Nonuniformity Correction Design and Implementation for Infrared Image Based on FPGA and Artificial Neural Networks

YuYangJunLu
Department of Physics, University of Science and Technology of China, Hefei, Anhui, 230026, China
lyyj@mail.ustc.edu.cn

Abstract: Infrared imaging technology is widely used in military and civilian applications. However, due to the materials and manufacturing technology, the response of each unit in the infrared detector is not completely consistent, which leads to the nonuniformity of the infrared focal plane array. In this article, we propose a way to use artificial neural network by self-adaptively updating the correction coefficients based on FPGA. Compared with traditional calibration-based method, our method is more flexible and can avoid the effects of temperature drift efficiently.

1. Introduction
Infrared thermal imaging technology is more and more common today, and can be widely used in medical, civilian and military fields. Among them, the imaging system with focal plane structure has become the mainstream of current research due to its simple structure, portability and the high quality of output image. The most important of this system is the infrared focal plane array [18]. When the focal plane array is facing almost the same heat radiation, the intensity value of each pixel’s output in the thermal imaging system is also different. This phenomenon is usually called the nonuniformity [13].

At present, the problem of nonuniformity will reduce the visual quality of infrared images. The main reason is that the photoelectric response rate of the detector’s each pixel unit is inconsistent due to the limitation of the process and material technology [10]. With the change of working status, environment temperature and circuit bias, the noise will also change and drift. The nonuniformity of infrared system will greatly affect the quality of the image, such as concealing the details of the edge and affecting the accuracy of temperature measurement [17]. Therefore, in order to obtain a clean infrared image and improve the visual quality of the infrared image, it’s very important to implement nonuniformity correction before getting the infrared images [20].

2. Related works
There are two main ways of correction for nonuniformity: one is the method based on the calibration, and the other is the method based on scene [9]. The typical representative methods include one-point correction, two-point correction, multi-point correction and polynomial fitting correction and so on [12]. However, due to the changes in temperature, the correction coefficient will drift [10]. Based on statistical models, typical method such as the time-domain high-pass filter proposed by Scribner et al. [1], which uses nonuniform noise as the low-frequency signal to remove from the high-frequency signal of the target image. The typical method based on the calibration is the motion compensation proposed by
Hardie et al [2]. This method calibrates multiple images before and after image frames and calculates the average value to obtain the estimated value, and then obtains the correction coefficient. The method based on the neural network was first proposed by Scribner et al. in 1990 [3], using the average value of pixel’s four-neighborhood as the objective image to get the correction coefficient iteratively. In 2005, the adaptive neural network algorithm was proposed by Vera et al [4], which modifies the step size in the correction coefficient to speed up the convergence. In 2009, Hardie proposed to use Gaussian filtering to obtain the objective image [5] and to increase the judgment of whether the scene is moving to reduce the ghost phenomenon. In 2010, Rossi et al proposed bilateral filtering instead of four-neighbor mean filtering to acquire objective image [6] to solve the problem of edge misjudgment by linear spatial filters. In 2016, FangLinChen proposed to use the corrected image to obtain the objective image by the four-neighbor mean filtering to solve the problem that the open-loop neural network is greatly affected by noise [7]. In 2018, Zhe Liu proposed a method based on adaptive sparse representation and global constrained learning rate to optimize the correction results [8]. In 2019, Qian Li et al proposed a method of adding a pre-processing layer and one more hidden layer before the traditional neural network, and using Gaussian filtering and mean filtering to remove fringe nonuniformity [9].

3. The algorithm of nonuniformity correction through artificial neural networks
The process of the artificial neural network correction is to obtain \( Y_{i,j,\text{mean}}(n) \) through the average value of the original pixel’s four-neighborhood as the expected image firstly, and then modifying the weights \( A_{ij}(n) \) and \( B_{ij}(n) \) (correction coefficient) to make the actual output value \( Y_{ij}(n) \) continuously approach to the expected output value \( Y_{i,j,\text{mean}}(n) \).

\[
Y_{i,j,\text{mean}}(n) = \left( X_{i,j-1} + X_{i,j+1} + X_{i-1,j} + X_{i+1,j} \right) / 4 \tag{1}
\]

\[
Y_{ij}(n) = A_{ij}(n) \ast X_{ij}(n) + B_{ij}(n) \tag{2}
\]

Using the error function \( F_{ij}(n) \) to ensure the \( Y_{ij}(n) \) is approach to the \( Y_{i,j,\text{mean}}(n) \).

\[
E_{ij}(n) = Y_{ij}(n) - Y_{i,j,\text{mean}}(n) \tag{3}
\]

\[
F_{ij}(n) = E_{ij}(n) \ast E_{ij}(n) = [Y_{ij}(n) - Y_{i,j,\text{mean}}(n)]^2 \tag{4}
\]

And then, we will use the fastest gradient descent method to find the partial derivatives and finally get the correction coefficient:

\[
A_{ij}(n + 1) = A_{ij}(n) - 2 \ast \lambda_{ij} \ast E_{ij}(n) \ast X_{ij} \tag{5}
\]

\[
B_{ij}(n + 1) = B_{ij}(n) - 2 \ast \lambda_{ij} \ast E_{ij}(n) \tag{6}
\]

At last, we use the \( A_{ij}(n + 1) \) and \( B_{ij}(n + 1) \) to get the final output of infrared image:

\[
Y_{ij}(n + 1) = A_{ij}(n + 1) \ast X_{ij}(n + 1) + B_{ij}(n + 1) \tag{7}
\]

In the equation (5) and (6), \( \lambda_{ij} \) is the learning rate. When \( \lambda_{ij} \) is large, the speed of convergence becomes faster, but it may vibrate near the minimum value of gradient. When \( \lambda_{ij} \) is small, it is easier to approach the minimum value of gradient, but the convergence speed will become slower. Therefore, in this paper, \( \lambda_{ij} \) is associated with a specific image position. The adaptive \( \lambda_{ij} \) value is used to reduce its value where the image changes greatly and increase its value where the image changes a little.

\[
\lambda_{ij}(n) = 0.1 \ast K_{ij} \tag{8}
\]

\[
K_{ij}(n) = 1/e^N \tag{9}
\]

\( N \) is the variance of the surrounding 9 input pixels. So that the \( \lambda_{ij}(n) \) is related to the change of the image, and the learning rate can be dynamically adjusted.

In order to avoid that the gradient changes of each frame in the formula above is too large to affect the convergence, we calculate the average value of every 5 frames, and then load them to the initial correction coefficient of the next 5 frames.
\[ A_{ij}(n + 5) = \frac{[A_{ij}(n) + A_{ij}(n + 1) + A_{ij}(n + 2) + A_{ij}(n + 3) + A_{ij}(n + 4)]}{5} \] 

\[ B_{ij}(n + 5) = \frac{[B_{ij}(n) + B_{ij}(n + 1) + B_{ij}(n + 2) + B_{ij}(n + 3) + B_{ij}(n + 4)]}{5} \]

Firstly, we realize simulation test and analysis on computer to verify that our algorithm is working correctly. As is shown in Figure 1, we add salt and pepper noise in the original image. And we add KB-noise in the original image in Figure 2. The “Corrected Image” in Figure 1 and Figure 2 is the result of our algorithm.

![Corrected Image](image1)

![Mean Filtering](image2)

![Original Image](image3)

**Figure 1. Salt and pepper noise**

![Corrected Image](image1)

![Mean Filtering](image2)

![Original Image](image3)

**Figure 2. KB-noise**

The “Mean Filtering” in Figure 1 and Figure 2 is the result of only using mean filtering method. As the result shows, the effect of nonuniformity correction for infrared image by artificial neural network is remarkable.

4. **Structural design of the algorithm based on FPGA**

The characteristics of high flexibility and low power consumption of FPGA makes it draw more attention to the algorithm implementation [14], especially in the field of video processing. On FPGA, there are many LUTs, multipliers and adders which are suitable for a mass of repetitive multiply-add operations [15]. The main hardware structure is shown in Figure 3. At first, we collect image data
through the infrared imager and then transfer the image data to FPGA by using our customized infrared drive protocol. After the algorithm processing on FPGA, the image data output to the monitor through VGA and the image data is also transmitted to PC through USB3.0 to do the other algorithms [16]. The computer can also transmit parameter and configure registers on FPGA through NIOS CPU using uart and Avalon bus. And the whole FPGA structural consist of five main modules: Drive and control module, Mean filter module, Processing module and DDR module.

4.1 Drive and control module
In this paper, we will use the Focal Plane Array (FPA) to get the pixel data. In the drive and control module, we write the drive program which contains the signal of Pix_data_in, MCK(main clock), and rst_n(reset). And the output contains the signal of Pix_data_out, FS (frame start), LS (line start), FE (frame end), Data_valid and Clk_out. We can use these signals to get pixel data of each frame. The program structure is shown as Figure 4. In this module, we use the method of serial to parallel to covert the 2-bit Pix_data_in into the 16-bit Pix_data_out.

4.2 Mean filter module
To get the data flow efficiently, we use the IP called shift register [21], and the shift register has two taps. The data flow structure is shown in Figure 5.
Figure 5. pixel data flow structure using shift register

M refers to the width of the infrared image. As is shown in Figure 6, the $Y_{i,j,\text{mean}}(n)$ can be calculated by the equation (1)

\[ Y_{i,j,\text{mean}} = \frac{X_{i-1,j} + X_{i,j-1} + X_{i,j+1} + X_{i+1,j}}{4} \]

In order to reduce the delay time of combinational logic, we choose to use pipeline structure [15]. If we use normal way to add the four-neighbor pixel number, it will cost three levels of combinational logic to get the result. But if we use the pipeline, it only cost two levels to get the result as being shown in Figure 7 [19].

Figure 6. The calculation of $Y_{i,j,\text{mean}}$

4.3 Processing module

The Processing module contains Calculating module and Error module. Through the original input
image data, the expected image $Y_{ij}(n)$ can be calculated by the correction coefficient $A_{ij}(n)$ and $B_{ij}(n)$, and the initial value of the two coefficient will be set by ourselves. $A_{ij}(n)$ and $B_{ij}(n)$ will modify in the artificial neural network due to the error function $F_{ij}(n)$ in the Error module.

At last we will calculate the correction coefficient in the Error module. Our algorithm can refresh the coefficient $A_{ij}(n)$ and $B_{ij}(n)$ in each frame. The $Y_{ij}(n)$ comes from Calculating module and the $Y_{ij,\text{mean}}(n)$ comes from Mean filter module will input into the Error module and this module uses them to get the new $A_{ij}(n+1)$ and $B_{ij}(n+1)$ to cover the previous coefficient.

4.4 DDR module

In this structure, we need the real time pixel data to calculate correction coefficient. So we need DDR to store $A_{ij}(n)$ and $B_{ij}(n)$. When FPGA calculates the correction coefficient, it needs to read the latest correction coefficient from the DDR in real time. The amount of data we need is $640\times 512\times 16\times 2\text{ bit} = 1280\text{ KB}$, so that we can exchange the data between DDR and Error module. In order to improve the efficiency of exchange, we add a DMA control module between DDR and Error module. The whole FPGA structure is shown in Figure 8.

5. Conclusion

The infrared image is widely used in different fields and it is very important to do the nonuniformity correction for the detector before using. Our artificial neural network method can correct the nonuniformity of each unit on the infrared focal plane array without calibration and can decrease the effect of temperature drift. In this paper, a structure suitable for FPGA implementation is proposed, which can obtain real-time data more conveniently and improve the efficiency of the whole system.

Reference

[1] Scribner D A, Sarkady K A, Caulfield J T, et al. Nonuniformity correction for staring IR focal plane arrays using scene-based techniques. Proceedings of Infrared Detectors and Focal Plane Arrays. International Society for Optics and Photonics, 1990, 224–234.

[2] Hardie R C, Hayat M M, Armstrong E, et al. Scene-based nonuniformity correction with video sequences and registration. Applied Optics, 2000, 39(8):1241–1250.
[3] Scribner D A, Sarkady K A, Krue M R, et al. Adaptive nonuniformity correction for IR focal plane arrays using neural networks. Proceedings of Infrared Sensors: Detectors, Electronics, and Signal Processing. International Society for Optics and Photonics, 1991, 100–110.
[4] Vera E, Torres S. Fast adaptive nonuniformity correction for infrared focal-plane array detectors. EURASIP Journal on Advances in Signal Processing, 2005, 2005(13):560759.
[5] Hardie R C, Baxley F, Brys B, et al. Scene-based nonuniformity correction with reduced ghosting using a gated LMS algorithm. Optics express, 2009, 17(17):14918–14933.
[6] Rossi A, Diani M, Corsini G. Bilateral filter-based adaptive nonuniformity correction for infrared focal-plane array systems. Optical Engineering, 2010, 49(5):057003.
[7] Rong S H, Zhou H X, Qin H L, et al. Guided filter and adaptive learning rate based non-uniformity correction algorithm for infrared focal plane array. Infrared Physics & Technology, 2016, 76:691–697.
[8] Fang Lin Chen. Scene-based infrared focal plane non-uniformity correction algorithm and FPGA implementation. D. Nanjing University of Science and Technology. 2016.
[9] Zhe Liu. Research on Algorithms of Nonuniformity Correction and Enhancement for Infrared Images. D. Huazhong University Of Science And Technology, 2018.
[10] Tai Cheng He. The Research for Non-uniformity Correction of Infrared Focal Plane Array[D]. Xidian University. 2008.
[11] Ying Yu Niu, Rui Jie Nie, Li Juan Li. Nonuniformity correction for infrared image based on FPGA. J. Laser and Infrared 08:1028-1032.
[12] Qian Li, et al. (2019) An Improved Algorithm for IRFPA Optical Nonuniformity Correction Based on Neural Networks. J. Infrared Technology, 41(03):53-57.
[13] Shao Sheng Dai, Ji Bi Li, Tian Qi Zhang, Jun Huang.(2015) Infrared focal plane array imaging and nonuniformity correction technology, Science Press, Beijing.
[14] Lu Yin, Design and Implementation of Noise Level Adaptive Video Noise Reduction Algorithm based on FPGA. D. University of Science and Technology of China. 2016.
[15] Ke Ning Zhang, Research on Visual Enhancement of Subtle Motions and Hardware Acceleration Technology. D. University of Science and Technology of China. 2017.
[16] Yan Yong (2020) Research on Technology of Finger Vein Pattern Recognition Based on FPGA. J. Phys.: Conf. Ser. 1453 012037.
[17] Yin Luo, Research on Adaptive Stripe Nonuniformity Correction Algorithm for Infrared Image. D. Huazhong University of Science & Technology, 2019.
[18] Zhen Nan Zhao, Hong Fei Song, Hong Kai Ren. (2020) An Improved Scene-based Non-uniformity Correction Method. J. Journal of Changchun University of Science and Technology (Natural Science Edition) 043(002):53-57.
[19] Meng Xing Zhao, Research on special heterogeneous accelerator of convolutional neural network based on FPGA. D. SHANDONG University, 2020.
[20] Jun Tao Hou, Research on Technologies of Infrared Image Quality Improvement. D. XIDIAN UNIVERSITY, 2020.
[21] Lei Huang, Deep Learning Algorithm Acceleration Based On FPGA. D. University of Electronic Science and Technology of China, 2020.