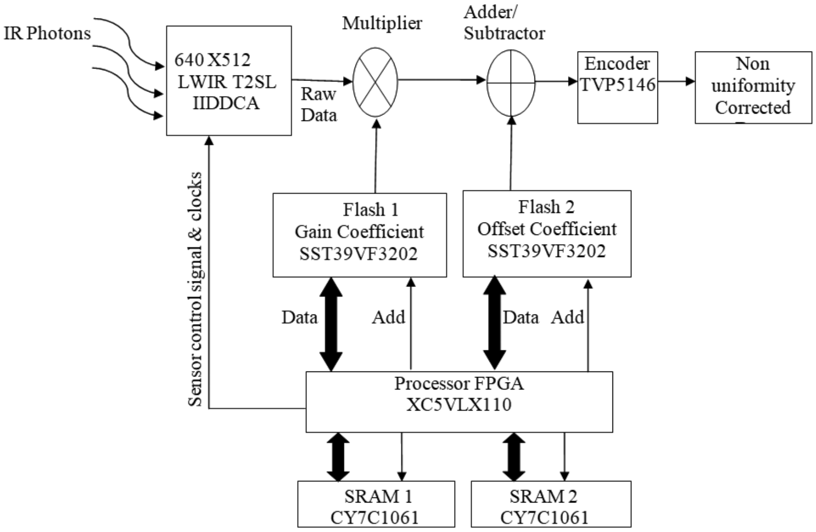


Figure 4. Hardware implementation of 2-point NUC.

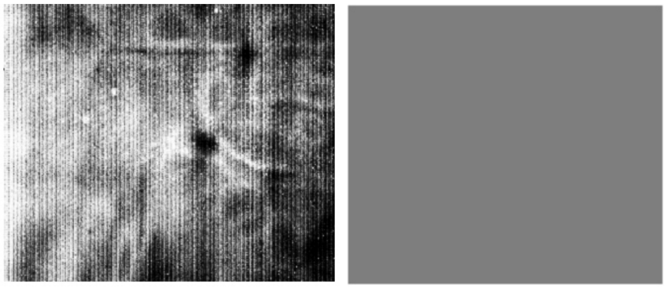
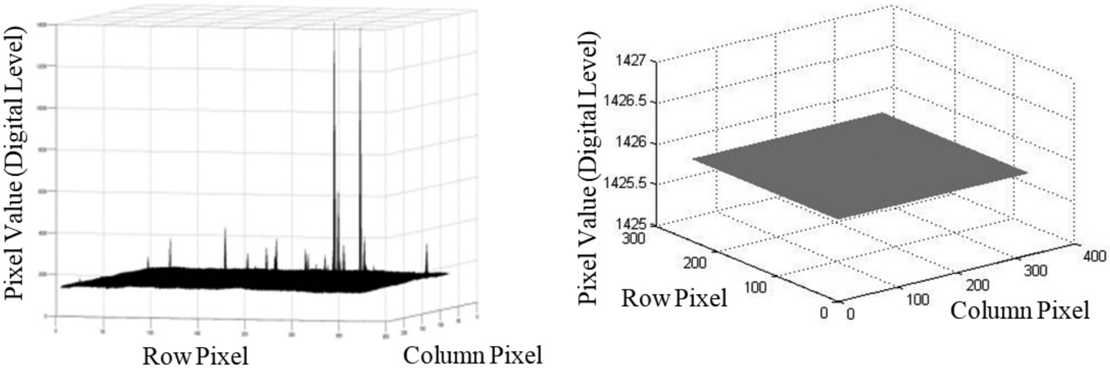

(a) (b)

Figure 5. Image of blackbody source (a) Uncorrected and (b) Non uniformity corrected.

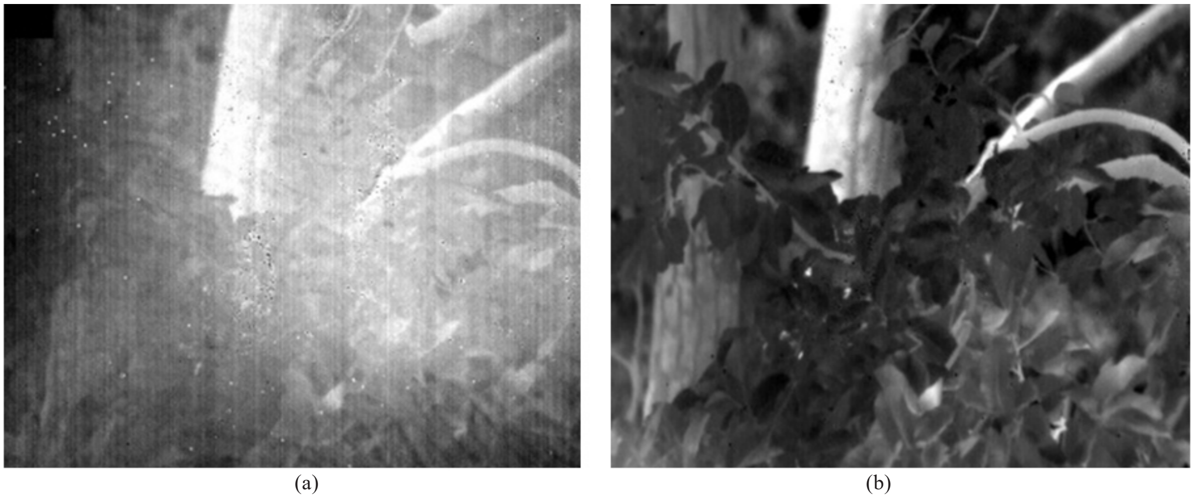


(a) (b)

Figure 6. 3-D representation of (a) Uncorrected and (b) Non uniformity corrected.

(a) (b)

Figure 7. Target 1 image (a) Uncorrected and (b) Non uniformity corrected.



(a) (b)

Figure 8. Target 2 image (a) Uncorrected and (b) Non uniformity corrected.

Residual Fixed Pattern Noise (RFPN)

Before NUC correction, measured standard deviation (σ) = 14.678

Mean (M)= 125

So, measured residual fixed pattern noise $RFPN = \frac{\sigma}{M} =$ 0.11742

After NUC correction, measured standard deviation (σ) = 1.2059

Mean (M)= 125

So, measured residual fixed pattern noise $RFPN = \frac{\sigma}{M} =$ 0.0096472

Residual noise is computed for both uncorrected and corrected image frames and it can be seen from the results that this algorithm improves the sensor non uniformities from 12 per cent to less than 1 per cent.

6. CONCLUSIONS

The detector used is 640×512 type two super lattice long wave infrared detector. A thermal imager has been realised around this detector. The uniqueness of the paper is in real time hardware implementation of blackbody calibration based two point non uniformity correction (NUC) technique for this detector. The significant reduction in fixed pattern noise in the output images in terms of RFPN after NUC have been obtained. Further, real-time performance of two-point non uniformity correction has been achieved. The complete scheme for real time hardware implementation of the NUC algorithm is discussed and the utilised FPGA resource is summarised for LWIR Thermal Imager. Future work may be extended for implementation of polynomial and scene based NUC algorithms. The presented algorithm and its implementation is generic in nature and can be easily applied in real time for higher format detectors such as 1024 × 768 and 1280 × 1024 in MWIR and LWIR spectral bands.

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In the current study, he has guided and supervised the work presented in this paper.