Compensation of IR-sensor Fixed Pattern Noise during Point Object Magnitude Recovering

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Abstract

The paper is devoted to describing a principally new method of recovering pulse magnitude which is the reaction of infrared (IR) scanning linear sensor on strobe light spots from point objects. Instead of traditional matching filtering where it is impossible to take into consideration deviations of the pulse magnitude and form depending strongly on a random spot position relatively photosensitive elements, fixed pattern noise (FPN) of sensitivity and FPN of dark current, the suggested method is almost invariant to FPN. The method uses the digital pulse stabilizer based on so-called probabilistic relay. The experimental results have shown that the suggested methods allows not only recovering both magnitude and form of the pulse sequence with good accuracy but leads to improving the quality of the formed image because the inverse coefficients of the stabilizer multiplier can be used for "on fly" IR-sensor calibration.

Keywords

Infrared sensor, fixed pattern noise, point object, pulse stabilizing, magnitude recovering.

1. Introduction

Estimation of the parameters of light point objects (PO) is an important task in thermal imaging, or infrared imagery [1-3]. As a rule, the reaction of a scanning analyzer with line(s) of photosensitive elements (PSE) to PO manifests itself in the form of bell-shaped electrical pulses appearing at the outputs of the corresponding PSE. This circumstance is due to the fact that the diameter of the scattering spot at the output of the analyzer lens is consistent (that is, equal) with the size of the photosensitive square [2]. The information parameters of such pulses are their amplitude and shape (fronts), which makes it possible to evaluate various parameters of the PO. For example, the distances (or the coordinates) to the PO are calculated from the amplitudes of the pulses. In robotics devices, sequences of light pulses carry control information that is embedded both in the amplitude and in the shape (fronts) of the pulses [4-8]. The task of the magnitude recovering of the PO also related to other approaches is being solved in this paper.

Most methods of measuring the parameters of point objects are based on various modifications of one-dimensional matched filtering algorithms, correlation-extreme processing, etc. [9-15]. At the same time, it is usually assumed that the noise of PSE is not correlated, background and structural interference are absent, etc. In such conditions, these methods provide high accuracy of amplitude measurement, preservation of pulse shape. However, for a set of optoelectronic scanning system developments containing infrared (IR) sensors, such assumptions are unacceptable for the following reasons. Firstly, since the diameter of the scattering spot is consistent with the size of the PSE square, the energy of the light spot is distributed over neighboring PSEs that leads to a significant decrease in the signal-to-noise ratio. Secondly, the so-called thermal noise in each electronic channel of the corresponding PSE is strongly developed due to the relatively large value of the PSE time constant. Thirdly, there is a significant structural interference due to the action of the dark current of the PSE, which manifests itself as slowly changing low-frequency interference. Finally, when sequentially multiplexing a large number

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
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of IR-sensor channels with a built-in electronic switcher (multiplexer), a pulse from PO appears to be represented by a limited number of discrete samples separated by the sampling period of the PSE line. The displacement of the maximum of the pulse signal relative to the sampling moments leads to a decrease in the signal-to-noise ratio, so the problem of weak signal detection arises.

2. Problem definition

Suppose that an IR-sensor with a line of non-overlapping PSEs is used to register optical signals. The sensor objective (lens) receives an input optical signal, which is a strobe of several light pulses of constant brightness (not less than 7 pulses in the sequence). In this case, the position of the light spot is random with respect to two adjacent PSE squares; therefore, the bell-shaped electrical pulses appear at the outputs of two adjacent PSEs. Obviously, the approximation of such pulses by a cosine-square function is too rough in the sense of detecting weak optical signals. Thus, we use an accurate mathematical model suggested by the authors in [20] for the PSE reaction to a light spot from a point object.

The detection problem is further aggravated by the fact that any IR-sensor has a fixed pattern noise (FPN) of sensitivity what leads to floating the transmission coefficients of the PSEs up to ± 30%. At the same time, the FPN of the dark current acts in the electrical channels (circuits) of the PSE providing significant shifts in the output signal of the PSE. It is proposed to use a sinusoidal signal with an amplitude of up to 50 % of the pulse amplitude and a frequency of 200..300 Hz as a model of the dark current FPN. As for a model of thermal noise of PSE, we consider additive white Gaussian noise with zero mean and variance which is changed during the research. Since the development of digital processing algorithms is required, it is proposed to use an analog-to-digital converter (ADC) with 14-bit and uniform quantization for experiments. Thus, the main goal of the paper is to develop method for detecting and stabilizing pulse sequences from point objects in a complex interference-signal environment. To achieve this goal, it is proposed to use a digital stabilizer of pulse signals developed by the authors and described in [16].

3. The suggested solution

Let us consider the basic idea of the proposed method of stabilizing a sequence of pulse signals from optical light pulse signals, which, as shown above, are the reaction of the IR-sensor that perceives them as point objects. It was also shown in the previous section that the position of the light spot is random, and in most cases the light spot falls on two adjacent PSE squares arranged in the form of a line. It is required to develop a method for stabilizing a sequence of pulse signals that are distorted by FPN of sensitivity which is considered as multiplicative interference, FPN of the dark current which leads to low-frequency interference in the output signal of the PSE, as well as a high-frequency additive thermal noise with a Gaussian distribution and zero mean.

In other words, we need to obtain a pulse sequence of electrical signals from light pulses at the output of the IR-sensor, stabilized at the level of a conventional unit. Since a light spot whose diameter is equal to the size of the PSE square is "split" into two parts (in the most cases), the main idea of the method is to stabilize channel pulses (after they are detected against the background of interference) at the level of 0.5 of the conventional unit. After processing, the signals from neighboring channels of the PSE are summed, thus obtaining a pulse sequence at the output of the IR-sensor at the level of a conventional unit.

Therefore, the processing of the output signals of the IR-sensor can be performed in the same way in each PSE channel. Hence, it makes sense to proceed to the consideration of a one-dimensional algorithm for stabilizing a sequence of pulses, the shape of which is known and their magnitude should be stabilized at the level of a conventional unit. The block diagram of the processing method is shown in Figure 1. Symbols on the diagram: $PSE_1 \ldots PSE_M$ are M photosensitive elements of the line; MUX is the electronic switcher (multiplexer); ADC is an analog-to-digital converter; DS_1 and DS_2 are the single-channel digital stabilizers, $\hat{U}_n$ is the amplitude estimator of the whole pulse magnitude U from the PO for the current sampling time n.

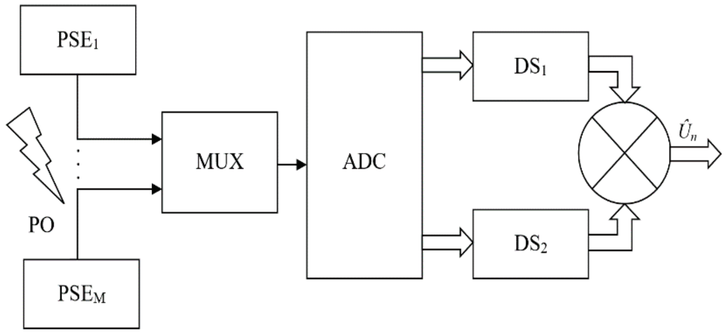


Figure 1: Block diagram of the processing method

4. Channel Digital Pulse Stabilizer

Below we render shortly the main idea of the digital pulse stabilizer based on our work [16]. In order to mathematically describe the pulse sequence, a set of states $\theta = \{\upsilon_0, \upsilon_1\}$, is introduced into consideration where the variable υ_0 determines the absence of a pulse or its presence below a given threshold *a* (in our case, this is the level 0.5); the variable υ_1 determines the pulse that exists above the threshold *a*. At each moment of time t_n, the detection of a pulse leads to the calculation of the value of the function:

$$v(\theta_n) = \begin{cases} 0, \, if \;\; \theta_n = \upsilon_0; \\ 1, \, if \;\; \theta_n = \upsilon_1. \end{cases}$$

The additive noise S_n (the thermal, or channel noise), the multiplicative interference λ (FPN of sensitivity) and the slow-changing low-frequency interference x_n (FPN of dark current) are superimposed on the pulse signal $v(\theta_n)$, as a result of which the observed signal has the following representation:

$$Z_n = \lambda\left[v(\theta_n) + s_n\right] + x_n = \lambda v(\theta_n) + S_n + x_n,$$

where $S_n = \lambda s_n$.

Denoting by $\overline{x}_n$ the a priori value of the low-frequency interference, it is possible to obtain an estimate of its magnitude by applying an exponential smoothing filter with a weighting factor α: $\hat{x}_n = \alpha\overline{x}_n + (1-\alpha)(z_n - \upsilon_n)$. After subtracting the obtained low-frequency interference estimator $\hat{x}_n$ from the input signal, the next task is to compensate for the multiplicative interference λ. For this purpose, it is necessary to set such a gain value K_n at the next clock cycle *n*, at which the amplitude of the pulses would be close to unity. At the same time, by the time t_n, the amplifier on the previous clock cycle *n*-1 will have a gain value of K_{n-1}, then, without taking into account low-frequency interference, the signal at the output of the amplifier will be equal to:

$$z_n = K_{n-1} Z_n = l_n v(\theta_n) + \xi_n,$$

where $l_n = K_{n-1}\lambda$; $\xi_n = K_{n-1} S_n$.

To fully compensate for the multiplicative interference, it is necessary to set such a value K_n that the ratio takes place:

$$K_n \lambda = K_n \frac{l_n}{K_{n-1}} = 1, \text{ or } K_n l_n = K_{n-1}.$$

Further, the errors ε_υ, ε_l and ε_k of value estimators $v(\theta_n)$, l_n и K_n are introduced into consideration, respectively. It is taken into account that information about the amplitude of the pulses, the possibility of estimating their amplitudes and controlling the gain of the amplifier are available only when $\nu(\theta_n)=1$. In the absence of pulses (when $\nu(\theta_n)=0$), there is no information about the amplitude of the pulses and there is no reason to change the previously obtained estimator of the pulse amplitude and the established gain already. Due to the effect of additive noise ξ_n, the errors will be random variables depending on the state of the signal θ_n and the amplitude l_n of the pulse, and have the form:

$$\varepsilon_\upsilon=(\upsilon_n-1)\nu(\theta_n)+\upsilon_n(1-\nu(\theta_n));$$

$$\varepsilon_l=(\hat{l}_n-l_n)\nu(\theta_n)+(\hat{l}_n-\hat{l}_{n-1})(1-\nu(\theta_n));$$

$$\varepsilon_k=(K_nl_n-K_{n-1})\nu(\theta_n)+(K_n-K_{n-1})(1-\nu(\theta_n)).$$

Using the minimum square error (MSE) criterion, we obtain an expression for an optimal estimate υ_n after some algebra:

$$(\upsilon_n-1)N_{z_n}\left(\overline{l_n,S_{z,1}^2}\right)\xi(\upsilon_1)\frac{1}{p_{z_n}}+\upsilon_nN_{z_n}\left(0,S_{z,0}^2\right)\xi(\upsilon_0)\frac{1}{p(z_n}=0.$$

It is easily to note that this ratio is a Bayesian formula and the variable υ_n represents the *a priori* probability that the pulse signal at the clock cycle *n* is in the state $\theta_n=\upsilon_1$, and the probability $\xi(\upsilon_1)=\overline{\upsilon}_n$ represents the *a priori* probability of that the pulse signal is in this state.

If we consider the change of state from cycle to cycle as a Markov chain with two states υ_0, υ_1, and with transition probabilities q_{ij}, $i,j\in\{0,1\}$, then the probability $\overline{\upsilon}_n$ is the result of a statistic prediction of probability υ_{n-1} by one step and is determined by the formula of total probability $\overline{\upsilon}_n=\upsilon_{n-1}(1-q_{01}-q_{10})+q_{01}$.

It is also convenient to introduce into consideration the likelihood ratio defined by the following relation:

$$\beta(z_n)=\frac{N_{z_n}(\bar{l}_n,S_{z,1}^2)}{N_{z_n}(0,S_{z,0}^2)} \tag{1}$$

The introduced notation allows us to write the formula for υ_n in a more convenient form:

$$\upsilon_n=\frac{N_{z_n}\left(\overline{l_n},S_{z,1}^2\right)\xi(\upsilon_1)/N_{z_n}(0,S_{z,1}^2)}{[1-\xi(\upsilon_1)]+N_{z_n}\left(\overline{l_n},S_{z,1}^2\right)\xi(\upsilon_1)/N_{z_n}(0,S_{z,1}^2)}$$

Or

$$\upsilon_n=\frac{\beta(z_n)\bar{\upsilon}_n}{1-\bar{\upsilon}_n+\beta(Z_n)\bar{\upsilon}_n}=\frac{\beta(z_n)\bar{\upsilon}_n}{1+[\beta(z_n)-1]\upsilon_n}. \tag{2}$$

Equation (2) gives a recurrent algorithm for threshold detection of the pulse existence interval under interference conditions and is discussed in more detail in [17, 18], as well as in [19], where it is called a probabilistic relay.

Defining the estimators $\hat{l}_n$, K_n in a similar way

$$\widehat{l}_n=m_1\upsilon_n+\widehat{l}_{n-1}(1-\upsilon_n),$$

$$K_n=q_nK_{n-1},$$

where

$$q_n=\frac{(1-\upsilon_n)+m_1\upsilon_n}{(1-\upsilon_n)+(m_1^2+S_1^2)\upsilon_n},$$

and also taking into account the low-frequency interference estimator obtained using a smoothing filter, the following ratio is derived after some algebra:

$$K_n = q_n K_{n-1} = \frac{K_{n-1}}{1 + b\upsilon_n (K_{n-1} Z_n - \bar{x}_n - 1)}.$$

The last equation gives the algorithm for stabilizing pulse signals and determines the internal structure of the digital pulse stabilizer; again, the more detailed description on how the equations and formulae above have been received one can find in our work [16].

5. Experimental results

To simulate and study the method described above for recovering pulse magnitudes of the IR-sensor, the MATLAB modeling environment has been used with the addition of scripts written in C++ to speed up routine calculations.

Let us consider the aspects of simulation modeling. First of all, it should be noted that the probability relay unit (PR) was modeled in a separate script using a simpler formula for the likelihood ratio [16]:

$$\beta(z_n) = e^{k(z_n - a)},$$

where a is a given threshold level, k is a coefficient determining the steepness of the function. In the absence of noise, the coefficient k is chosen to be large; then the value of k decreases if the noise variance increases.

Modeling of a light spot fitting on the PCE squares was performed as follows. At first, using a random number generator (RNG), the values of the spot offset relative to two neighboring PSE squares were generated, and then the procedure for calculating the shape of two pulse signals was started, depending on which part of the spot falls on the first or second PSE squares. At the same time, the simulation of the output signal from each PSE was carried out on two scales: at a small scale, a continuous signal was actually simulated, and at a large scale, a small number of discrete samples L (5..9) were selected at an equal sampling period. Thus, the operation of the electronic switcher (multiplexor) of the IR-sensor, sequentially interrogating the PSE in the line, was modeled. Since the selection of these samples was carried out at random points in time, the sampling effect was taken into account in this way, when the pulse is shifted relative to the sampling moments.

As follows from the problem definition, when a scattering spot from a point object falls entirely on one PSE square of size d, an electric pulse of known duration and shape occurs at the output of the non-inertia light-signal converter:

$$s(t) = U\gamma(t),\ t \in \tau_u,$$

the amplitude U of which is proportional to the intensity of radiation from a point object. At a known scanning speed, the pulse duration is defined as $\tau_u = 2d / V$, where V is the scanning speed, and its shape, described by the Bessel functions [5, 7], depends on the nature of the radiation intensity distribution over the area of the scattering spot and the zone characteristic of the PSE square. The most common laws of radiation intensity distribution in the literature are Gaussian and uniform, and with a constant differentiated steepness of the transformation at all points of the PSE square, the pulse shape is close to bell-shaped [5].

Therefore, two cases of mutual location of the point object and the IR-sensor are possible. Below we render our results from the work [20].

1. The point object does not fall into the scanning area, then $\bar{y}_0 > r$ (Figure 2, a). Taking into account the size of the PSE square ($2r \times 2r$), the following expression describing the output signal has been obtained:

$$U(t) = U_1(t) = \begin{cases} 0,\ t < t_1,\ t > t_4; \\ F(r) - F(a),\ t_1 \le t < t_2; \\ F(b) - F(a),\ t_2 \le t < t_3; \\ F(b) - F(r),\ t_3 \le t \le t_4; \end{cases} \tag{3}$$

where

$$t_{1,4} = \frac{\left(\bar{x}_0 \mp r \mp \eta\right)}{V},\ t_{2,3} = \frac{\left(\bar{x}_0 \mp r \pm \eta\right)}{V},\ \eta = \sqrt{2\left|\bar{y}_0\right| r - \left|\bar{y}_0\right|^2},$$

$$F(n)=\frac{n-\lambda}{2}\sqrt{r^2-\lambda^2}+\frac{r^2}{2}\arcsin\frac{n-\lambda}{r}+\left\|\overline{y_0}\right|-r\right|(n-\lambda),$$

$$a=\lambda-\eta;\ b=\lambda+\eta;\ \lambda=\overline{x_0}-\upsilon t;\ \lambda_0=n-\lambda.$$

2. The point object is located in the scanning area, then $\overline{y}_0 \le r$ (Figure 2, b).

$$U(t)=\begin{cases}0,\ t<\dfrac{\overline{x_0}-2r}{V}\ \text{and}\ t>\dfrac{\overline{x_0}+2r}{V};\\ A(\lambda)-U_1(t)\ \text{when}\ \dfrac{\overline{x_0}}{V}\le t\le\dfrac{\overline{x_0}+2r}{V};\\ A(-\lambda)-U_1(t)\ \text{when}\ \dfrac{\overline{x_0}-2r}{V}\le t<\dfrac{x_0}{V};\end{cases} \tag{4}$$

where

$$A(n)=2r^2 arctg\sqrt{\left(\frac{-n}{2r+n}\right)^{-1}}-\sqrt{2rn-n^2}(r-n).$$

The values of $U_1(t), \lambda, t_i, i=1\div 4,$ are calculated according to (3).

Figure 3 shows curves reflecting the shape of electrical pulses that are the reaction of the IR-sensor to the effects of a point object at different values. This figure also reflects significance of differences between the real signal and its standard approximation based on the $\cos^2$ function. Our experiments have shown that the error for amplitude estimating by matching filter can reach up 30 % when interferences are absent. In other words, it is similar to the FPN of sensitivity.

Formulae (3) and (4) show that the shape of the channel pulses depends on the vertical coordinate of the scattering spot center $\overline{y}_0$ and can vary from quasi-rectangular ($\overline{y}_0 > r$) and ($\overline{y}_0 - r$) has a small value) along with a length decrease (Figure 2, a) to bell-shaped ($\overline{y}_0 = 0$) for the situation on Figure 2, b.

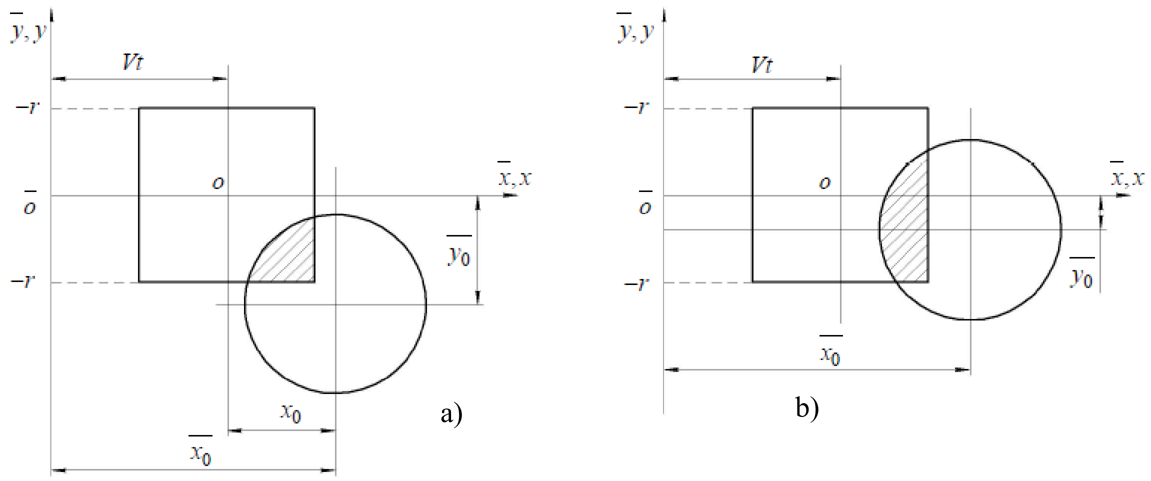


Figure 2: Two situations of the mutual location of the light spot and the PSE

The input signal was distorted by low frequency interference (LFI), representing FPN of dark current:

$$x_n = A_x \sin(\pi n/T_x),$$

where A_x is the amplitude of LFI, T_x is its period.

The amplitude of the LFI (the dark current) varied up to 50 % of the amplitude of the pulses, and the period T_x was determined through the frequency at 200..300 Hz.

The multiplicative interference λ (floating transfer coefficients of PSEs) was modeled using two RNGs generating transfer coefficients for each of the two PSE from a range of ± 30%. The additive noise was also modeled using a RNG with a given variance. The pulses formed in this way were fed to the input of a digital stabilizer, which detects a useful signal using the probabilistic relay and leads it to the conditional level a=0.5. The results of the digital stabilizer operation for one PSE channel are shown in Figure 4 [16].

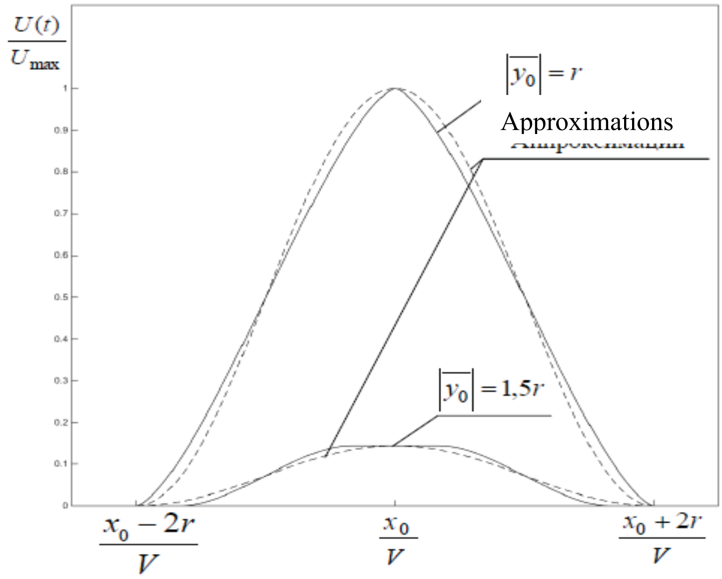
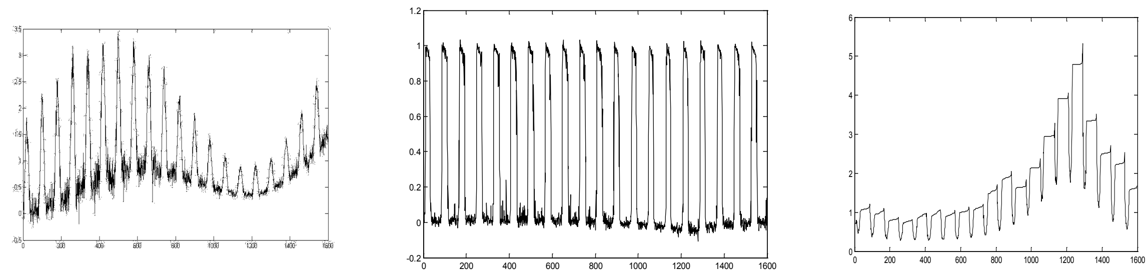


Figure 3: The pulse signal model (solid line) and its approximation by the cos^2 function



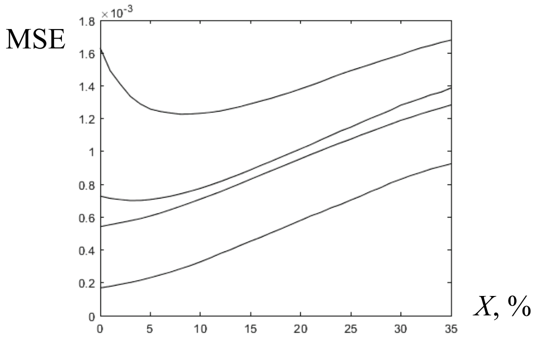
a) Distorted input pulses. b) The stabilized channel output. c) Control signals for the stabilizer internal multiplier.

Figure 4: The experimental results (1)

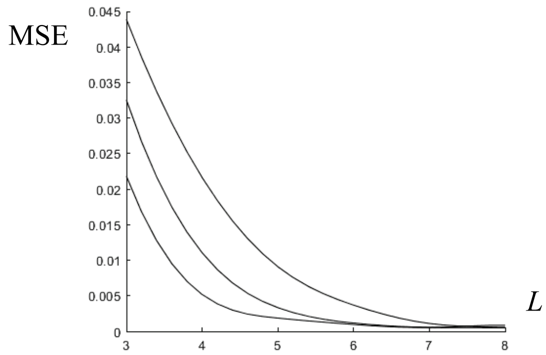
To evaluate the effectiveness of pulse stabilization from point objects, the mean-square error (MSE) of estimating the amplitude of the total signal from a conventional unity obtained through channel estimators of the amplitudes of the corresponding pulses stabilized to the level of 0.5 from a point object was calculated.

During the experiments, the dependences of the MSE pulse amplitude estimators on the LFI X (as a percentage of one) were obtained for a different number of pulse samples (Figure 5, a), on the intensity of high-frequency noise (Figure 5, b), on the number of samples L (Figure 6, a), from the number of pulses N in the sequence (Figure 6, b).

The obtained dependences allow us to conclude that the proposed method for processing the pulse sequences of the IR-sensor as a reaction to point objects allows us to confidently stabilize the output pulses relative to a conventional unit with a relatively small MSE.

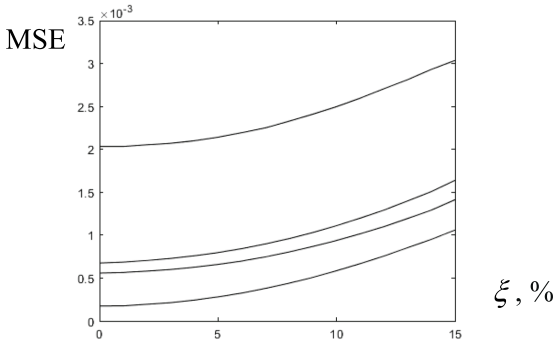


a) The dependence of the MSE estimating pulse amplitude on the LFI *X* (as a percentage of one) for the quantity *N* of pulses in the sequence to be equal to 6, 7, 8, 9 (the upper curve corresponds to *N*=6, the lower – to *N*=9, noise is absent).

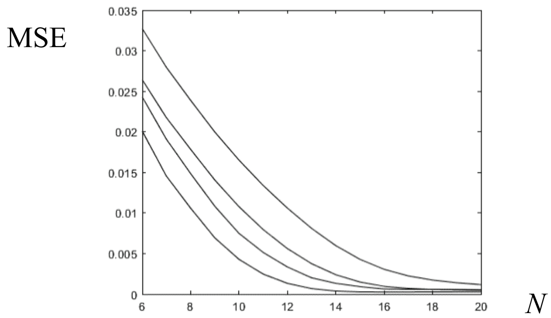


b) The dependence of the MSE estimating pulse amplitude on the number of samples *L* for the quantity *N* of pulses in the sequence to be equal to 15, 20, 25 (15 from above, 25 from below, noise is absent).

Figure 5: The experimental results (2)



a) The dependence of the MSE estimating pulse amplitude on the intensity of high-frequency thermal noise (as a percentage of the signal amplitude) for the number of samples *L* equal to 6, 7, 8 and 9 (the upper curve corresponds to *L*=6, the lower curve – to *L*=9).



b) The dependence of the MSE estimating pulse amplitude on the quantity of pulses *N* in the sequence for the number of samples per pulse *L* equal to 6, 7, 8, 9 (the upper curve corresponds to *L*=6, the lower curve – to *L*=9).

Figure 6: The experimental results (3)

6. Conclusion

The developed method does not take into account the features of constructing the lines of modern IR-sensors. In particular, the technological gap between the PSEs can lead to the loss of the light spot energy. On the other hand, there are various types of lines with overlapping PSEs to avoid possible losses of light energy. From our point of view, such situations can be interpreted as an additional change in the transfer coefficients of the PSE electronic channels, accompanied by a change in the shape of the pulses, as follows from our model. Nevertheless, it should be noted that the proposed method for processing pulse sequences restores the amplitude of the detected pulses to a given level; therefore, it can be expected that the obtained solution will remain operational in both cases.

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