IR Sensor Test System

Eugene Larkin [1], Aleksandr Privalov [2] and Tatiana Akimenko [1]

[1]*Tula State University, 92 "Lenina" prospect, Tula, 300012, Russian Federation*
[2]*Tula State Lev Tolstoy Pedagogical University, 125 "Lenina" prospect, Tula, 300026, Russian Federation*

Abstract
Methods for testing IR sensors, which are currently widely used as a source of information about the environment in various sectors of the national economy, are being investigated. It is shown that due to the transformation of the informative parameters of the observed scene by the sensor, information loss at the output of the device is possible. The structure of the testing system has been developed, the main element of which is a patented generator of reference test signals, which makes it possible to evaluate the following informative parameters: thermal signal characteristic, distortion, resolution. The heat-signal characteristic is built as a result of scanning heated plates, statistical processing of measurement results and approximation of the results of statistical processing by a linear dependence. Distortion is estimated based on the results of assessing the coordinates of the IR LEDs on the stage of the generator of reference test signals. The resolution is estimated by the results of constructing the surface of values of the output signal of the IR sensor when scanning heat-generating plates located at some angle to each other. For each case of assessing the information content, an appropriate assessment methodology is proposed. The results are recommended for use at enterprises involved in the development, production and operation of IR sensors.

Keywords
Infrared sensor, thermal signal generator, informative parameters, information loss, thermal signal characteristic, distortion, resolution.

1. Introduction

Scene observation systems operating in the infrared range are currently widely used in various sectors of the national economy: in industry, ecology, the military sphere, etc. [1-4, 14]. The main advantage of such systems is the ability to work in difficult operating conditions, such as insufficient illumination of objects of observation in the visible range of electromagnetic radiation, high humidity, fog, smoke. As an element that converts electromagnetic radiation into a scene image, such systems use IR sensors that form a video signal transmitted to the observation and control point, where the information received is perceived and interpreted by a human operator or an artificial intelligence system. The efficiency of the functioning of systems operating in the infrared range is largely determined by the technical characteristics of IR sensors, which must remain consistently high for a long time in a wide range of scene observation conditions, since it is difficult to restore information lost at the stage of the initial formation of a thermal image of a scene by further digital image processing.

Verification of sensors is carried out by a testing system that creates test IR images of scenes that allow measuring and evaluating the parameters of the main nodes and sides of the IR sensor and the entire sensor as a whole [5–9]. A similar approach based on the creation of reference test signals is widely used in television, microfilming and scanning documents [10–16], and other information systems. However, the control of the main parameters of IR sensors has its own specifics, due to the fact that the test object must generate, rather than transform, thermal images of the reference scene, which presents known technical difficulties.

[1]*GraphiCon 2022: 32nd International Conference on Computer Graphics and Vision, September 19-22, 2022, Ryazan State Radio Engineering University named after V.F. Utkin, Ryazan, Russia*
EMAIL: elarkin@mail.ru (E. Larkin); privalov.61@mail.ru (A. Privalov); tantan72@mail.ru (T. Akimenko)
ORCID: 0000-0001-7471-1524 (E. Larkin); 0000-0003-3311-0751 (A. Privalov); 0000-0003-1204-2657 (T. Akimenko)

Thus, the need to create an information-measuring system that provides an assessment of the quality of IR sensors and the lack of a general theory of analysis and calculation of the parameters of such systems explains the need and relevance of the studies.

2. Digital control system

To assess the loss of information in the IR sensor, a digital testing information-measuring system is used, the general structure of which is shown in Figure 1. In the testing system, the reference test signal $Q_Э(x, y, t)$ is fed to the inputs of real and virtual IR sensors. In a real sensor, signal conversion $f_Р(Q_Э)$ is carried out at the physical level by real physical nodes and blocks, as a result of which a real digital model $[D(i, k)]_Р$ of the reference signal $Q_Э(x, y, t)$ is formed. Virtual conversion of the reference signal $Q_Э(x, y, t), f_В(Q_Э)$, is carried out as a result of simulation modeling of its sequential conversion by nodes and blocks of the IR sensor with ideal settings. The deviation is estimated by the norm of the difference $ε = ||\boldsymbol{h}[D(i, k)]_В - \boldsymbol{h}[D(i, k)]_Р||$ signals at the output of real and virtual systems. If the norm does not exceed the threshold value of $ε_П$,, then the IR sensor is considered serviceable, otherwise it must be adjusted.

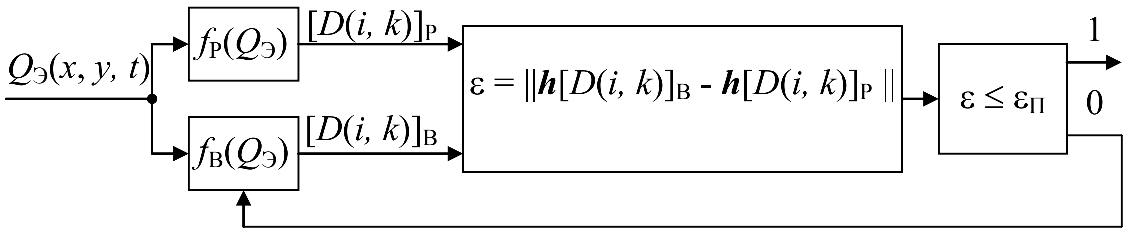

Figure 1: Digital testing information and measuring system

Informative parameters of IR sensors are control tests, thermal signal characteristic, distortion, resolution. To estimate the flow rate obtained at the output of IR sensors when converting the flow rate of informative parameters, a reference thermal signal generator (RTSG) is used, the block diagram of which is shown in Figure 2 [8,9], where the generator is presented in the *yOz* coordinate system associated with the scene and located in the subject area of the IR sensor lens.

The composition of the RTSG includes: 1 - plates of conductive material, on which temperature sensors 2 t_1°, t_2°, are installed, which are installed on cooling elements 3. infrared LEDs 4, located at the edges of the scene manifestations; control unit 5, to which signals t_1°, t_2°, and with which control signals u_{11}, u_{12}, u_{21}, u_{22} are applied to conductive plates 1, cooling elements 2 and infrared LEDs 4. The conductive plates are located at an angle of α to each other, which allows measuring the hit to the resolution of the IR sensor.

When testing, the RTSG is scanned by a sensor, at the output of which a digital image of the scene is formed, which is a facsimile digital image model (FDIM) $V = [v_{i(y),i(z)}]$, where $i(y), i(z)$ are the FDIM indices denoting the numbers of rows and columns of the matrix, and tied to the spatial coordinates y and z, respectively. Information losses are estimated based on the results of the FDIM analysis.

Thermal signal characteristic of the IR sensor, i.e. Dependence $v(t^\circ)$ using RTSG is measured as follows. The cooling elements 3 are supplied with signals u_{12}, u_{22} from the control unit 5, as a result of which these elements create the required background temperature t_0°, relative to which the control unit 5, using the readings t_1°, t_2° sensors 2 as feedback, sets the set temperature values of $t^\circ(1), ..., t^\circ(n), ..., t^\circ(N)$ sections of the plates 1. which fall inside regions $[i(z,\text{min}) \le i(z) \le i(z,\text{max}),\ i(y1,\text{min}) \le i(y) \le i(y1,\text{max})]$, $[i(z,\text{min}) \le i(z) \le i(z,\text{max}),\ i(y2,\text{min}) \le i(y) \le i(y2,\text{max})]$, circled in Figure 2 dotted line.

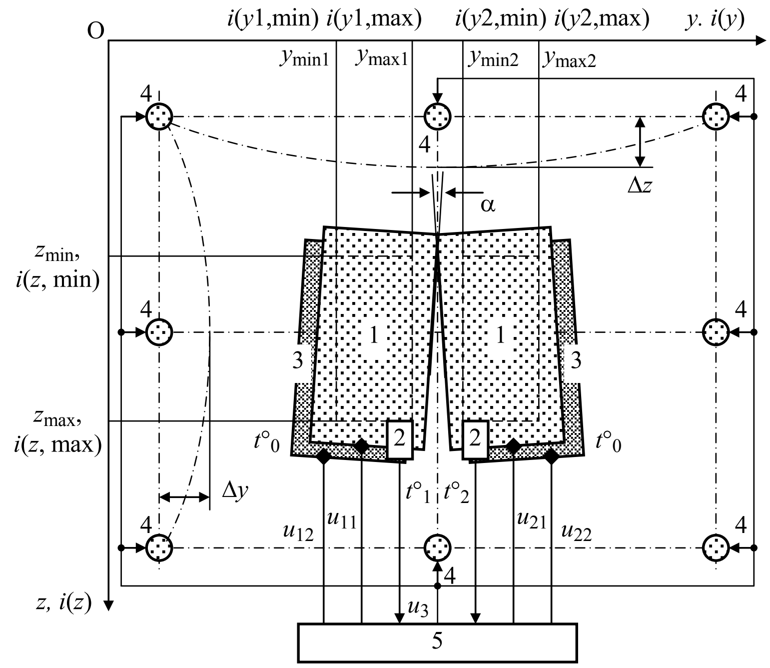

Figure 2: Reference thermal signal generator (test object) to control the loss of information in the IR sensor

Based on the measurement results, the mathematical expectation and dispersion of pixel values are determined according to the dependencies [18]:

$$\mathfrak{v}(n) = \{[i(y1,\max) - i(y1,\min) + 1][i(z,\max) - i(\quad (1)$$

$$+[i(y1,\max) - i(y1,\min) + 1][i(z,\max) - i(z,\min) + 1]\}^{-1} \times\times \left[\sum_{i(y)=i(y1,\min)}^{i(y1,\max)} \sum_{i(z)=i(z,\min)}^{i(z,\max)} \right.$$

$$D(n) = \{[i(y1,\max) - i(y1,\min) + 1][i \quad (2)$$

$$+[i(y1,\max) - i(y1,\min) + 1][i(z,\max) - i(z,\min) + 1] - 1\}^{-1} \times\times \left\{ \sum_{i(y)=i(y1,\min)}^{i(y1,\max)} \sum_{i(z)=i(z,\right.$$

In the event that inequality $\sqrt{D(n)} < \varepsilon_1$ is not satisfied for at least one value of $t^\circ(n)$, the IR sensor is considered to have failed the test.

As a result of the test tests of the IR sensor for different heating temperatures of the plates 1, two data arrays are formed: an array of temperatures $[t^\circ(1), ..., t^\circ(n), ..., t^\circ(N)]$ for which testing was carried out, and an array of values $[\mathfrak{v}(1), ..., \mathfrak{v}(n), ..., \mathfrak{v}(N)]$ of the temperature measurement results by the sensor. In the event that a logarithmic thermal signal characteristic is implemented in the IR sensor, then the temperature array must be converted into an array of temperature logarithms as follows:

$$[t^\circ(1), ..., t^\circ(n), ..., t^\circ(N)] \rightarrow \left[\ln\frac{t^\circ(1)}{t_0^\circ}, ..., \ln\frac{t^\circ(n)}{t_0^\circ}, ..., \ln\frac{t^\circ(N)}{t_0^\circ}\right] = [\mathfrak{t}^\circ(1), ..., \mathfrak{t}^\circ(n), ..., \mathfrak{t}^\circ(N)]. \quad (3)$$

If the scale is proportional, then

$$[t^\circ(1), ..., t^\circ(n), ..., t^\circ(N)] = [\mathfrak{t}^\circ(1), ..., \mathfrak{t}^\circ(n), ..., \mathfrak{t}^\circ(N)]. \quad (4)$$

Smoothing the experimental dependences $\mathfrak{v}(\mathfrak{t}^\circ)$ by the least squares method [19, 20] gives

$$\mathfrak{v} = a\mathfrak{t}^\circ + b, \quad (5)$$

where

$$a = \frac{N\sum_{n=1}^{N} t^{\circ}(n)\vartheta(n) - \sum_{n=1}^{N} t^{\circ}(n)\sum_{n=1}^{N}\vartheta(n)}{n\sum_{n=1}^{N}[t^{\circ}(n)]^2 - \left(\sum_{n=1}^{\mathrm{Nn}} t^{\circ}(n)\right)^2};$$

$$b = \frac{\sum_{n=1}^{N}[t^{\circ}(n)]^2\sum_{n=1}^{N}\vartheta(n) - \sum_{n=1}^{N} t^{\circ}(n)\sum_{n=1}^{N} t^{\circ}(n)\vartheta(n)}{n\sum_{n=1}^{N}[t^{\circ}(n)]^2 - \left(\sum_{n=1}^{\mathrm{Nn}} t^{\circ}(n)\right)^2}.$$

The sensor is considered to have failed the test if $\|a - a_s\| < \varepsilon_2$, where a and a_s are respectively the reference and measured values of the transfer coefficient ε_2 - the largest allowable deviation of the transfer coefficient from the reference value. Also, the sensor is considered unusable if the approximation error $\vartheta(t^{\circ})$ of the straight line (15) is greater than the threshold value, namely

$$\sum_{n=1}^{N}\|\vartheta(n) - \mathrm{at}^{\circ}(n) + b\| > \varepsilon_3,$$

where $\|\ldots\| = (\ldots)^2$.

The distortion of the IR sensor is determined by the deviation of the centers of thermal images of infrared LEDs located at the centers of the boundaries along the y, z coordinates from the straight lines connecting the centers of the images of the corner LEDs. To do this, a signal u_3 is sent from the control unit 5, which turns on the LEDs 4. The scene is scanned and formed by the FCMI. on which there are only thermal images of the background and LEDs. Further, the FCMI is subjected to binarization and filtering by a median filter [21, 22], as a result of which a binary image of the LED is formed, the $i(z)$-*th* row of which consists of a chain of ones with indices $j[y, i(z),\min] \le j[y, i(z)] \le j[y, i(z),\max]$. Similarly, the $j(y)$-th column of the binary image of the LED includes chains of ones with indices $i[z, j(y),\min] \le i[z, j(y)] \le i[z, j(y),\max]$. In this case, the entire image is inscribed in a rectangle with coordinates $i[z, j(y),\min]_{\min[j(y)]} \le i(z) \le i[z, j(y),\max]_{\max[j(y)]}$, $j[y, i(z),\min]_{\min[i(z)]} \le j(y) \le j[y, i(z),\max]_{\max[i(z)]}$. The total number of pixels that form the image of the LED is

$$N_{\Sigma} = \sum_{i(z)=i[z,j(y),\min]_{\min[j(y)]}}^{i[z,j(y),\max]_{\max[j(y)]}}\{j[y, i(z),\max] - j[y, i(z),\min] + 1\}.$$

The coordinates of the center of the binary image of the LED are defined as the coordinates of its center of mass as follows

$$i\quad(z) = \frac{1}{N_{\Sigma}}\sum_{j(y)=j[y,i(z),\min]_{\min[i(z)]}}^{j[y,i(z),\max]_{\max[i(z)]}}\sum_{i(z)=i[z,j(y),\min]}^{i[z,j(y),\max]} i(z). \quad (6)$$

$$j\quad(y) = \frac{1}{N_{\Sigma}}\sum_{i(z)=i[z,j(y),\min]_{\min[j(y)]}}^{i[z,j(y),\max]_{\max[j(y)]}}\sum_{j(y)=j[y,i(z),\min]}^{j[y,i(z),\max]} j(y). \quad (7)$$

After determining the centers of the thermal images of the LEDs, the conditions are checked

$$\varepsilon_4 > \left\|\frac{i_{\mathrm{lt}}\ (z) + i_{\mathrm{rt}}\ (z)}{2} - i_t\ \right\|;\ \varepsilon_4 > \left\|\frac{i_{\mathrm{lb}}\ (z) + i_{\mathrm{rb}}(z)}{2} - i_b\ \right\|$$

$$\varepsilon_4 > \left\|\frac{j_{\mathrm{lt}}\ (y) + j_{\mathrm{lb}}\ (y)}{2} - j_l\ \right\|;\ \varepsilon_4 > \left\|\frac{i_{\mathrm{rt}}\ (y) + i_{\mathrm{rb}}(y)}{2} - i_r\ \right\|, \quad (8)$$

where ε_4 - maximum allowable distortion; $i_{\mathrm{lt}}\ (z)$, $j_{\mathrm{lt}}\ (y)$ - measured coordinates of the image of the upper left LED; $i_{\mathrm{rt}}\,(z)$, $j_{\mathrm{rt}}\ (y)$ - coordinates of the image of the upper right LED; $i_{\mathrm{lb}}\,(z)$, $j_{\mathrm{lb}}\,(y)$- measured coordinates of the image of the lower left LED; $i_{\mathrm{rb}}(z)$, $j_{\mathrm{rb}}(y)$- coordinates of the image of the lower right LED; $i_t\ (z)$, $j_j\ (y)$ - coordinates of the image of the upper central LED; $i_b\ (z)$, $j_b\ (y)$ - coordinates of the image of the lower central LED; $i_l\ (z)$, $j_l\ (y)$ - coordinates of the image of the left central LED; $i_r\ (z)$, $j_r\ (y)$ - coordinates of the image of the right central LED.

If at least one of the conditions (8) is not met, the IR sensor is considered unusable.

The resolution control of the IR sensor is illustrated in figure 3, where the signal $v(y, z)$ is given in dimensionless units, which is formed at the output of the device when scanning a section of a scene consisting of two conductive plates turned relative to each other at a small angle α. The plates are heated to a certain temperature, at which a signal is formed at the sensor output, indicated by unity in Figure 3. Due to the fact that the optical-electronic subsystem of the sensor is a spatial filter [23], the signal at its output can be described by the following expression

$$v(z, y) = 1 - \frac{1}{\sqrt{2\pi\beta}}\left\{\int_{-\infty}^{y}\exp\left[-\frac{(\xi - \alpha z)^2}{2\beta}\right]d\xi - \int_{-\infty}^{y}\exp\left[-\frac{(\xi + \alpha z)^2}{2b}\right]d\xi\right\}, \quad (9)$$

where β – parameter that determines the bandwidth of the filter; α→0 - insert angle; ξ - auxiliary variable.

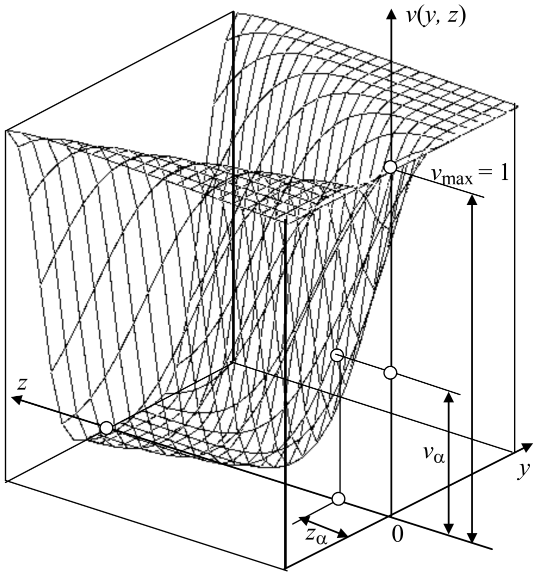

Figure 3: Resolution control

At z→0, $v(z,y)$→1; at z→∞ and y = 0 $v(z,0)$→1. Obviously, the value of function (9) v_α at some critical value z_α can characterize the resolution of the sensor. Information loss in this case occurs due to the reduction of the dynamic range of the parameter $v(z,y)$.

It follows from the foregoing that when controlling the resolution, it is necessary to scan the generator of reference thermal signals in the direction y, perpendicular to the axial line of the location of the conductive plates 1. With each scan at the location of the axial one, it is necessary to determine the value of function (9). When a function value equal to v_α appears, it is necessary to determine the z_α at which this happened. If $v_\alpha > \varepsilon_5$, then sensor adjustment is required, otherwise the IR sensor is serviceable.

3. Conclusion

Thus, an approach to testing information-measuring systems operating in the IR range is proposed, based on the physical generation of thermal signals that have certain properties necessary to control the corresponding informative parameters. It is shown that the linearity of the dependence of the informative parameters of the observed scene on the informative parameters generated at the output of the IR sensor implies the transmission of this parameter without loss. Otherwise, there are losses that can be estimated during digital processing of the facsimile digital model of the image formed at the output of the sensor.

Further research in this area can be aimed at creating a system for automatic control of the parameters of IR sensors.

This article was written with the support of the Russian Foundation for Basic Research under project 19-47-710004 r_a.

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