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DETECTION OF LOCAL CHANGES ON TRUNK PRODUCTS PIPELINES ROUTES BY MEANS OF THERMAL IMAGING: INTRODUCTION

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In this article the problem of detection of local changes on trunk products pipeline routes by means of thermal imaging has been formulated, and ways of its decision have been proved.[1]

Keywords: *trunk pipeline, unauthorized cut-in, thermal reconnaissance, detection parameters.*

Nowadays oil-and-gas industry is the source of a half of national currency income. Housing and communal services is one third of all national funds, state of which impacts psychological effect in population's perception of current political system.

The key part in the feed systems of above-mentioned fields of economy is pipelines. Considering the standard life duration of the most part of transport infrastructure is expired, the increase of losses of products dispensed is expected. It is reported that oil product losses when dispensing in trunk pipelines are estimated from 1 to 1.2 % of dispensed capacity. In Tyumen oblast alone this losses are 2,5 million tones [1].

The situation with unauthorized withdrawal of dispensed oil products is extremely disturbing in the country last years. It is reported in annual report of Russian Government that the withdrawal of oil products in 2003 is estimated as 3 % of dispensed oil products, and this percentage has been increasing by 2 % a year.

Cited data say that there were some mistakes in the organization of security of pipeline systems and moral health of the population of our country has become worse. Interest of terrorists makes draw attention on this problem. There are several precedents of blasting the trunk pipelines. Considering the scales of damage brought by such subversive acts, the increase of such crimes is expected in future.

Losses reduction of dispensed products is the task of the pipelines state control (monitoring) services. Ideally these services must fix the place of product leakage in coordinate's detection.

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There are more tough requirements to detection of unauthorized accesses to a pipeline: when time of the access and coordinates of expected place are registered. Requirements to detection of a planted bomb are not formulated.

There are many works published concerning methods and means of control and searching of product leakages. Not all of these works meet the requirements concerning sensitivity needed, detection operability, control continuity, precision of leakages (accesses) localization. The change of consumption rate and also the negative percussion waves' method can be put to methods' class providing detection of the emergency situation appearance in real time. However the threshold sensitivity of these methods (≥ 100 m^3/h) easily allows solving the problem of unregistered unauthorized withdrawal of dispensed products.

Analysis of technology creation task of "theft canal" detection on the stage of accessing to trunk pipelines allows drawing a conclusion that there is a lack of alternatives to acoustic like control. Internationally recognized technology of oil leakages control LASP (Leak Alarm System for Pollutants) is based on usage of special hose laid along the pipeline. There is a method of improving this technology: installation of vibroacoustic sensors on a pipeline cover with data transmission via telemechanic channel. Disadvantages: large quantity of sensors put a question of financial viability besides it is hard to avoid false alarms in such system (intruders can simulate special situations). There is need for periodical check of alarms reliability for example by means of aviation. Visual method of estimation of a route state is described by high missing probability: branch pipes are masked within visible wave band, and output of escaped product can occur on considerable distance from product pipeline.

Improving "patrol control" systems is possible by means of thermal imaging reconnaissance. New age thermal imaging devices provide thermal images of pipeline routes of excellent quality. But to talk about thermal imaging (optical) reconnaissance technology there is need as to estimate risk of decisions made.

Basic problems of visual reconnaissance come to search of changes on pipeline route for the certain time span after previous check and their interpretation. Typical problems: oil seepage detection on the surface (when leakages occur), registration of unauthorized works on the route.

The spot of rounded or extended shape distinguished against the underlying surface can be interpret as seepage of liquid leaking from pipeline on the border "soil-atmosphere". If the image is constructed by the reflect radiation, a physical property of leakage is the change of reflection ratio at the local zone of the route. Thermal contrast is defined by large quantity of factors: specified gradient of reflection ratio, local change of thermal physic parameters of soil, bounds of reflection ratio and temperature in the place of product's leakage.

If we base on physics of thermal images forming in the environment with unsteady flows of energy, it should be supposed that thermal imaging systems must register the spread front of liquid in soil before it reaches the border between the environments. In this case practitioners have interest in usage of the ground intrinsic emission in estimating of the pipeline transport state.

Another problem is detection of the places of unauthorized withdrawal of the dispensed product. An intruder has enough time to access the pipeline for the time span between two checks of the route, lay a branch pipe for product withdrawal and hide it. A long time is required to see visual contrast in the place of laying of the branch pipeline (because of drying up of masking topsoil, more fast drying up of sandy soil above the branch pipe etc.). At the same time the fact of change of natural consistency of the soil necessarily alternates the thermal field of the underlying surface; on the thermal image there is thin band being formed practically in real time along withdrawal branch pipe. Is thermal contrast "object-background" sufficient to be detected on the background of related real-time?

On the fig. 1 there is the scheme of data transformation in the optical-to-electrical intrusion detection system in "normal" state of pipeline. The most important property of the source image is signal-to-noise ratio SNR_q. While spreading optical radiation in the atmosphere, its absorption is observed. However on the low attitude (~ 300 m) the absorption is insignificant and will not have impact on the results drawn below.

Radiation flux density to electric signal converter can be presented as the no noise photo receiver *PHR*, the noise source σ_N and the summator Σ. Up-to-date receivers are defined by the noise level corresponding to the temperature drop below 0,05 *K*. When working with real signals (> 0,1 *K*), a receiver's noise can be neglected.

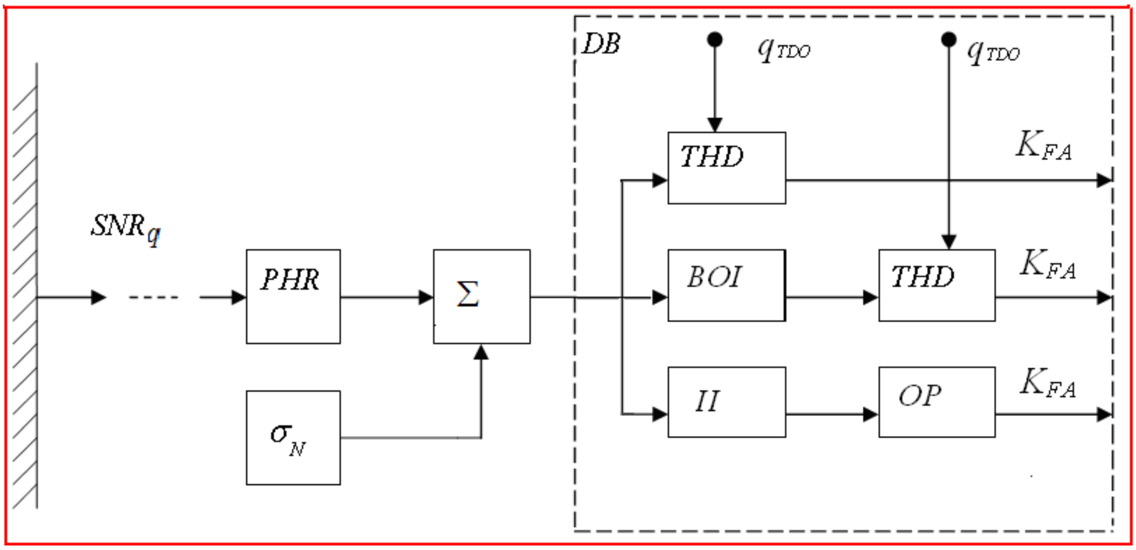

Figure 1. Structural scheme of the optical-to-electrical system of pipeline route reconnaissance: q_{TDO} – decision threshold

The decision block *DB* can be built by one of the next alternatives. More simple alternative is the threshold device *THD* that finds application if SNR_q on the input is large enough to provide acceptable number of false alarms K_{FA}. If not, there is need to search the ways of increase of SNR_q. It is possible by increasing the initial value of SNR_q (for example, by fitting of the wavelength range) or via special processing in *BOI* block (mainly with help of prior knowledge about deference between spatial signal spectrums and background fluctuations).

When processing a halftone image of the underlying surface, known block diagrams *BOI* are complex enough. There are simple engineering solutions providing increase of SNR_q to and acceptable level. However such solutions are occasional but success is achieved by successful suggestions about the use of special features of certain signals and backgrounds. Thus the *DB* block is often coming as the image indicator *II*. Decision-making functions are entrusted on the operator *OP*.

The optical-to-electrical detection system of mentioned above changes on the pipeline route is defined by three parameters: K_{FA} , SNR_q, q_{TDO}.

The false decisions flux density K_{FA} depends on the noise fluctuations power $\sigma^2_{q_B}$, the form of the correlation function $x_{qq}\ (x,y)$, the decision threshold q_{TDO} [2]:

$$K'_{FA}=\left(\frac{K_{FA}}{l_{zax}}\right)=\frac{\eta_{FA}(q_{TDO}-\overline{q}_B)}{\sqrt{2\pi}\,\sigma_{q_B}}\exp\left[\frac{-(q_{TDO}-\overline{q}_B)^2}{2\sigma_{q_B}^2}\right], \quad (1)$$

where $\overline{q}_B$ – average radiation flux density of a background; l_{zax} – band width of monitoring system;

$$\eta_{FA}=\left[\frac{\partial^2 x_{qq}(x,0)}{\partial x^2}\cdot\frac{\partial^2 x_{qq}(0,y)}{\partial y^2}-\left(\frac{\partial^2_{qq}(x,y)}{\partial x\,\partial y}\right)^2\Bigg|_{\substack{x=0\\y=0}}\right]^{0,5}\cdot(2\pi\sigma_{q_B}^2)^{-1}. \quad (2)$$

The physical meaning of $\frac{(q_{TDO}-\overline{q}_B)}{\sigma_{q_B}}$ member is minimal signal-to-noise relation $(SNR)_{\min}$. For its estimation consider backgrounds with fluctuation power spectral density by spatial frequencies in the form of

$$G_1(\omega_x,\omega_y)=C_{1M}\cdot(1+\rho_{1x}^2\omega_x^2+\rho_{1y}^2\omega_y^2)^{-3/2}; \quad (3)$$

$$G_2(\omega_x,\omega_y)=C_{2M}\cdot\exp(-\rho_{2x}^2\omega_x^2-\rho_{2y}^2\omega_y^2), \quad (4)$$

being a kind of extreme positions. Real descriptions are combinations from (3) and (4) expressions;

ω_x, ω_y – spatial frequencies; ρ_x, ρ_y – lengths of ejections for coordinate axes; C_{1M}, C_{2M} – constants.

For getting comparable results there is need to normalize (3), (4), that is to provide the fulfillment of conditions $C_{1M} = C_{2M} = C_M$ and

$$\begin{aligned}\sigma_{q_{B1}}^2&=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_1(\omega_x,\omega_y)\,d\omega_x d\omega_y=\frac{C_{1M}}{2\pi\rho_{1x}\rho_{1y}}=\\&=\sigma_{q_{B2}}^2=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_2(\omega_x,\omega_y)\,d\omega_x d\omega=\frac{C_{2M}}{4\pi\rho_{2x}\rho_{2y}}=\sigma_{q_B}^2\end{aligned} \quad (5)$$

The first normalizing condition denotes if $\rho_x\to0$, $\rho_y\to0$; $G_1(\omega_x,\omega_y) = G_2(\omega_x,\omega_y)$ i.e. if fluctuations degenerate in the white noise, fluctuation power spectral densities must be equal. The requirement of the second condition is obvious.

Let's define the correlation area of the spatial interference of the radiation field as $\pi\rho_{Bx}\rho_{By}$. Then $\rho_{1x}=\rho_{Bx}/\sqrt{2}$; $\rho_{1y}=\rho_{By}/\sqrt{2}$; $\rho_{2x}=0{,}5\,\rho_{Bx}$; $\rho_{2y}=0{,}5\,\rho_{By}$.

For isotopic background $\rho_{Bx} = \rho_{By} = \rho_k$, and if we introduce the transformation operation (3), (4) for generalization problem by the aperture (filter) that is described by the transparency distribution as the gaussoid bivariate function with the conditional radius ρ_a then

$$G_{a1}(\omega_x,\omega_y)=\sigma^2_{q_B}\pi\rho^2_k\left[1+0{,}5\,\rho^2_k(\omega^2_k+\omega^2_y)^{-\frac{3}{2}}\exp(-\rho^2_a(\omega^2_x+\omega^2_y))\right]; \quad (6)$$

$$G_{a2}(\omega_x,\omega_y)=\sigma^2_{qB}\pi\rho^2_k\exp\left[(-\frac{\rho^2_k}{4}+\rho^2_a)(\omega^2_x+\omega^2_y)\right]. \quad (7)$$

For computing of $\sigma^2_{aq_B}$ and derivatives of correlation function in (2) we use the relation from [3]

$$\int_0^\infty \exp(-c_k z_k) z_k^{v-1}(1+z_k)^{\mu_k} dz_k=\Gamma(v)\cdot u(v,\mu_k+v+1,z_k), \quad (8)$$

where $u(\ldots)$ – Kummer's confluent (hyper geometric) function,

$$u(1;0{,}5;\frac{\rho^2_a}{\rho^2_k})=2\exp(\frac{\rho^2_a}{\rho^2_k})\cdot D_{-2}\left(\frac{\sqrt{2}\,\rho_a}{\rho_k}\right);$$

$$u(2;1{,}5;\frac{\rho^2_a}{\rho^2_k})=4\exp(\frac{\rho^2_a}{\rho^2_k})\cdot D_{-3}\left(\frac{\sqrt{2}\,\rho_a}{\rho_k}\right), \quad (9)$$

D_{-2}, D_{-3} – parabolic cylinder functions that are equal [3]:

$$D_{-1}(z_\mu)=\exp(\frac{z^2_\mu}{4})\cdot\sqrt{\frac{\pi}{2}}\cdot\left[1-erf(\frac{z_\mu}{\sqrt{2}})\right], \quad (10)$$

$$D_{-2}(z_\mu)=-\exp(\frac{z^2_\mu}{4})\cdot\sqrt{\frac{\pi}{2}}\cdot\left\{z_\mu\left[1-erf(\frac{z_\mu}{\sqrt{2}})\right]-\left(\frac{\sqrt{2}}{\pi}\right)\exp\left(-\frac{z^2_\mu}{2}\right)\right\},$$

$$D_{-3}(z_\mu)=0{,}5\cdot[D_{-1}(z_\mu)-z_\mu\cdot D_{-2}(z_\mu)].$$

The probability interval with the relative error $2{,}5\cdot10^{-5}$ is approximated by the expression [4]:

$$erf(z_f)\approx1-F(z_f)\exp(-z^2_f).$$

$$F(z_f)=0{,}348\,(1+0{,}47_f)^{-1}-0{,}095879\,(1+0{,}47z_f)^{-2}+ +0{,}74785\,(1+0{,}47z_f)^{-3}. \quad (11)$$

With a glance of (2), (5) - (11) we get

$$\sigma^2_{aq_{B1}}=\sigma^2_{q_B}\left[1-\sqrt{2\pi}\frac{\rho_a}{\rho_k}F(\frac{\sqrt{2}\,\rho_a}{\rho_k})\right];$$

$$\eta_{FA1}=\frac{1}{\pi\rho_k^2}\cdot\frac{\rho_a}{\rho_k}\cdot\left[\frac{0{,}5\sqrt{\frac{\pi}{2}}\left(\frac{\rho_k}{\rho_a}\right)F\left(\frac{\sqrt{2}\,\rho_a}{\rho_k}\right)}{1-\sqrt{2\pi}\left(\frac{\rho_a}{\rho_k}\right)F\left(\frac{\sqrt{2\pi}\,\rho_a}{\rho_k}\right)}-1\right];$$

$$\sigma^2_{aq_{B2}}=\sigma^2_{q_B}\frac{\rho_k}{\rho_k+4\rho_a}\ ;\ \eta_{FA2}=\frac{1}{\pi}\cdot\frac{1}{\rho_k^2+4\rho_a^2}\ . \tag{12}$$

To avoid the effect of the aperture background fluctuation filtration and come to image domain analysis, accept minimal radius of detectable element $\rho_{ZN}=100\rho_a$. Then using (1), (12) we can calculate the relations we are interested in $K'_{FA}=f\left[(\mathrm{SNR})_{\min}\right]$.

On the fig. 2 there are curves reproducing the relation between $\lg K'_{\mathbf{FA}}\pi\rho_T^2$ and $SNR_{\min}$ for different ratios of the background fluctuation correlation radius to the radius of objects on the route ρ_k/ρ_T.

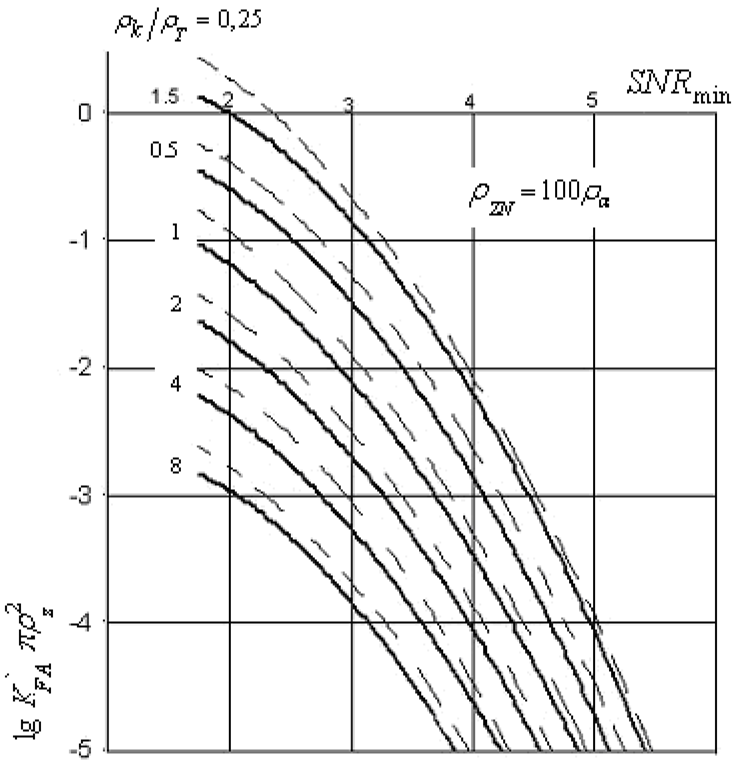

Figure 2. Curves for estimation of $SNR_{\min}$ for specified number of false ejections when detecting objects on backgrounds with Gaussian correlation functions (dashed lines) and exponential correlation functions (solid line)

Thus, the simplest alternative of the decision block *DB* – threshold device – will be effective when SNR_q on the input is equal-to-or-greater than five. If not, there is need to search the ways (to introduce additional signal processing in the *BOI* block) to increase signal-to-noise ratio.

The second problem to solve, when flying the pipeline route with the purpose of low-contrast objects fixation, is that the operator should be substituted by the automatic device for solving decision-making problems. A human is relatively inertial identifying and executing adopted decisions system.

If we base on the results of multiple published works, we come to the conclusion that: the main factors defining detection time of the object on the gray-tone display screen τ_{TD}, are its contrast μ_T, angular sizes γ_T, visual signal-to-noise ratio $(SNR)_\beta$, detection probability ρ_{TD}, screen brightness B_S and its angular sizes β_S:

$$\rho_{TD}=\left\{1-\exp\left[\frac{c_{p1}\cdot\mu_T^2\cdot\gamma_T^3\cdot B_S^{0,3}\cdot\tau_{TD}}{2\cdot\beta_S^2}\right]\right\}\left\{1-\exp\left[0,15\left((OC\Pi)_\beta-1\right)^2\right]\right\},$$

where c_{p1} =16 deg^2 · cor · min^{-3} · (cd/m ^{2})$^{-0,3}$ · c^{-1} – empirical coefficient, corresponding average observer, $\tau_{0c} = L_k / \upsilon_{up}$, L_k – the size of the area image observed on the screen along-flight direction; $(SNR)_\beta = (SNR) \cdot\sqrt{c_{p2}\cdot f_r(S_T/S_N)}$; $f_r = D_T\cdot f_{rs}/\upsilon_{up}$; c_{p2} – time constant of the eye; f_r – update rate of the information; f_{rs} – frame rate of visualization system; D_T – the size of the object to find; S_T – its surface; S_N – the surface of noise correlation on the monitor; υ_{up} – flight speed.

For getting numerical estimates with use of given formula, accept that the diameter of underlying surface pixel is equal to 0.1 meter (if resolution is lower then it's hard to distinguish between a human and cobble-stone). So in case of standard image dissector in 600 lines on the monitor screen we have L_k = 60 m. Let $(SNR)_\beta$ =5; $D_{T\,\min}$=0,1 м; β_s=50 cd/m^2; screen size 0,3 x 0,3 m; ρ_{TD} = 0,99; distance "screen-operator's-eye" 1 m, we get following estimates: if μ_T = 0,05, then $\upsilon_{up} \le$ 30 km/h; if μ_T = 0,2, then $\upsilon_{up} \le$ 100 km/h. This is unacceptable speed limit of the flight.

It's important to underscore that produced estimations of flight speed-limit fit the experimental data for detection problems solution of known objects on the noise background on moving image. These estimates provide the understanding of the problem considered.

Masking unauthorized cut-ins to product pipelines forces to come into invisible radiation range (for increase of μ_T) for pipeline detection. The requirement of detection of the work marks makes it ineffective to record the images of the laying route on magnetic (photographic) medium with next decipher on “the ground station”. The use of “radiation converter - monitor - operator” system is possible when the flight speed is inadmissibly low. The analysis of all the components of the problem considered leads to the following conclusion.

The up-to-date technology of pipeline route state control with an aircraft based on video recording of discovered area and consequent decipher on the ground station must be supplied with the departure from the norm automatic detection system on the control object to transfer the results of decipher to the control station in real time.

Is it possible to surely fix stated departures from the norm and to automate a detection process in the variant of route control considered above? Answers to this question can be found in next articles.

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