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MODELS OF A COHERENT CONTROL OF THE PARAMETERS OF AN UNMANNED AERIAL VEHICLE

This article offers models and a method of implementation of coherent control of node modules of a phased array antenna (PA) and a movable object. Application of the offered method and models is radar systems of an increased spatial selectivity in the systems of detection of stealthy objects and monitoring of the environment of the advanced multi-operated unmanned aerial vehicles (UAV). Models and a device for a selective detection of stealthy objects in radar systems of the onboard control system of UAV are analyzed. Complicated complexes with UAV today are widely applied in different areas of the national economy. A market of such complicated technical systems is constantly growing and expanding. Modeling of such systems is particularly essential at an early stage of their experimental testing. In order to detect major characteristics of UAV in the sphere of incipient technologies the most essential indices of the operation of complexes with UAV are described. Indices of coherent systems in such complexes are the most sensitive and their criticality can be estimated by the known identification methods.

Keywords: *complicated technical systems; complexes of unmanned aerial vehicles; technical level; integral and singular estimates; life cycle.*

Introduction

Modern radar systems for the detection of different types of movable objects during monitoring of the environment by an unmanned aerial vehicle (UAV) apply passive and active phased array antennas (PA), whose spatial selectivity considerably depends on the UAV antenna equipment [1, 2]. However, a significant gain of UAV geometrical dimensions leads to the problems of the system structural stiffness, which is connected with PA linear dimensions, and with certain restrictions to their geometrical dimensions, to a physical impossibility of their realization. There occurs a necessity in an additional search and development of the new reasonable approaches to solve such technical tasks [3]. One of the possible variants to solve this problem is to assume structural flexibility (probability of UAV structural movement) of mechanical links between the node modules of UAV PA with simultaneous control of their current coordinates in a real time.

A known method of coordinate obtaining [4] includes an optical system to project an image on the object's surface, forming a dot image array on the object's surface. The task is solved here by means of technical implementation of the method including the following main operations:

– image projection on the surface of a photosensitive object through an array of microlenses, with a formation of the array of point source images on the object's surface (a separate image for every source);

– registration of every dot image by an emission detector array with its transformation into an electric signal;

– digitalization of an electric signal by means of an analog-to-digital converter (ADC), forming of an envelope of a received signal;

– determination of position and a max value of a signal's envelope by a respective algorithm (program) and a calculation device;

– determination of a position and values of a signal's derivatives in the points, where a signal was digitalized;

– forming of a mismatch in relation to a reference signal in the points, where a signal was digitalized;

– processing of a mismatch by a digital filter and determination of an image coordinate.

A proposed method of control is aimed at an increase of accuracy of determination of the image coordinates of a point source on a CDD matrix surface. And based on the image received one could form a data set which is sufficient to construct a surface model of the second order of PA elements deviation from a respective surface.

A model of the coherent system of detection of movable objects

A coherent reception of a certain message for a multi-operated information measurement coherent system IMCS is a reception of an electromagnetic signal of a known phase, but in practice it is difficult to realize a coherent reception, and then one could take a quasi-coherent reception of an electromagnetic signal when the reference electromagnetic oscillations coinciding in phase with a received signal, are formed by means of narrow-band filters, phase-locked loop systems with an input signal.

A total probabilistic characteristics of the IMCS system is its probability density function $f(Y,s;t)=f^{(s)}(Y,t)$ that features a distribution of phase coordinates $Y(t)$ and a state probability of a coherent structure $s(t)$ at the moment of time t, i.e.

$$P^{(s)}(t)=\int_{-\infty}^{+\infty} f(Y,t)dY,\ s=\overline{1,S}. \tag{1}$$

An estimate s of a coherent system state shall be found from the formulas [2]

$$\dot{\hat{P}}_s=-\sum_{r=1}^{S}\left(\hat{P}_s\nu_{s_r}\left(\hat{Y}^{(s)},R^{(s)},t\right)-\hat{P}_r\nu_{rs}\left(\hat{Y}^{(s)},R^{(s)},t\right)\right)+ \\ +\frac{1}{2}\hat{P}_s\sum_{r=1}^{S}\hat{P}_r b^{(s)}\left(\hat{Y}^{(s)},Z,t\right), \tag{2}$$

$$\dot{\hat{Y}}^{(s)}=f^{(s)}\left(\hat{Y}^{(s)},t\right)+\sum_{r=1}^{S}\frac{\hat{P}_r(t)}{\hat{P}_s(t)}\nu_{rl}\left(\hat{Y}^{(s)},R^{(r)},t\right)\left[\hat{Y}^{(r)}-\hat{Y}^{(s)}\right]+ \\ +R^{(s)}C^T\left(\hat{Y}^{(s)},t\right)Q_Z^{-1}\left(Z-H\left(\hat{Y}^{(s)},t\right)\right),$$

$$\dot{R}^{(s)}=R^{(s)}\frac{\partial f^{(l)T}\left(\hat{Y}^{(s)},t\right)}{\partial\hat{Y}}+\frac{\partial f^{(s)}\left(\hat{Y}^{(s)},t\right)}{\partial\hat{Y}}R^{(s)}+ \\ +f_0^{(s)}\left(\hat{Y}^{(l)},t\right)f_0^{(s)^T}\left(\hat{Y}^{(sl)},t\right)+\sum_{r=1}^{S}\frac{\hat{P}_r(t)}{\hat{P}_s(t)}\nu_{rs}\left(\hat{Y}^{(r)},R^{(r)},t\right)\times \\ \times\left(R^{(r)}-R^{(s)}+\left(\hat{Y}^{(r)}-\hat{Y}^{(s)}\right)\left(\hat{Y}^{(r)}-\hat{Y}^{(s)}\right)^T\right).$$

The methods and models developed in the 54 ICS RAS laboratory to control the states of coherent systems are based on fundamental principles of radiophysical principles. They initially presume their multi-component interoperation in a theoretical part, as well as a preparation for experimental researches on the basis of a general theory of signal coherency. A theory of coherent signals of electromagnetic waves is based on the known Maxwell's equations (describing a circulation of vectors of electric and magnetic fields, in which one of the particular solutions of wave equations are elementary trigonometric functions (the simplest terms) of the forms $E=E_{\max}\cos(\omega t-\frac{2\pi}{\lambda}+\alpha)$ for an electric field of a wave and $H=H_{\max}\cos(\omega t-\frac{2\pi}{\lambda}+\alpha)$ for a magnetic field of a wave, in which: $E_{\max}$, $(\omega t-\frac{2\pi}{\lambda}+\alpha)$ is a maximum amplitude and a total phase of a harmonic signal with a wave length λ and with an initial phase α, for the second component of an electromagnetic wave as $H=H_{\max}\cos(\omega t-\frac{2\pi}{\lambda}+\alpha)$ we shall reason in a similar way. Let us consider a superimposition of two linearly-polarized waves with similar directions of electromagnetic oscillations

$$E_1=E_{\max 1}\cos(\omega t-kS_1+\phi_1)$$

$$\text{and } E_2=E_{\max 2}\cos(\omega t-kS_2+\phi_2),$$

where S_1, S_2 are the respective paths of electromagnetic waves to a certain point o.

A resulting motion also has a form of harmonic oscillation with an intensity

$$J_{1,2}=J_1+J_2+2\sqrt{J_1J_2}\cos\nu_\delta, \\ \nu_\delta=(kS_1-kS_2)+(\phi_1+\phi_2) \tag{3}$$

and a maximum amplitude of electromagnetic oscillation

$$E_{\max}^2=E_{\max 1}^2+E_{\max 2}^2+2E_{\max 1}E_{\max 2}\cos\nu_\delta. \tag{4}$$

Many reception facilities of quasi-coherent systems take a time-averaged intensity,

$$\nu_\delta = (kS_1 - kS_2) + (\phi_1 + \phi_2) = \text{const},\ \nu_\delta > 0,\ J_{1,2} > J_1 + J_2,$$
$$(\text{при}\ J_1 = J_2 \Rightarrow J = 4J_2)$$

If a trigonometric function is as follows $\cos\nu_\delta = 2n\pi$, $n = 1, 2, 3, \ldots$, the waves and their sources in relation to phases shall be consistent with each other, i.e. coherences, so a monochromatic wave is a coherent wave and its phase shall not "disorder" in time. Redistribution of intensities with a formation of the respective minimums and maximums as the result of superposition of coherent electromagnetic waves (electromagnetic waves addition) is also called interference in a signal theory.

In practical tasks and in mathematical modeling of many movable objects in information multi-operated IMCS, a signal in electromagnetic field is also featured by the respective characteristics of amplitude and phase [1, 2, 7]

$$U(t) = A(t)\exp\left[-j(\phi_M(t) + \phi_c(t)\right], \tag{5}$$

where $A(t)$, $\varphi_c(t)$ is an amplitude and an own phase of an electromagnetic signal, time dependence of which is explained by fluctuations of a quasi-coherent signal under the impact of random factors; $\varphi_M(t)$ is a phase modulation of the components, which is introduced to a signal to ensure its detection with a provision of an interference for IMCS.

Any of these parameters contains information about the objects of different nature and can be used to solve wide problems of radio detection and location. Based on the known method of a coherent signal time average for the objects moving non-periodically with a constant speed the most famous papers give a working formula

$$I(r) = I_0(r)\frac{\sin^2\left[\frac{2\pi}{\lambda}V(r)\tau\right]}{\left[\frac{2\pi}{\lambda}V(r)\tau\right]^2}, \tag{6}$$

where $I(r)$, $I_0(r)$ are the symbols of a signal's intensity from a target object and intensity of the signal corresponding to an "undisturbed" object; $V(r)$, τ is a speed of movement and a time of observation (exposition) of a target object; λ is an electromagnetic wavelength. In the works by the professors Prangishvili, A.N. Anuashvili and V.V. Maklakov (ICS RAS) a similar formula is derived for emission intensity (time-averaged) under an observation of a target object at a certain angle α:

$$I_s = I_{0S}\sin^2\left[\frac{2\pi}{\lambda}VT\cos\alpha\right], \tag{7}$$

with $0 < VT \le d$ and $I_s = I_{0S}\left[1 - \frac{d}{VT\sin\alpha}\right]^2$, if the condition $VT\sin\alpha \ge d$, where d is a geometrical size of the observed structure (the structure of the observed object on a time interval of the exposition of this object T=τ).

In general [1, 2, 3], in detection systems an input signal in the reception facility is represented by a useful component $S(t)$ and a disturbance $N(t)$ in the following form:

$$X(t) = S(t) + N(t). \tag{8}$$

A signal takes a receiving facility's characteristics into account (for instance, in coherent RS, missiles, etc), it includes emission power, reflection form a target object and an overhead, as well as a phase shift and an inversely proportional value from the fourth degree of range D to the i-th point of structure of a target object, and is described by the known formula [1, 2, 3, 7]

$$S_i(t) = \sigma_i(Z_i, D_i)\exp\left\{j\left[\omega t - \frac{4\pi D_i}{\lambda} - \frac{2\pi}{\lambda}\frac{(Z - Z_i)^2}{D_i}\right]\right\}, \tag{9}$$

where ω, Z is a cyclic frequency of the emitted electromagnetic signal and a distance of movement along the axis of observation of the object z, respectively, an indicator of the type $\sigma_i(Z_i, D_i)$ takes into account a receiving facility's characteristics and random terms of observation of a target object.

With consideration of the principle of superposition, an input signal in the IMCS receiving facility should be considered by n of constituents for a movable object as [1, 2, 6, 7]

$$S(t) = \sum_n S_n(t) =$$
$$= \sum_n \sigma_n(Z_n, D_n)\exp\left\{j\left[\omega t - \frac{4\pi D_n}{\lambda} - \frac{2\pi}{\lambda D_n}(Vt - Z_n)^2\right]\right\}. \tag{10}$$

By uncomplicated transformation by means of Kravchenko-Bernstein theorem, a signal for the detection system with consideration of possible disturbance of IMCS (natural and jamming) are reduced to the form [6, 7]:

$$S(U, t) = U\exp\left[-\phi\, t\right], \tag{11}$$

where U, φ is a random constituent of the signal with consideration of a current disturbance $N(t)$, which is frequently interpreted in simulation modeling as a random noise with an intensity G_N, a mathematical expectation and signal dispersion shall be defined by the symbols m_u, D_u.

An algorithm of the detection of a movable target object in a multi-channel IMCS shall be represented by the following "threshold" dependence [6, 7]:

$$C = \frac{b_0\hat{P}_1}{a_0\hat{P}_2},\quad \begin{cases} 1, \text{при}\ \Lambda_0(u_{\alpha_1}, u, T) \le C; \\ 2, \text{при}\ \Lambda_0(u_{\alpha_1}, u, T) > C, \end{cases} \tag{12}$$

where C is a detection threshold; T is a time of observation of a quasi-coherent signal; u_{α_1} is an a priori value of a random variable U; u is a realization of a random variable U; $\hat{P}_2$ is an estimate of a priori probability of a useful signal; $\hat{P}_1 = 1 - \hat{P}_2$ is an estimate of a priori probability of a disturbance $N(t)$; b_0, α_0 are the losses under the miss of a useful signal and false alarm; index 2 means availability of a useful signal in common structure of the signal $X(u,t)$, operating at the input of a quasi-coherent system, index 1 means there is no useful signal in IMCS environment [6, 7].

$$X(u,t)=\begin{cases} X_2(u,t)=u\exp(-\phi\tau)+N(t); \\ X_1(u,t)=N(t). \end{cases} \tag{13}$$

An indicator function $\Lambda_0(u_{\alpha_1}u,T)$ shall be defined as follows

$$\Lambda_0(u_{\alpha_1},u,T)=$$
$$=hE(u_{\alpha_1}u,T)\left\{1+\frac{1}{2}D_u\left[\vartheta_1^2(u_{\alpha_1},u,T)+\vartheta_{11}(u_{\alpha_1},u,T)\right]\right\};$$
$$E(u_{\alpha_1}u,T)=\exp\left\{\int_0^T g(u_{\alpha_1},\tau)X(u,\tau)d\tau-\frac{1}{2}\beta(u_{\alpha_1},T)\right\};$$
$$\vartheta_1(u_{\alpha_1},u,T)=\int_0^T \dot g(u_{\alpha_1},\tau)X(u,\tau)d\tau-\dot\beta(u_{\alpha_1},T);$$
$$\vartheta_{11}(u_{\alpha_1},u,T)=\int_0^T \ddot g(u_{\alpha_1},\tau)X(u,\tau)d\tau-\ddot\beta(u_{\alpha_1},T); \tag{14}$$
$$g(u_{\alpha_1},T)=$$
$$=\int_0^T g(u_{\alpha_1},\tau)f(u_{\alpha_1},\tau)d\tau;\, g(u_{\alpha_1}.\tau)=(u_{\alpha_1}/G_N)\exp(-\phi\tau);$$
$$h=1/(u_{\max}-u_{\min}),\, f(u_{\alpha_1},\tau)=S(u,\tau);$$
$u_{\max}, u_{\min}$ – extremum of random value U.

Derivative components $g(u_{\alpha_1},\tau)$, $\beta(u_{\alpha_1},T)$ are taken by u_{α_1}.

These formulas can be used to find the next equation in the form

$$\beta(u_{\alpha_1},T)=-\frac{u_{\alpha_1}^2}{2G_N\phi}(1-\exp(-2\phi T). \tag{15}$$

For the observed signal in IMCS the additional components

$$\dot g(u_{\alpha_1},\tau)=(1/G_N)\exp(-\phi\tau);\ \ddot g(u_{\alpha_1},\tau)=0;$$
$$\dot\beta(u_{\alpha_1},T)=-\frac{u_{\alpha_1}}{G_N\phi}(1-\exp(-2\phi T)); \tag{16}$$
$$\ddot\beta(u_{\alpha_1},T)=-\frac{u_{\alpha_1}}{G_N\phi}(1-\exp(-2\phi T)).$$

By the next transformation for the formula (14) we shall get

$$\Lambda_0(u_{\alpha_1},u,T)=$$
$$=h\left[1+\frac{D_u}{2G_N^2}(J^2(u,T)+\alpha_1 u_{\alpha_1}J(u,T)+bu_{\alpha_1}^2+dG_N\right]$$
$$\exp\left\{\frac{u_{\alpha_1}}{G_N}J(u,T)+\frac{\alpha_1}{4}\frac{u_{\alpha_1}^2}{G_N}\right\}; \tag{17}$$
$$J(u,T)=\int_0^T \exp(-\phi\tau)X(u,\tau)d\tau;$$
$$\alpha_1=(1-\exp(-\phi T))/\phi;\, b=\alpha_1^2/4;\ d=\alpha_1/2.$$

A required value for an output signal in IMCS is

$$Y_T(m_{\alpha_1},u,T)=\begin{cases} 2, \text{ при } \Lambda_0(u_{\alpha_1},u,T)>C; \\ 1, \text{ при } \Lambda_0(u_{\alpha_1},u,T)\le C, \end{cases} \tag{18}$$

where the initial data for the modeling represent values as $u_{\alpha_1}=m_u=0$; $D_u=48$; $h=1/24$; $G_N=6$; $T=5c$; $\varphi=5$; $\alpha_1=0{,}2$; $b=0{,}01$; $d=0{,}1$; $C=1{,}5$, that corresponds to the estimates for the probabilities $\hat P_2=0{,}4$; $\hat P_1=0{,}6$ and the ratio $b_0/a_0=0{,}042$, therefore the cost for a false alarm is approximately 25 times higher than for the miss of the respective useful signal.

A real value for an output signal in IMCS is

$$Y(m_u,G_N)=\begin{cases} 2, \text{ при } \Lambda_0(m_u,G_N,D_u)>C; \\ 1, \text{ при } \Lambda_0(m_u,G_N,D_u)\le C, \end{cases} \tag{19}$$

where m_u, G_N, D_u are not sufficiently known to us.

Task of system optimization is to define the components m_u^*, G_N^*, D_u^*. The event θ will be a conjunction of the events $\theta_1\cap\theta_2$, where for the event θ_1 – $Y_T(m_u,u,T)=Y(m_u,G_N,D_u)$ with $X(u,t)=X_1(u,t)$, a symbol θ_2 is the event that means the execution of the equation $X(u,t)=X_2(u,t)$. As the result of random search we have $m_u^*=0{,}092$; $G_N^*=4{,}47$; $D_u^*=50{,}34$. For the detection system, an output signal of which will be the signal (11), the probability of a wrong decision is 0,351. For the detection system with an output signal (18) with $m_u=m_u^*$, $G_N=G_N^*$, $D_u=D_u^*$, the probability is 0,442. With noise reduction the probability of wrong decisions decreases considerably.

A model of coherent control of PA movable objects

The proposed method of control of objects and its realization in the form of a simulating model of the facility give the possibility to perform spatial estimate of coordinates of the modules by a flexible antenna array with large aperture in real time (Fig. 1). It helps to create the system to control the phases of receive/transmit node modules, that eventually raises the PA characteristics [3, 7].

A developed model and a mock-up (in 54 lab of ICS RAS) for the implementation of the device for the control of node modules coordinates of flexible antenna array with large aperture contain the sequentially installed laser ranger 1, rotary mirror 2, focusing lens 3, partially reflecting mirror 6, long-focus lens 7, moving mirror 8 and optical scanner 9, controller 13. On basic structure 11 receive/transmit modules 12 are installed, where reflecting elements (RE) 10 with light emitting diodes are fixed. Behind a partially reflecting mirror 6 there is a light filter 5 and CCD matrix 4. The whole system is controlled by a controller 13.

Let us consider the principle of a device operation. On reflecting modules of an antenna array, in their phase centers there are reflecting elements 10. Emission of a laser ranger 1 through a rotary mirror 2 and a lens 3, focal distance of which is aligned with a long-focus lens 7, totally packs a lens aperture. Spreading in an angular field of the

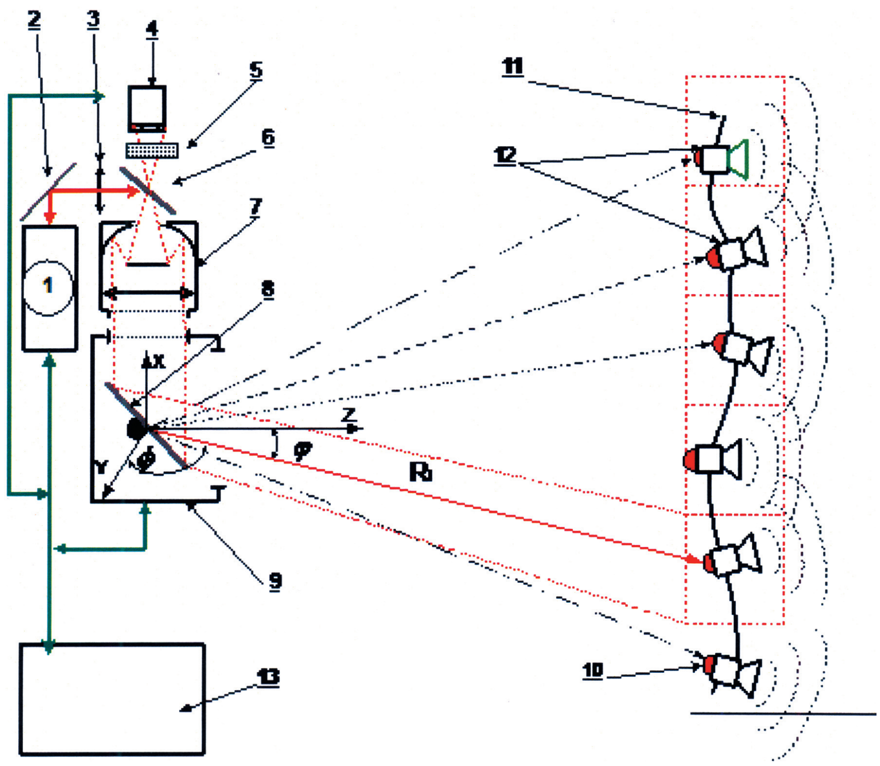

Fig. 1. Model of the device for control of coordinates of PA elements: 1 – laser ranger, 2 – rotary mirror, 3 – focusing lens, 4 – CCD matrix, 5 – light filter, 6 – partially reflecting mirror, 7 – long-focus lens, 8 – moving mirror, 9 – optical scanner, 10 – reflecting elements, 11 – basic structure, 12 – receive/transmit modules, 13 – controller

lens, laser emission lightens some area of the array with receive/transmit modules 12. A light flux reflected from the array, in a beam return, is collected by an analyzer of the received emission to a receiving device, at the input of which there is an amplitude comparator with an operating threshold, consistent with a level of reflection from RE. Measurement of a distance is made within the accuracy of 1 millimeter. Simultaneously the lightened array area is projected by the lens 7 through a partially reflecting mirror 6 and a light filter 5 to a CCD matrix 4. Spectrum of emission of lightning diodes does not coincide with a spectrum of emission of a ranger, thus, on a CCD matrix 4 a contrast image of light emitting diodes is formed that are aligned with a phase center of the module. Fig. 2 represents the evolution of a light emitting diode image on a pixel field of a CCD matrix 1. Angular movements of the module lead to the shifting of image 2, it helps to measure their angular coordinates.

Measurement of the respective geometrical coordinates of the array node modules is performed by a sequential scanning by a long-focus lens 7 of the PA UAV antenna area with an optical scanner. A coordinate origin is connected with an axle of rotating of a scanner's mirror. Measurement device is controlled by a controller 13, a typical industrial computer with an input-output board is taken for its basis. A model of the device has the following advantages: non-contact measurement of the node modules coordinates, high spatial resolution of the phase center position. Control of the total surface of UAV antenna is made by means of scanning of the lens field by a scanning device. RE structure is shown in Fig. 3.

Conclusion

The proposed model of control of the node modules coordinates of a flexible UAV PA ensures an increase of

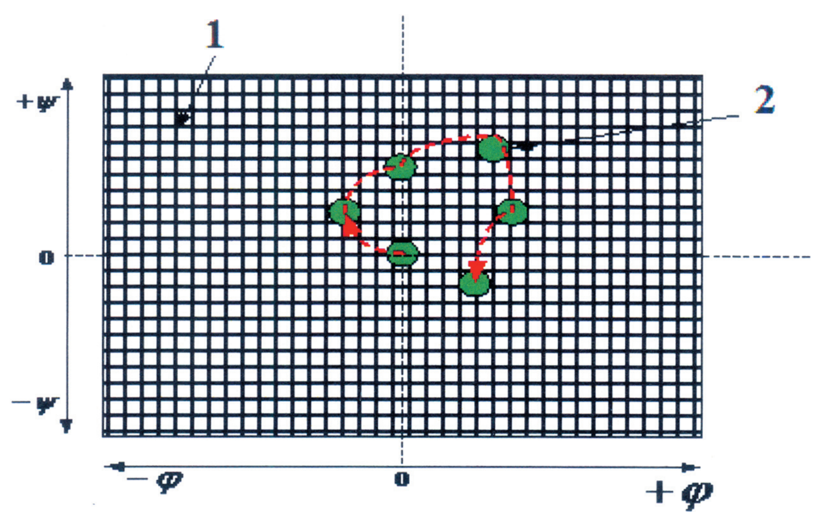

Fig. 2. Evolution of a light emitting diode image on a pixel field of a CCD matrix: 1 – pixel field of a CCD matrix; 2 – image

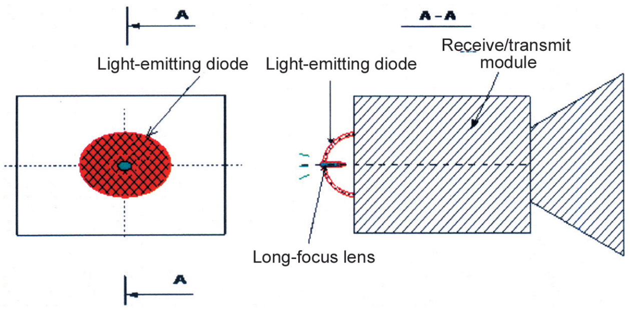

Fig. 3. Structure of a reflecting element and a light emitting diode
of the lightning

spatial selectivity of radar systems of the detection of multi-operated UAVs [3, 4], implemented by the technology of PA phased arrays.

It is the first time when the model and device are offered for the measurement of geometrical coordinates of the elements of a flexible array with large aperture relatively to a basic (chosen as initial) point for the IMCS UAV systems. The device is based on a coordinated functioning of heterogeneous: laser ranger and CCD matrix installed in an optical path of a long-focus lens and a radio technical part of IMCS system.

This model and the device described above serve to construct a 3D graph of deviations of orientations of all emitters from the normal position with a further entering of quasi-coherent correction signals into the control system of (CS) of PA of a multi-function UAV.

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