Calibration-based NUC Method in Real-time Based on IRFPA

Meng Sheng\textsuperscript{a}, Juntang Xie\textsuperscript{b}, Ziyuan Fu\textsuperscript{c}\textsuperscript{*}

\textsuperscript{abc}School of Information and Electronics, Beijing Institute of Technology, Beijing 100081, China

Abstract

The non-uniformity of Infrared Focal Plane Array (IRFPA) resulted from the limits of the detector’s materials and the manufacturing process affects the performance of the staring IR imaging system. To address this problem, non-uniformity correction (NUC), applied for real-time resolution, is the important issue in the IR imaging information processing system. This thesis introduces method of non-uniformity correction. Considering the nonlinear character of IRFPA, the calibration-based polynomial NUC method is proposed in the hardware system. Comparing with the conventional NUC schemes, polynomial method can achieve better NUC performance and implement in real-time. The algorithm is designed based on System architecture for FPGA hardware, for which is the Xilinx ML402 platform dedicated for video processing, which consists of A/D and D/A converter, and Virtex-4 FPGA on the mother board. The polynomial method reduces the non-uniformity in the infrared image largely, implemented at real-time, as well as the advantage of wide dynamic range.

Key words: Infrared Focal Plane Array (IRFPA); calibration-based non-uniformity correction; polynomial method; FPGA; real-time

Given different factors affecting the Infra Red Detector Unit, two detectors measuring the same uniform refracted rays will present different results, which phenomenon is called calibration-based non-uniformity, and which is also called inherent space noise. The cause of this non-uniformity is internal, resulting from the level of technology used in production of the detector, which cannot guarantee exactly the same result. Another cause is external, resulting from the change in temperature, the imperfection of the optical system used, and the list goes on. Because of the existence of calibration-based non-uniformity effect, the Infra Red image obtained by our system will have a resulting non-uniform noise called ‘fixed-pattern noise’, which will blur the image, reducing its quality and the imagery system’s thermal accuracy, perturbing severely the desired information. The non-uniformity is a barrier to the IR plan focal capacity,
so the creativeness of the plan matrix focus has always been the major key in the technology and research of the Infra-Red imagery.

The non-uniformity of Infrared images refers to the fact that because each detector has a different output response characteristic, when detecting the same uniform radiation field the same input will produce different results in the output, creating an inconsistency between the various detectors. This inconsistency is usually called non-uniform noise. That specific noise in the image is known as spatial noise or fixed-pattern noise[1]. The spatial noise will generate a strong interference in the visual image of the observer, manifested as texture or bands in the vertical scanning direction; or will be reflected in a certain pattern for the array in gaze. This spatial noise due to the non-uniformity is typically much larger than the time-domain noise, thus cannot be inhibited by the average time domain becoming the most important limiting factor of IRFPA in infrared imaging performance. Even after the non-uniformity correction (NUC), due to the difference between the nonlinear response and the targeted components of the radiation spectrum, the non-uniformity noise still remains. Its noise level will even surpass that of time-domain noise. The existence of non-uniformity noise heavily interferes with the true image signal, submerging the target in a weak non-uniformity noise. The accuracy of the targeted strong signal will also be compromised.

1. A method of Calibration-based correction

Non-uniformity has become a bottleneck to further improve image quality. For trying to improve the image quality by using the methods of signal processing to correct this non-uniformity, a lot of algorithms have been made, such as: algorithm based on one point correction of light source, two-point non-uniformity correction method, multi-point non-uniformity correction method, temporal high pass filtering correction method, Neural Network Correction method, constant-statistics constraint correction method, Kalman filter algorithm method, and so on.

Correction based on technical requirements for the light source at a specific temperature generated by a uniform blackbody radiation calibration of infrared focal plane arrays, usually using two or more point calibration technique[2]. Algorithm based on the advantages of the light source is simple, easy to implement and can be done in real time by the hardware; both two-point non-uniformity correction and multi-point non-uniformity corrections are more suitable for hardware real-time processing of non-uniform algorithm.

1.1 Method of two-point temperature calibration

Assuming the response of the infrared detection is a linear response, the figure 1(I) represents the response curves for the calibration of the detector. Figure 1(I) (a) represents the input-output response curves of different response rate to different dark current of the two photosensitive detectors. Figure 1(I) (b) represents the response curve of the detectors respectively to the change in rotation. Figure 1(I) (c) shows the gain and offset correction of the input output curve[3].

The purpose of two-point correction method is to make the correction so that the detector’s gain and offset parameters within the same temperature parameters should have the same response. First set two high and low temperatures as our choices of given punctuation.
Punctuation for the infrared focal plane array detector works temperature range. Detector response is approximately linear in the case. The output signal detector can be expressed as:

\[ V_{ij}(\varnothing) = R_{ij} \times \varnothing + O_{ij} \]  

(1)

Where \( V_{ij}(\varnothing) \) is the output signal of the (i, j)th detector with the incident radiation \( \varnothing \) at time; \( R_{ij} \) is the corresponding degree of radiation spectrum of the (i, j)th detector, independent to \( \varnothing \); \( O_{ij} \) is the output signal caused by the dark current, independent to \( \varnothing \). The purpose of correction is so that the correction of output signal \( V_{ij}(\varnothing) \) of any detector in a given incident irradiance \( \varnothing \) be equal to the spatial average signal \( \overline{V}(\varnothing) \) for the entire CCD area array, thus \( V_{\varnothing} = \overline{V}(\varnothing) \). For that, assume two-point calibration blackbody temperatures \( T_1, T_2 \), and two incident irradiances \( \varnothing_1, \varnothing_2 \), given the relation in (1) we get \( V_{ij}(\varnothing_1), V_{ij}(\varnothing_2) \), after calculating the average of \( V_{ij}(\varnothing_1), V_{ij}(\varnothing_2) \) we get:

\[ \overline{V}(\varnothing_1) = \frac{1}{M \times N} \sum_{i=1,j=1}^{M,N} V_{ij}(\varnothing_1) \]

\[ \overline{V}(\varnothing_2) = \frac{1}{M \times N} \sum_{i=1,j=1}^{M,N} V_{ij}(\varnothing_2) \]  

(2)

With the relation in (1), calculate the spatial average we get:

\[ \overline{V}(\varnothing) = \overline{R} \times \varnothing + \overline{O} \]  

(3)

To (3) into (1) we get:

\[ V_{ij}(\varnothing) - O_{ij} = \frac{R_{ij}}{\overline{R}}[\overline{V}(\varnothing) - \overline{O}] \]  

(4)

By (4), we know, \( V_{ij}(\varnothing) - O_{ij} \) and \( \overline{V}(\varnothing) - \overline{O} \) are proportional, as shown in figure 1(II):

\[ V_{ij}(\varnothing) - O_{ij} = K_{ij} \overline{V}(\varnothing) + b_{ij} \]  

\[ K_{ij} = \frac{V_{ij}(\varnothing_2) - V_{ij}(\varnothing_1)}{V_{ij}(\varnothing_2) - V_{ij}(\varnothing_1)} \]

\[ b_{ij} = \frac{V_{ij}(\varnothing_2)\overline{V}(\varnothing_1) - V_{ij}(\varnothing_1)\overline{V}(\varnothing_2)}{V_{ij}(\varnothing_2) - V_{ij}(\varnothing_1)} \]  

(5)

(6)

From the above analysis we can see, two-point correction algorithm fixed the error on both the output response and gain coefficients, resulting in a high accuracy, especially when the IRFPA response is nearly linear, the two-point calibration method is one of the best correction algorithms. In practice, the response of photosensitive detector is nonlinear, with increasing of nonlinearity, the accuracy in two-point calibration method decreases, as can be seen from the chart analysis of accuracy of nonlinear two-point calibration method. Figure 2(I), curve 1 represents the actual response curve of photosensitive detector,
curve 2 represents the linear approximation response of the photosensitive element, curve 3 represents the actual response by the two-point method calibration. When using the linear approximation of two-point correction method, $\phi$ is converted to radiant flux $\phi'$, so the output voltage $V'(\phi)$ can be converted to $V'(\phi')$, deviation from the actual $V'(\phi)$, after a two-point method correction, the residual spatial noise still has a serious impact on the correction of two-point method:

![Diagram](image.png)

Fig. 2. (I) schematic diagram of two-point method in non-linear response; (II) response curves of two-point calibration method and multi-point correction method

1.2 Sub multi-point calibration method

In practice, for different incident illumination, the corresponding voltage curve for the detector is an S-shaped. When the dynamic range is large, the nonlinearity of response curve of the detector becomes prominent, and two-point correction algorithm is not well adapted to the working condition of the detector. To reduce the effect of nonlinearity on the calibration, a sub-multi-point calibration method is proposed: Take a number of temperature calibration points, in a small range of the two non-uniform sub-calibration lines with a number of off the nonlinear approximation of the response curve shown in figure 2(II). Divide the interval, the more divisions, the better correction is. However, in practice, because the number of sub-range selection and determination of calibration points of temperature lack of uniform standards for reliability, we need to store more calibration parameters, and the dividing the intervals increases the complexity of the algorithm, even constrains the algorithm for further applications.

1.3 The curve fitting method of calibration

Let the IRFPA system be a causal nonlinear physical systems; for any detector unit, a response to the input irradiance $x$, we can use $x$ to represent the infinite polynomial. Ignoring the relatively small terms with high-exponent, we can use the Nth degree of $x$ in the polynomial approximation of the detector's response to the radiation:

$$y_n(x) = \sum_{n=0}^{N} a_{mn} x^n$$ (7)
The focal plane of the same radiation intensity, the average response for the correction of expected value:

\[ y_c(x) = \frac{1}{M} \sum_{m=0}^{m} \sum_{n=0}^{N} a_{mn} x^n \]  

(8)

According to principles of non-linear fitting for the response of a detector unit value \( y_m(x) \), by equation (7) we get the incident irradiance \( x \), substituting it into (8) we get the corresponding correction. This correction algorithm due to the higher-order correction in the case involving more divisions and square roots, and when the order of correction is higher than third when there is no formula for finding roots, cannot be resolved in the form of the correction formula, solving by software and hardware becomes more difficult. As \( y_m(x) \) and \( y_c(x) \) are polynomials of \( N \) order of \( x \), similar to a class of functions, so you can use \( K \) sub-polynomials of \( y_m(x) \) to represent \( y_c(x) \):

\[ y_c(x) = \sum_{n=0}^{K} b_n y_m^n(x) \]  

(9)

Through the the calibration data, in the sense of least square curve fitting, coefficients of the polynomial can be obtained. Many works refer to the response curve of the detector as the parabola, to find the approximate expression for the calculated curve, measured by multiple fixed punctuation, \( M \) set of experimental data have been calculated for each detector, if you select the appropriate function type for the \( M \) group least-squares fitting the data, it is easy to get an approximation of the detector’s response function. The response curve can be expressed as a quadratic polynomial as follows:

\[ y_c(\varnothing) = \sum_{n=0}^{2} b_n \cdot y_m^n(\varnothing) \]  

(10)

2. Introduction of FPGA hardware platform

Fig. 3. (I) ML402video development board; (II) gray scale images of bold response before and after correction

The task is achieved on hardware platform of Xilinx video input and output development kit ML402, shown in figure 3(I). Include a video processing board, providing video interfaces of HD (high definition), SD (standard definition), computer video interfaces VGA, DVI, SDI, and signal processing motherboard. Through a variety of standard video interfaces and A-D converter chip, video processing board receives and processes video signals stream. And it does packet processing solutions depending on different video protocols on Virtex-ⅡXLXCV2P7 FPGA, and extracting video signals to be processed, transmits video signals to the motherboard by extending access, and processes signals. When processed signals return to
the video processing board, video processing board packages the signals, meeting the requirements of video formats for transport, and outputs corresponding video stream signals through A-D converter chip.

3. Implementation and Evaluation of Non-uniformity Correction Method

3.1 Evaluation of calibration standards

The measurement methods of non-uniformity (NU) used solve non-uniformity problems of Infrared focal plane array (IRFPA).

Schultz and Caldwell proposed the definition of non-uniformity:

\[ NU = \frac{1}{\bar{y}} \sqrt{\frac{\sum (y_i - \bar{y})^2}{N}} \]  

(11)

The \( \bar{y} \) represents the average response value of the image. Due to time drift effect to the correction, non-uniformity corrected is different under different time calibration and different scenarios. However, this method is a more objective measure.

With non-uniform definitions of Schultz's method, calculate non-uniformity before and after correction. Before correction non-uniformity is 0.3767, and after correction it is 0.0210, with an order of magnitude lower. With Matlab, draw the grayscale image before and after correction. We can see that, after correction, infrared focal plane response to the same radiation intensity is more evenly, and non-uniformity greatly reduces, shown in figure 3(II).

3.2 Algorithm processes and hardware systems

Algorithm design is processed in integrated environment of Xilinx ISE8.1, and timing simulation tool is Modelsim 6.0, with Verilog HDL hardware description language. The relationships between the various Algorithm modules are shown in figure 4. The signals input FPGA are clock signal, 10-bit uncorrected video signal, row sync signal, field sync signal, odd-even field signal and 32-bit ZBT SRAM corrected data. Output signals are 32-bit address signal of SRAM memory, read and write control signals, 10-bit corrected video signal, sync signal corresponding to video signal and A / D and D / A clock signals of video processing board.

Fig. 4. Algorithm Block Diagram
Use polynomial correction method and there are three correction factors, with a 2400Kb storage size. Although the FPGA's internal storage resources of this subject are more adequate, taking the occupancy of the storage resources in the process of computing and extend of function in the future into account, store correction factors in external memory. Flash read time cannot meet the requirements of high-speed computing, but considering that store correction factors in external ZBT SRAM after power, meet the real-time requirements of algorithm.

After connecting the experiment system, the hardware development board is reset and FPGA and peripherals completely initialized. Select the boundary scan load mode in the iMPACT configuration downloading tool, from the programming menu. Configure the FPGA hardware by using the JTAG port, then download the design process (in *. bit file). After the download is completed successfully, FPGA starts to run the correction algorithm ① management module generated by the DCM clock 200MHz, memory clock is 13.5MHz of pixels. ② Wait for the clock to be stable, ZBT SRAM write in effect, the external flash memory set with a good calibration correction factor, write address generated by the control module. After the load factor of ZBT SRAM read is effective, determine whether FIFO is in write or read mode, if in write mode, the address appears on the read address bus address, data ports ui read_data data read out there. ③ When FIFO write is ineffective, the input data line din from the ZBT SRAM data bus is written, as shown in figure 5(I). If the FIFO is full, ZBT SRAM suspends reading, the write operation is also pending, Since the FIFO read frequency 200MHz is much larger than the write frequency 13.5MHz, FIFO is not empty; the current video signal is ready before the arrival of the desired non-uniformity correction factor, and the correction factor is placed and read out according to the order of pixels.

![Fig. 5. (I) timing diagram of ZBT SRAM write to the FIFO; (II) call coefficient, waveform](image)

④System waits for the video signal input, when the video signal is effective i.e: vs_valid and hs_valid effective, the correction factor is read from the FIFO. Each correction factor of 8, a pixel in the FIFO memory is a correction factor of the word. [23:16] for the coefficient a, [15:8] for the coefficient b, [7:0] for the coefficient c, the correction computing happens in the same clock cycle unit, as seen in figure 5(II) of the timing diagram.

The use of the calibration data, respectively with the two-point calibration method or the curve fitting algorithm calculates the correction factor, the image non-
uniformity correction. Calibration results are shown in figure 6, after a comparison it can be seen clearly, the corrected image in the strip and the space shot noise has been significantly inhibited; with calibration curve fitting algorithm, the details of the image contours is clearer than two points correction algorithm.

![Fig. 6. rendering based on correction of calibration (a) image before correction; (b) image corrected by two-point method; (c) image corrected by curve fitting](image)

4. Conclusions

Because of the materials used to build the detector and manufacturing process reasons, the pixels of infrared focal plane array have differences in the sensitivity, the characteristic parameters of the detector are not exactly the same, this leads to the non-uniformity of the response, reducing the image resolution, affecting the detection results of infrared imaging systems. The main subject of this study treated the theoretical principles of non-uniformity correction of the infrared focal plane array, focusing on FPGA-based hardware platform and correction curve fitting algorithm. The main tasks are as follows:

1. The analysis is based on scaling theory of non-uniformity correction algorithm, for subsequent non-uniformity correction and provides a theoretical basis.

2. We focused on the characteristics of an Infrared focal plane detector for nonlinear response, and consider real-time hardware implementation issues in the current correction in the selected calibration curve fitting based correction method. By comparing images before and after correction and analysis of non-uniformity can be seen, the curve fitting algorithm than the traditional two-point correction method has better performance, and is conducive to hardware implementation, avoiding the multi-select sub-method breakpoints and coefficient storage capacity short comings.

3. Using the Virtex-4 FPGA hardware platform, we designed and implemented the curve fitting algorithm based on the calibration. Uniformity correction has been a key point and a difficult one of the infrared focal plane technology.

So as to improve the image quality, the non-uniformity correction in real-time application, non-uniformity correction of infrared detector has improved the image quality, so is an important technology
to improve the performance of infrared imaging. Algorithms have to be made in order to achieve practical application and a follow-up study should be carried to further deepen this work.

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