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New method of digital modulative adaptative auto-calibration of infrared imaging devices

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Abstract

This paper describes the new method of digital auto-calibration IR imaging systems based on using low-amplitude 2D cyclic scanning and solving multi-dimensional inverse problem. The method does not require the use of reference bodies and stages of registration and calibration can coincide. Mathematical algorithms require $\approx 100\,N^2$ operations and are realized by using IBM PC/AT for $N < 256$.

1. Introduction

Modern technology allows to develop IR imaging systems with noise equivalent temperature difference (NETD) of about 0.001 K [1] but the practical realization of these systems and their metrology encounters some problems [2 to 4]. Non-uniformity of IR registrating device is one of these problems to be discussed in the present paper.

Non-uniform sensitivity of IR camera can be due to non-identical elements in the arrays, optical distortions and background irradiation. Digital correction of these effects is possible if the relationships between IR radiation intensity $I_{i,j}$ and output electrical signals $a_{i,j}$ are known. In linear approximation:

$$a_{i,j} = g_{i,j} \cdot I_{i,j} + h_{i,j} \qquad 1 \le i,j \le N \qquad (1)$$

where N is the number of pixels per line or column.

Coefficients $g_{i,j}$ and $h_{i,j}$ are usually determined by use of calibration procedure with two reference bodies, having intensities $I1$ and $I2$. Unfortunately, for systems with wide spectral and dynamic range and NETD < 0.1 K, this procedure has some drawbacks.

The best IR arrays use the InSb and CdHgTe detectors [5 and 6] but the attempts to enhance their uniformity, stability and sensitivity up to theoretical limits have still been unsuccessful. Better results were obtained on the base of Si-made Schottky diodes arrays [7]. In general, they provide worse than InSb detectors sensitivity but much better uniformity and lack of low-frequency noise [8 and 9]. But even in this case the random variations of spectral sensitivity from one detector to another will limit the temperature resolution of IR systems [10].

It is important that such a problem arises even for single — or few — detectors arrays, for example when high metrological accuracy is needed.

We suggest the new method of adaptive auto-calibration which uses the ideas of modulative spectroscopy [11] and methods of solution for non-correct multi-dimensional inverse problems [12]. The method does not require the use of reference bodies and the stages of registration and calibration can coincide.

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2. Discussion of inverse problem

The basic idea is to use the low-amplitude two-dimensional (2D) cyclic scanning of the IR camera itself or view angle scanning with additional mirror mounted on the camera. This idea is not new for image processing [13] but the basic problem is choosing of scanning law as simple as possible which permit from minimum number of images to determine correctly all $g_{i,j}$, $h_{i,j}$ and $I_{i,j}$ without any essential assumptions about its space characteristics.

The working analog of such a system with $N \approx 10^4$ is probably the human's eye. During observing the eye do many moves and fast low-amplitude 2D scanning with frequency $\approx$ 30-60 Hz (tremor) is one of them [14]. Researches in this field last more than fifty years [14 to 16] but the role of tremor in visual information processing is not clear still.

As the basis we have used the simplest 2D cyclic discrete scanning consisting of 3 points. Each pixel is moving for one pixel up or down and one pixel left or
4 right. For this scanning consequence of 3 basic images:

$$\{a_{i,j}\},\ \{b_{i,j}\},\ \{c_{i,j}\} \tag{2}$$

minimum necessary for further processing can be obtained. Unfortunately, restoration of full input information $\{I_{i,j}\}$ is possible if at least one matrix of coefficients $\{g_{i,j}\}$, $\{h_{i,j}\}$ is known or has small dispersion. In a case of essential dispersion of both matrices, it is necessary to make two measurements of an object under the following condition:

$$I1 < I2 \tag{3}$$

For absolute and independent calibration of IR system it is enough to place two small-size reference emitters with different $I1$ and $I2$ into the frame.

3. Equations system and algorithms

According to (1-3) and scanning law an initial system of equations for $4\,N^2 + 4\,N$ unknown quantities $g_{i,j}$, $h_{i,j}$, $I1_{i,j}$ and $I2_{i,j}$ can be written as following:

$$\begin{aligned} & g_{i,j}.IK_{i,j} + h_{i,j} = aK_{i,j} && K = 1,2 \\ & g_{i,j}.IK_{i+1,j} + h_{i,j} = bK_{i,j} && 1 \le i,j \le N \\ & g_{i,j}.IK_{i,j+1} + h_{i,j} = cK_{i,j} && g_{1,1} = G^{-1}\ ,\ h_{1,1} = G^{-1}.H \end{aligned} \tag{4}$$

where constants $G > 0$ and H are determined by the scale of $I_{i,j}$.

For correction of non-uniformity it is enough to suppose $G = 1$, $H = 0$. It is important that the structure of system (4) permits to split procedures of restoration $\{g_{i,j}\}$, $\{h_{i,j}\}$, $\{I1_{i,j}\}$ and $\{I2_{i,j}\}$.

After subtraction of equations (4) with $K = 1$ from ones with $K = 2$ and elimination of terms $I2_{i,j} - I1_{i,j}$, the system for $g_{i,j}$ can be written as:

$$\begin{aligned} & g_{i+1,j} = U_{i,j}.g_{i,j} && 1 \le i \le N,\quad 1 \le j \le N\text{-}1 \\ & g_{i,j+1} = V_{i,j}.g_{i,j} && 1 \le i \le N - 1 < ,\quad 1 < j < N\ ,\ g_{1,1} = 1 \end{aligned} \tag{5}$$

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where:

$$U_{ij} = (|a2_{i+1,j} - a1_{i+1,j}| + w) / (|b2_{i,j} - b1_{i,j}| + w)$$

$$V_{ij} = (|a2_{i,j+1} - a1_{i,j+1}| + w) / (|c2_{i,j} - c1_{i,j}| + w)$$

and the empirical parameter $w > 0$ is necessary for corrrect division when differences $(b2_{i,j} - b1_{i,j})$, $(c2_{i,j} - c1_{i,j})$ are close to noises value d.

If all $g_{i,j}$ are determined then the system of equations for $f_{i,j} = (h_{i,j}/g_{i,j})$ can be received from first ($K = 1$) or last ($K = 2$) part of (4) and written as:

$$f_{i+1,j} = f_{i,j} + q_{i,j} \qquad 1 \le i \le N\text{-}1, \quad 1 \le j \le N$$

$$f_{i,j+1} = f_{ij} + p_{ij} \qquad 1 \le i \le N, \quad 1 \le j \le N\text{-}1, \quad f_{1,1} = 0 \qquad (6)$$

where:

$$q_{i,j} = (a1_{i+1,j} / g_{i+1,j}) - (b1_{i,j} / g_{i,j})$$

$$p_{i,j} = (a1_{i,j+1} / g_{i,j+1}) - (c1_{i,j} / g_{i,j})$$

are known values.

Digital correction of any image $\{a_{i,j}\}$ for arbitrary G and H come to be according to expressions:

$$I_{i,j} = G.(a_{i,j} / g_{i,j}) - (f_{i,j} + H) \qquad 1 \le i,j \le N \qquad (7)$$

Overdetermined non-correct systems of linear equations (5) and (6) in principle can be solved by well known least squares method. According to theoretical estimates [18] this method permits to restore $\{I_{i,j}\}$ with accuracy:

$$D \approx (\ln N)^{1/2} . d \qquad (8)$$

close to detectors' noise d practically for any N. But its numerical realization encounters some problems because of large operations' number (from $\approx N^4$ to $\approx N^3 - N^{5/2}$ for best iterative methods) and principal limitation on computer accuracy [18 and 19].

We have developed non-iterative hierarchical method for solution systems (5) and (6) which are matched by accuracy the detectors' noise and require only $\approx 100\ N^2$ arithmetical operations for any N.

Equations of system (5) can be interpreted as recurrent expressions which permit to found any $g_{i+k,j+l}$ (with $k = 0, 1$ and $l = 0, 1$), if g_{ij} are known. Because of 2D $\{g_{ij}\}$ there are many ways for such a procedure and average with using some of neighbouring ones can be done. Thus if $g_{1,1} = 1$, then first order approximation $g_{12}^{(1)}$, $g_{21}^{(1)}$, $g_{13}^{(1)}$, $g_{22}^{(1)}$, $g_{31}^{(1)}$,... $g_{NN}^{(1)}$, can be obtained and new recurrent expressions for next order approximation $\{g_{ij}^{(2)}\}$ can be written. This procedure is repeated $m \le [\ln N] - 2$ times with using every one more large-scale nets $[N/2].[N/2]$, $[N/4].[N/4]$,...$[N/2^m].[N/2^m]$ and more large detectors' blocks (2.2), (4.4)... $(2^m.2^m)$ considered as one element, respectively. Consideration for system (6) is the same.

It is important that in conveyor regime the algorithms could be reduced up to N^2 operations.

Practical realization of the algorithms has been done by using IBM-PC/AT for

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$N < 256$. Results of numerical simulation agree with theoretical estimate (8) and some of them for $N = 128$ and case when $h_{i,j} = 0$ are demonstrated on *figure 1*.

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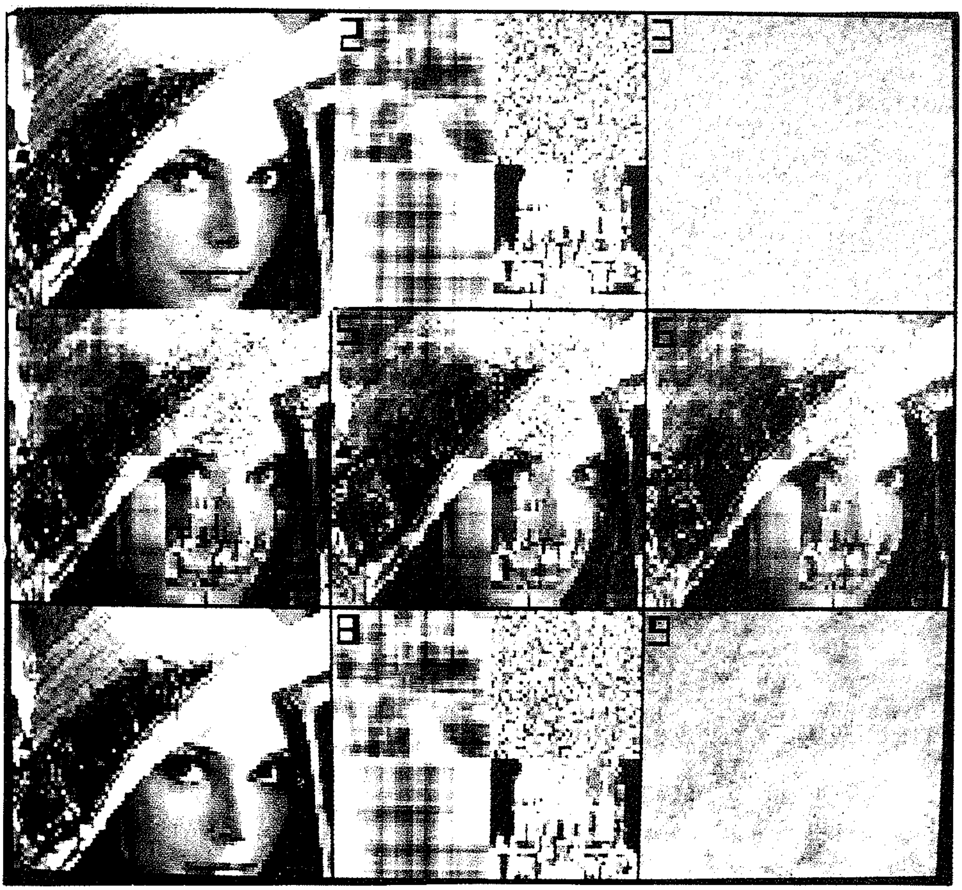

Fig.1. - Results of numerical simulation: (1,2) correspond to test images $\{I_{i,j}\}$ (I_{min} = 65, I_{max} = 216), $\{g_{i,j}\}$ (g_{min} = 0.54, g_{max} = 1.50); (3) is an example of detectors' noise $\{d_{i,j}\}$ ($<d_{i,j}> = 0$, $<d_{i,j}^2> = 1$) amplified by factor 8; (4-6) are the results of simulation for direct problem and correspond to $\{a_{i,j}\}$. $\{b_{i,j}\}$. $\{c_{i,j}\}$ with independent additive detectors' noises; (7,8) are images $\{I'_{i,j}\}$. $\{g'_{i,j}\}$ restored from (4-6) and (9) is difference between $\{I_{i,j}\}$ and $\{I'_{i,j}]$ multiplied by factor 8.