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CONCEPTION OF INTERCONNECTING SECURITY SYSTEM FOR TRUNK PIPELINES AGAINST INTENDED THREATS [1]

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Abstract: *In the article there is the information about growth of unauthorized works on trunk pipelines and about corresponding economic losses as the result of the works. The structure of interconnecting security system for mentioned objects is offered. The interconnecting security system includes optical, vibroacoustic and seismic data acquisition channels and provides decision making algorithm for these channels analysis. An approach to estimate basic parameters of the system is justified. The approach is based on minimization of amount of expenditures for security object and minimization of losses from not prevented unauthorized works on trunk pipelines.*

Keywords: *trunk pipeline, unauthorized actions, detection, seismic channel, vibroacoustic channel, thermal optical channel, interconnecting, system economics.*

Annually hundreds illegitimate cut-ins with the purpose of theft of dispensed oil products are fixed on linear parts of trunk pipelines [1, 2]. The level of the loss from these infringements can be estimated from the next data. In 2003 losses of Russian oil and gas companies are approximately 3 % from the product transported [3]. The electronic media “Federal investigations Agency” (http://www.flb.ru/info/36302.html) reports that 177 unauthorized cut-ins in product pipelines are detected around Novokuybyshevsk petroleum refinery only from 2002 to 2005 and the annual loss from these cut-ins are none less than 8.000 tonnes. In 2005 China 2.900 persons were arrested for unauthorized cut-ins and the loss was $124.6 million.

Reported estimations of increase rate of such law infringements are disturbing: in Russia 2 % per year, in Kazakhstan’s company «KazTransOil» only the number of cut-ins have been increased in 13 times during last 6 years [2, 3]. That is the counteraction to this kind of the offences is not enough and not effective.

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Law-enforcement authorities of China see the decision of the problem through hardening the punishment for oil products theft up to enactment of death penalty [4]. The Decree of the President «About creation of complex system for population security on transport» is subscribed in Russia. This Decree provides prevention of force majeure and terrorist acts on transport. Stated in the Decree task is impracticable in the aspect of pipeline transport if there is not trunk pipeline security system against intended threats: products pipeline cut-ins, bomb planting for terrorist act commission, violation of management information channel, false signal of «leakages» for vibroacoustic pipeline integrity control systems used and so on. It's enough for example to install «generator of leakages» under insulation to paralyze security service over a long period of time.

Nowadays model structure of such system is emphasized: radar reconnaissance complex, stationary sensors system, pilotless vehicle with the telecamera aboard, data collector [5]. There is neither validity of using of the systems listed nor interaction algorithm between these systems.

The article's purpose is to give proof of probable appearance of interconnecting security system for trunk pipelines against intended threats.

The interconnection concept is that if required event detection probability with usage of the event's description in certain attribute space doesn't answer consumer needs and further increasing of the probability is connected with rather considerable costs, there is need to find out an additional independent attribute. Package of such attributes lets get the effect needed with less losses. Actually, on the basis of the general theory of experiments replication, achievement of the result needed can be shown while the number of informative independent attributes analyzed by the detection system is successively increasing (Table 1).

Table 1. Data for understanding of interconnecting system efficiency

Event detection probability by:			
one attribute	two attributes	three attributes	four attributes
0.100	0.190	0.270	0.340
0.500	0.750	0.870	0.930
0.900	0.990	0.995	0.999

If each of the attributes provides events detection with the probability 0.1, when using all four attributes the number is increasing up to 0.34.

Let's define the borders of the interconnecting system of the considered purpose.

The stage of preparatory work precedes execution of crime. Preparatory work comprises definition of the place for plan realization and earth work implementation (for underground pipelines). The time that a person staying at the zone of pipeline laying is an indication of danger for the pipeline owner. For getting the information of this type the seismic detection system is offered with registered signal transmission to decision making centre by radio channel [6].

The main difficulty on the way of integration of seismic security systems is unacceptable distance of detection of a person. By means of point seismic sensors a person steps are registered at 20-100 meters distance.

Knowing the cost of seismic sensors the project costs are estimated at billions (for deploying more than 1 billion sensors for oil pipeline system of a country). Costs of such level are needed for using of distributed sensors (triboelectric, fibre optic - Table 2).

Table 2. Seismic sensors costs

Sensor type	Detection distance, meters	Cost, RUB
Geophone "BC-120"	Up to 20	17 000
Molecular-electronic sensor "METR 03"	50-100	50 000
Molecular-electronic sensor "MTSS-2003"	50-100	35 000
Fiber optic (440 meters)	-	44 000

Considering the information above seismic systems using for registration of preparatory works on trunk pipelines can be employed for security of especially important objects (pump stations, convenient for infringement zones and so on). However it's important to take into account that there can be false signals produced by interested persons. To avoid security system work blocking by false signals there is need to use additional information, for example, video images. Automatic decoding of the images of such type is not difficult task. Interconnecting of seismic and TV channels for detection of intended threats against pipeline functionality on the stage of preparations takes away the problem of false signals and increase the reliability of investigation of true situation on the pipeline route. If the area is not crowded with low-density of animality, it's preferable to use break-the-wire devices (microwire) [6].

The special addition for the detection system is analytical and human intelligence that based on the results of online monitoring of different types data sources and allows finding out the time and the place of the preparing infringement [7].

The second stage is defined by factors of interaction of the intruder with the pipeline. When executing cut-ins, pipeline insulation is removed, the pipeline is drilled and striked. Each of the impacts listed generates elastic wave that carries over the pipeline [8]. Registration of the wave serves as a signal about intruder's interaction with the pipeline that occurred. Recognition of the waveform allows us to reveal the type of interaction: drilling, strike and so on. Nowadays this area is considered as most prospective in struggle with intruders on trunk pipelines [9]. But the practice of vibroacoustic channel applying has exposed a number of points.

Pipeline covering is the source of noise. The noise is formed under influence of many causes concerned with interaction between oil-products dispensed and pipeline covering: status and mode of working of pump equipment, the impact of outer seismic vibrations sources and so on. Noise process is nonstationary. Nonstationarity is caused by:

– changing working mode of pump equipment with the average frequency about $(12 \text{ hours})^{-1}$;

– fault incidence in the pump equipment with the average frequency about $(1 \text{ week})^{-1}$;

– appearance of leakages of the oil-product dispensed $(1 \text{ month})^{-1}$;

– short-term noise of artificial origin (repair work on the route, transport driving and so on) with the average frequency $(20\text{-}100 \text{ hours})^{-1}$ depending on the place of pipeline laying;

To avoid decrease of signal detection probability on nonstationary background, there is need to use skilful technologies that complicate decision-making system.

Another restriction of vibroacoustic channel is the distance where required signal detection is reliable. The distance is defined by damping ratio and by noise of pipeline covering. Existing security systems have ~330 meters distance [10]. It's reported that in Russian territory, next automatic detection systems are used: «Magistral», «Kapkan», «Intelkon», SNCG N-2 [15]. Principle of action of the systems is extraction of signals made by mechanic interaction on the pipeline covering and when corrosive failure on the acoustic noise background. Data range declared by distance between sensors is 150-500 meters. Information about target drop-out and false alarm probabilities is not specified.

Are there opportunities to increase the distance between sensors when realizing considered principle of signal detection?

Elastic wave amplitude when propagating in the environment decreases with the distance under the law

$$u = u_0 \exp(j\omega t) \cdot \exp(-\gamma r)/r^{\nu},$$

where r – distance between signal source and receiver; $\gamma = \delta + jK$ – complex propagation constant; $K = \omega / c$ – wave number; c – speed of propagation of acoustic waves; δ – damping ratio; u_0 – original mode amplitude. For spherical wave its damping goes inversely ($1/r$, $\nu = 1$). For plane wave $\nu \rightarrow 0$, for cylindrical wave $\nu = 0.5$ [11].

The expression cited gives grounds for conclusion about strong dependence between wave damping and its frequency. This conclusion specifies experimental data cited on the fig. 1 [8].

Fig. 1. Dependence between signal-to-noise ratio and propagation distance of elastic wave in the pipeline covering

From the experimental data cited on the Fig. 1 we can conclude that to create economically sound pipeline security system there is need to use low-frequency range of elastic vibrations. If we try to forecast the trend of curve at the 1 kHz frequency, there is a hope to bring the distance between sensors up to 3-5 km. That border lets consumer see positively on this type of trunk pipeline security. The conclusion made is confirmed by the information published in [16] with description of the system WaveAlert (ASI-«ALDS» company) that detects leakages in pipelines. The system uses low frequencies (range is not specified) that allowed deploying sensors at 50 km distances. Principle of system action is not clearly specified and there is no opportunity to analyze the reliability data cited.

When unauthorized work has been finished, impact marks are masked. Rate of unregistered infringements on the first two stages was not published in literature. The information given at the beginning shows that the rate is not considerable. So there is need to employ a rider. Disadvantages of «patrol control»: low efficiency and insufficient detection reliability of masked targets.

To avoid the disadvantages, implementation of route inspection from aircraft is offered. Nowadays from among well-known systems only radiolocating and optical systems allow implementing the observation over 100 m distance. Comparing systems by resolution parameter allows giving preference to optical devices. When probing in 3 mm wavelength radio band, the resolving power of 1.5 diameter antennas averages millirads. For optical devices with optic diameter of 0.3 m, the resolving power averages fractions of millirads. On 100 m distance probing spot will has diameter about 1 m for radiolocator and about 1 mm for optical system. Subsurface connections with the sizes we interested doesn't appear in radio-frequency bandwidth [9], but ones appear clearly enough in thermal optic range [12]. In frequency window of atmosphere $\lambda \in 8;14\,\text{мкм}$, contrast «object-background» is defined by two components:

$$\mu_8 \approx \frac{\Delta \varepsilon_8}{\varepsilon_{8B}} + \frac{\Delta T}{T_B - 230} \cdot \left(1 + \frac{\Delta \varepsilon_8}{\varepsilon_{8B}}\right),$$

where $\Delta \varepsilon_8$ – radiative contrast; ΔT – temperature contrast «object-background» on underlying surface, ε_{8B} – average degree of background blackness, T_B – average background temperature.

For well-masked trenches of product disposal, radiation contrast can be absent: $(\Delta \varepsilon / \varepsilon_B) = 0$. Only temperature component $\mu_T = \Delta T / (T - A_T)$ uncovers the object. Seeping of the oil-product pumped (as a result of leakage) leads to appearance of optical $\Delta \varepsilon / \varepsilon_B$ and temperature $\Delta T / T_B$ contrasts.

Despite on long period of time from publishing of thermal images with oil leakages places form pipelines, wide integration of thermal reconnaissance means in oil and gas industry is not observed. The main reason is that contrast component μ_T is function of time having difficult enough form and changing values from positive to negative during a day. Similar conclusion goes from analyzing noise dispersion. Therefore useful signal detection algorithms are difficult on changing in time backgrounds. There is need to carry out additional researches in improving of the rates.

Another point of using air reconnaissance for pipeline state is automation of desired targets detection process. It's possible to show that airspeed will be located at the range of 30-100 km/h. It's true when observing pipeline zone is of 60 m width, underlying surface resolution is 0.1 m, signal-to-noise ratio equal to 5 and other typical parameters used for getting video. If not, target drop-outs can occur because of visual system features. Therefore using air reconnaissance, detection of wanted objects on the route of pipeline laying must be automated. As we know this issue has not been raised in open literature.

Thereby the interconnecting system for trunk pipelines security against intended threats must comprise four parts:

– information reconnaissance;

– seismic reconnaissance;

– vibroacoustic reconnaissance;

– thermal reconnaissance.

Besides, desired targets detection process must be automated.

On the Fig. 2 system's structure chart is represented.

Seismic sensors 4 form the first echelon of pipeline security. Unauthorized works detection probability increases with decreasing distance between seismic sensors. However the more number of sensors the more costs it require. Therefore choice of keyword parameter – density of seismic sensors installation – is defined via minimization costs of the system in whole (see below). Information from seismic sensors goes to data processing block via telemechanic channel 3. Data processing block calculates the probability of unauthorized works beginning. Knowing this probability, security service make a decision about further actions. The probability is used in the interconnecting system as prior information to make decision in compliance with the Bayes strategy or for counting of attack probability in the replication of experiments algorithm. There are other variants possible for appliance in decision making algorithms.

If there is data in information reconnaissance channel, posterior probability of attack is converted to probability of «attack» hypothesis with formulae of Bayes hypothesis. Probability of «attack» hypothesis by-turn is used as prior probability in the making decision algorithm working with two channel: seismic and vibroacoustic.

The second echelon of control object security is based on vibroacoustic sensor appliance 2, connected by telemechanic channel 3 with data processing block.

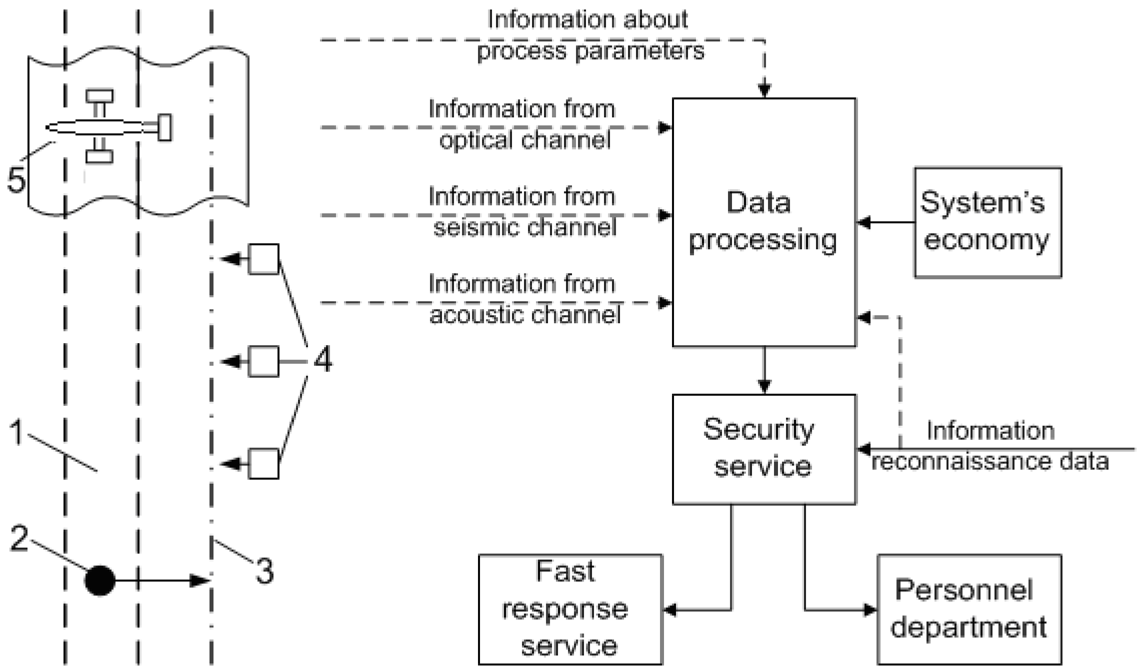

Fig. 2. Structure chart of interconnecting security system of trunk pipelines against intended threats:
1 – underground pipeline; 2 – vibroacoustic sensor; 3 – data cable for pumping process management; 4 – seismic sensors; 5 – aircraft with optical equipment

In the frames of statistical procedure of decision making, on the output of the channel there is the probability of unauthorized interaction of subject with pipeline is formed. More difficult variant of the block construction allows to distinguish the kind of interaction: earth works, isolation removing and so on. The output of the channel is connected to decision making block that is constructed with use of one of well-known classification (detection) algorithms. Positive decision accepted saying that there is unauthorized works is realized in extra flight of aircraft (economically pilotless aircraft[2] is preferable) to the place of alert source.

Besides checking on presence of works in the denoted channel, other channels are employed to search infringements on the whole line of aircraft flight. Received from optical range information is transmitted to control station (data processing block) where automatic detection and identification of targets are lead. The results of processing are transmitted to fast response service and serve as prior information for first two channels of intruder detection.

Thereby the principle of channels interconnection for detection of unauthorized works is «circle work». Simulation of system functionality in whole has confirmed system's efficiency.

Channel of information reconnaissance transmits to the personnel department the data about employees participation in planned or implemented infringements on the route of trunk pipeline.

Block «System's economy» on the Fig. 2 is required to the developer for decreasing owner's aggregate expenditures on purchase of the system and recovery of expenses from target drop-outs and false alarms.

There is well-known principle for every system: the more expenses the consumer bears when creating and maintaining system the more success he gets in purposes achievement. The feature of this principle using is illustrated on the Fig. 3.

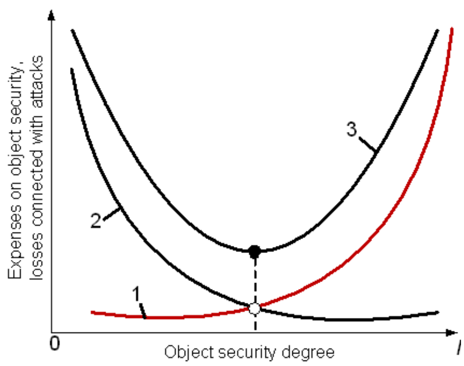

Fig. 3. Illustration of rational principle of object security by economic criteria:
1 – expenses connected with object security; 2 – losses connected with attacks passed; 3 – total losses of object owner

2 As an example state the pilotless helicopter Nitrohawk, which fits into automobile trunk, has flight speed more than 250 km/h, has hovering mode above suspicious place, has not high price (1 million rubles) [17]

Y-axis has expenses which business entity bears to protect pipeline system (curve 1) and clearing losses connected with attacks passed (curve 2). Total losses of object owner are described by curve 3. X-axis shows object security degree with range of values 0-100 % or 0-1.

The minimum point defines the rational level of object security against inner and outer attacks when using economic criteria. The security degree $I=f\left(N_{2,}\alpha,\beta\right)$ is the function of number of defenders N_2, their qualifications α, standard of technical and soft hardware used β.

The security degree can be found via Lancaster model of battle. As equipments of warring parties there are β ratios (β' is for attacker) in the model, as numbers of the parties there are αN_2 and αN_1 (for attacker), where N_1 is a number of successful attacks. In easier variant (illustrated), *I* value can be estimated like that. Let's «losses-from-attacks/security-expenses» relation is equal to 0. Then I=1, $\left((dN_1/dt)=0\right)$. Object owner defines when the security is not effective (*I* = 0). Exactly how many times *n* the losses may be greater than expenses? When linear dependence *I* (*n*) and *n* = 10, the optimal value is $I_{opt}=0{,}9$ and (losses/expenses) = 1. Current expenses and losses must be available to the organization. All the data allows to estimate current object's security degree I_t, resources required to switch to I_{opt} mode, defender's skill level α and theirs number N_2, kind of hardware and software for contention.

More general approach to decision of the task goes from generalized relationship of attack increase on object secured [13]

$$\frac{dN_1(t)}{dt}=\left[K_1\left(\frac{D}{P}\right)N_1(t)-K_2\left(\frac{LA_{90}}{LA_t}\right)N_1(t)\right]\left(1-I_t\right), \tag{1}$$

where (*D/P*) – ratio of intruder's average income from executed operation to expenses on operation implementation; LA_{90}/LA_t – moral country's (region's) population health in 90s and in analyzed period respectively. Function $K_1(D/P)$ describes cupi-dity degree of population – population percentage ready to break a law depending on expected income and knowledge for the crime in considered field of activity. It's obvious when (*D/P*)=1, $K_1\left(D/P\right)=0$ (there is no reason to do operation without any income; revenge factor is not considered). Curve $K_1(D/P)$ has saturation region when potential resources of society members is being exhausted and they cannot execute infringements of this kind (lack of knowledge, law-abiding members of society, owners of control object and other). For different societies that are described by various combinations of limiting factors, curve shape is constant, but describing function's ratios are changing

$$K_1(D/P) = a/[1 + v \cdot \exp(-c \cdot D/P)],$$

where *a* – ratio defining part of society ready to go over to delinquent camp with selfish ends. Ratios *a*, *v*, *c* are determined by expert technologies using per capita gross domestic product. Versions of function $K_1(D/P)$ behavior are shown in the Fig. 4.

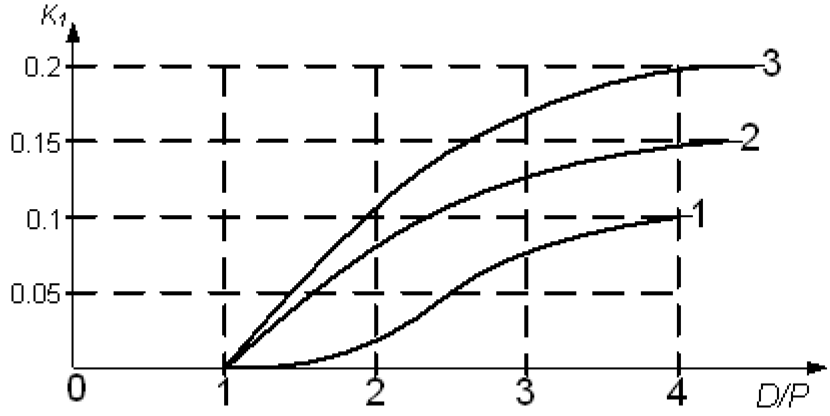

Fig. 4. Versions of function $K_1(D/P)$ behavior:
1 – poor community; 2 – average income community; 3 – rich community

Function $K_2(LA_{90}/LA_t)$ describes how citizen are law-abiding (*LA*), standard of culture and legislative power in the struggle with denoted crimes. The factors listed are represented in integral index LA_t to estimate which we need to use «index method for various indexes union» [14]. The number of such indexes is up to 40: per head alcohol consumption, murder and suicide number, museum attendance by population degree and so on. Versions of curves $K_2(LA_{90}/LA_t)$ are shown in the Fig. 5.

The curves are constructed keeping in mind that in the initial year (1990) public health was on the level that excepts crimes increasing on pipeline transport, $(dN_1(t)/dt) = 0$. This condition holds if $LA_{90} = LA_t$ и $K_1(D/P) = K_2(LA_{90}/LA_t)$ (see (1)). When $(LA_{90}/LA_t) < 1$, depending on formed social order in initial year, curves behavior can changing according to one of 5 trajectories offered. In idealized version (curve 3) the next is correct

$$K_2(LA_{90}/LA_t)=(LA_{90}/LA_t)\cdot K_1(D/P),$$

and relation (1) is rearranged in the form

$$(dN_I(t)/dt)=\left[K_1(D/P)\,\left(1-(LA_{90}/LA_t)\right)\cdot N_1(t)\cdot(1-I_t)\right].$$

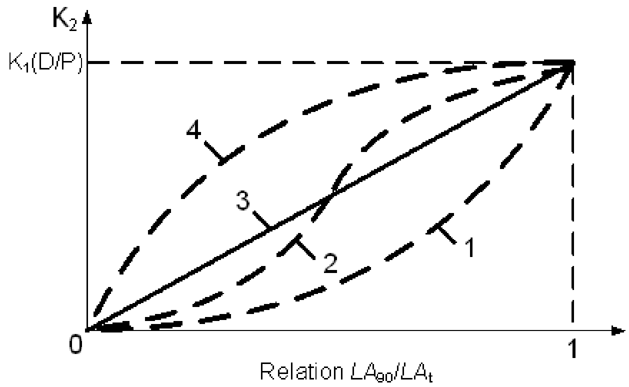

Fig. 5. Versions of function $K_2(LA_{90}/LA_t)$ behavior:
1 – totalitarian society; 2 – typical variant; 3 – idealized variant; 4 – democratic society

The estimation to *I* is giving by registering $dN_I(t)/dt$, current expenses and losses (Fig. 3), the *D/P* value determined by expert technologies and tracking LA_{90}/LA_t relation. Using described above algorithm, I_{opt} index is estimated for defining requirements to attack detection and false alarm probabilities of developing security equipment.

Conclusion

The growth trend of unauthorized works on trunk pipelines has appeared sufficiently clear and it is justified by reasons of the systemic nature. General-system growth laws in the social structures have an exponential nature. Ignore the growth trend more would be wrong.

Nowadays in Russia there are not effective tools for the stabilization of the transgressions on pipeline transport, except the originated security system. However, its technological level is not sufficient to reduce a positive growth trend of attacks on delivery ducts.

The appreciable advance in solving the considered problem would be to create an interconnecting protection system that includes interacting with each other seismic, vibroacoustic and optical channels of receiving information about the state of the pipeline system. In order to begin this «process», it is necessary to show the owner of the object that the application of such system is economically sound. The approach of solving this problem is justified in this article.

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