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Methods to Increase Resistivity against Jamming in Selected Types of Optoelectronic Seekers

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Abstract:

The paper deals with dilemma of the linear image field of view of the optoelectronic system which is intended for the measurement of the location of remote optical radiation sources. There is a brief description of the lay-out of the detection assemblage and conditions which have to be guaranteed to achieve the pulse position modulation which is needed to the objects detection responsive to the location. The importance of the field of view for jamming resistance and the feasibility of the field of view reduction by the electronic method is explained. This paper also deals with objects discrimination in image data using position prediction. To predict the object position in pictures sequence, principles of Kalman filtration are used. Objects discrimination is realised for matching true and predicted trajectories, when in case of their deviation the object is eliminated.

Keywords:

Pulse position modulation, field of view, jamming resistance, optical radiation, object discrimination, position prediction, Kalman filtration

1. Introduction

The biggest threat to aircraft in current war conflicts are man-portable air-defence systems (MANPADS). These systems use mostly infrared guided missiles. Many of them incorporate guided missiles with imaging infrared (IIR) seekers. But older types with the seekers using opto-mechanical modulation are used as well. The protection against these systems is solved by means of omnidirectional or directional aircraft self-protection systems or their combination. Most widespread omnidirectional systems are decoys called flares which cause jamming of the guidance system and thus prevent the shot down of the protected aircraft. At the present time, these systems are very

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sophisticated. They allow setting different periods between the shots and their sequences or the direction of the flares. To be able to determine optimal parameters, it is imperative to know how the flares affect the function of the guidance systems of the missiles especially those which are equipped with circuits serving for the increasing of resistance against jamming [1].

This paper deals with possible methods of resistance enhancement against jamming for the seekers with pulse-position modulation of radiant flux and IIR detector. In the first type, we analyse the method of electronic reduction of the field of view. In the second type, the method of false objects elimination by means of their movement prediction is described.

2. Seeker with Pulse-Position Modulation

2.1. Arrangement of Detection Assemblage and Measuring System

Detection of radiant flux is accomplished by means of a quaternion of rectangular photodetectors which are arranged as in picture (see Fig. 1). Sensitive regions are placed onto the image plane of the receiving optical system. In some cases it is sufficient to utilize only two detectors. For the purpose of the demanded function, it is necessary so that the spot of received radiation circulates along the so-called modulation circle (MC). This spot represents the real image of the object tracked with the missile seeker (MS), [2, 3]. Let us call the centre of the MC *virtual object image* (VOI). The radius of the MC must correspond to sizes of the detection assemblage and to the required scale of the measurement. The duration of one round determines the measurement period T_m. The relative linear position of the VOI is proportional to the angle between the direction to the detected object (DO) and the MS axis. The deviation of DO from the MS axis modulates intervals between optical pulses impinging onto the individual opposite photodetectors [4].

The fact that the pulses of different detected objects are generally separated in time is extraordinary significant from the point of view of the protection against interference. It results in feasibility of independent processing of signals of the diverse objects. This circumstance enables to apply numerous protective functions. One of them is the reduction of the field of view of the MS.

2.2. Field of view of Measuring System

We can distinguish two linear image fields of view of the MS with four detectors (see Fig. 2). There are both the field of view with detection of optical radiation (FOVD) and the field of view with the measurement of the object deviation (FOVM) which is part of the FOVD. The FOVD is an area where the VOI has to lie in order to detect the radiation of the appropriate objects by at least one detector. Provided the radiation of the object is detected with all four detectors, the location of the object is measurable. Such situation occurs only when the VOI exists in the FOVM. The sources of optical radiation which are situated close to measured object cause interferences if their VOI reach the FOVD. The probability of this phenomenon is proportional to sizes of the FOVD; therefore, diminishing of this FOV is one of the possibilities which can be used to improve the MS resistance against jamming.

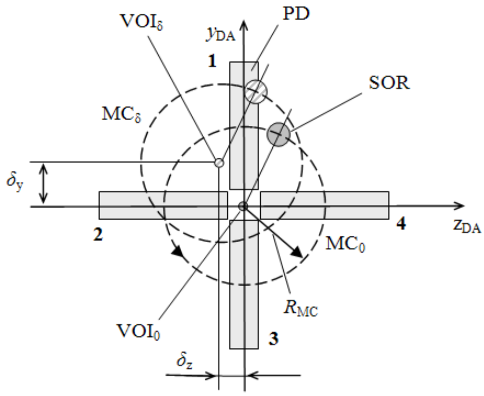

Fig. 1 The detection assemblage

MC_0, MC_δ, VOI_0, VOI_δ – modulation circles and virtual object images for the zero and non-zero object deviation, respectively, PD – the photodetector (1 – 4), R_{MC} – the radius of the modulation circle, SOR – the spot of optical radiation, y_{DA}, z_{DA} – transversal axes of the coordinate system of the detection assemblage, δ_y, δ_z – components of the linear VOI deviation

2.3. Reduction of Field of View

The FOVD decrease is achievable in the electronic way in such a way that individual target signal receivers are blocked with defined mode at an interval which is shorter than the measurement period. Electric signals which appear due to intrusive radiation at the output of the detector can be inhibited. They consequently do not affect the process of the target location measurement. This measure results in virtual contraction of the FOVD. The so-called reduced FOVD can be regarded as a circle of the diameter which roughly equals the length of one photodetector.

Let us suppose that the MS detects one useful and two false objects. It means that three pulses occur at the most at the output of one photodetector in one measurement period T_m.

This situation is illustrated in the picture (see Fig. 3). There are time behaviours of signals s_d and time intervals when a signal amplifier is either disconnected or connected to deviation measurement circuits.

The pulses *1* and *2* represent useful object. The pulses 1_{F1} and 1_{F2} correspond to false objects. The trailing edge of the pulse *1* starts interval of Δt_d when the amplifier is disconnected and any signal is interrupted. At an instant of t_c the interval Δt_c starts and afterwards every output signal of the amplifier is processed in the next circuits. The size of the reduced FOVD is proportional to the interval Δt_c.

The reduced FOVD of one detector is depicted in the picture (see Fig. 4). Its Y size is constant but the Z_c one changes in dependence on the SOR movement phase of α_c which the spot has at the instant of t_c.

For all detectors, the entire reduced FOVD can be considered approximately to be a circle with the diameter $2R_r$. The optimal situation will arise if the amplifier is connected in the moment when the radiation spot of useful object reaches the detector edge and the z component of the spot position is equal Z_{cmin} (see Fig. 4). In that event, the reduced FOVD is minimal.

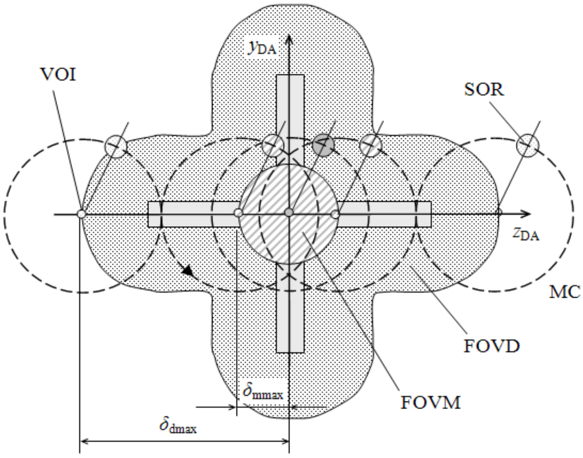

Fig. 2 Fields of view of the measuring system
FOVM, FOVD – fields of view with the measurement of the deviation and with detection of optical radiation, respectively, δ_{mmax}, δ_{dmax} – maximum measurable and detectable values of the linear VOI deviation, respectively

In accordance with the picture, the following equations can be written

$$2 \cdot R_r = \begin{cases} Y & \text{for } Y \geq 2Z_c \\ Z_c & \text{for } Y < 2Z_c \end{cases}, \tag{1}$$

where $Y = a - D_{\mathrm{SOR}}$, $Z_{\mathrm{c}} = Z_{\mathrm{cmin}} + \delta(\Omega_{\max})$, $Z_{\mathrm{cmin}} = \dfrac{b + D_{\mathrm{SOR}}}{2}$,

$\delta(\Omega_{\max}) = \Omega_{\max} \Delta t_{\mathrm{dmax}} f$, a, b are the length and the width of the detector, D_{SOR} is the diameter of the spot of optical radiation, f is the focal length of receiving optical system, Δt_{dmax} is the amplifier disconnection interval corresponding to the maximum permissible relative angular velocity $\Omega_{\max}$ of the useful object and $\delta(\Omega_{\max})$ is the variable which expresses the influence of the relative movement between the MS and the useful object.

The SOR movement phase α_{c} in the beginning of the amplifier connection is given by the formula

$$\alpha_c = \begin{cases} 2\pi - \arcsin \dfrac{Z_{cmin}}{2R_{MC}} & \text{for } \Omega = 0 \\ 2\pi - \Delta\alpha_{cmax} & \text{for } \Omega \neq 0 \end{cases}, \tag{2}$$

where

$$\Delta\alpha_{\mathrm{cmax}} = \arcsin\frac{Z_{\mathrm{cmin}} + \Omega_{\max}\left(\dfrac{2\pi - \Delta\alpha_{\mathrm{cmax}}}{\omega_{\mathrm{MC}}}\right)f'}{R_{\mathrm{MC}}}\,, \tag{3}$$

$\Delta\alpha_{\mathrm{cmax}}$ is the phase interval of the amplifier connection and ω_{MC} is the angular velocity of the SOR movement along the MC.

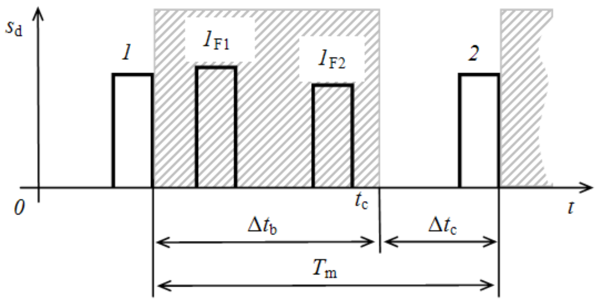

Fig. 3 Output signals of one photodetector
s_d – output detector signals, t – time, t_c – the instant of time when the measurement process starts, T_m – the measurement period, Δt_b, Δt_c – interval when the signals are detached or connected to measurement circuits, respectively, 1, 2 – pulses of one useful object in two adjacent periods, 1_{F1}, 1_{F2} – the pulses of two different false objects

According to the Eq. (3) it is apparent that the interval $\Delta\alpha_{\mathrm{cmax}}$ has to be solved numerically.

Let us suppose that the false objects are spread around the useful one. Let the space distribution of them is uniform; as a result, the reduction of the FOV involves the decrease of the probability of processing of the false signals. It is caused by the contraction of a solid angle where the objects have to be situated in order that the MS is able to detect them.

The reduction of the mentioned probability is proportional to the factor k which is given by the following expression:

$$k = \frac{R_r^2}{R_{eo}^2}\,, \tag{4}$$

where R_{eo} is the radius of the circular equivalent field of view and R_{r} is the radius of the reduced FOVD, see the Eq. (1).

The equivalent field of view has the same area as the original FOVD (see Fig. 3). In an ideal situation, the sizes of the reduced FOVD and the FOVM are the same. But it has to be emphasised that such a astate will occur only if the following condition is fulfilled:

$$Y \geq Z_{\mathrm{c}}\,. \tag{5}$$

The value of the relative angular velocity of useful object has to be near zero. In that case, the phase α_{c} is maximal and the interval Δt_{d} is maximal as well.

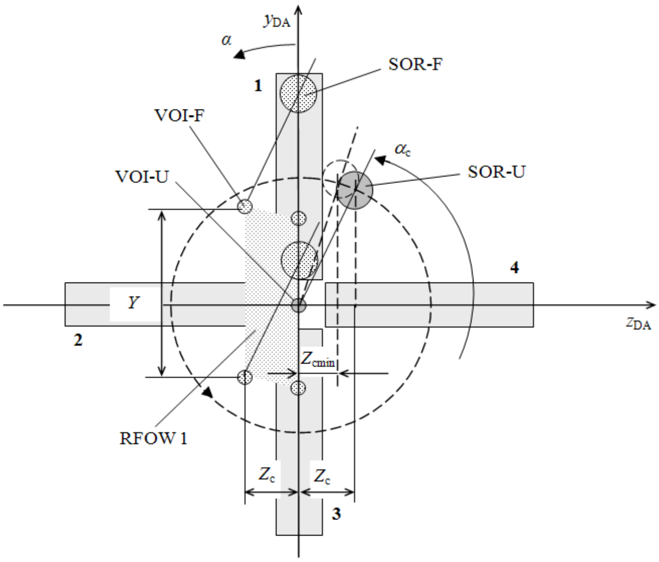

Fig. 4 The reduced field of view of one detector RFOW 1
SOR-F, SOR-U, VOI-F, VOI-U – the spot of optical radiation and virtual object image of the false and useful object, respectively, Z_c, α_c *– the z component of the SOR-U position and the phase of the SOR movement at the instant of time when the measurement process starts, respectively,* α *– the phase of the SOR movement*

3. Seeker with IIR Detector

For predicting the location of an object in pictures sequence, it is very useful to use so-called predictive filters, such as Alpha-Beta filter, see [5], or Kalman filter. Calculations of predicted values the Alpha-Beta filter algorithm use constant levels of uncertainty all the time. This feature of the Alpha-Beta filter is not suitable for objects which accelerate or decelerate. Therefore, for tracking and location prediction of manoeuvring aircraft, it is suitable to use Kalman filtering.

3.1. Using Kalman Filter for Prediction of Object Position

The principle of Kalman filter for predicting the position is given e.g. in [6]. One cycle of Kalman filter consists of the following five steps:

- Extrapolation of the state vector (target position).
- Extrapolation of the covariance matrix (error estimates).
- Calculation of filter gain.
- State vector update.
- Covariance matrix update.

These five steps are performed at each new value of object location. If the target is manoeuvring, the so-called manoeuvre noise should be added to the covariance matrix. This increases the uncertainty of the determination of the predicted position and the uncertainties area. Manoeuvre noise is attributed to the covariance matrix either in every step (all the time) or only in cases when the distance between the predicted and actual position achieves the selected value. Movement of an object can be described by the following differential equations:

$$v(t) = \dot{x}(t) = \frac{\mathrm{d}x(t)}{\mathrm{d}t}, \tag{6}$$

$$a(t) = \dot{v}(t) = \frac{\mathrm{d}v(t)}{\mathrm{d}t}, \tag{7}$$

where $x(t)$ is the position, $v(t)$ is the velocity and $a(t)$ is the acceleration of the object.

The state vector is then as follows:

$$\begin{bmatrix} x \\ v \\ a \end{bmatrix} = \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} \mapsto \begin{bmatrix} x + v\Delta t + \frac{1}{2} a\Delta t^2 \\ v + a\Delta t \\ a \end{bmatrix}, \tag{8}$$

where Δt is measurement step.

Then the propagation matrix $\boldsymbol{\Phi}(\Delta t)$ is obtained from Eq. (8):

$$\boldsymbol{\Phi}(\Delta t) = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}. \tag{9}$$

The covariance matrix $\boldsymbol{P}$ contains error estimates of the object location determination. At the initialization of this matrix, main diagonal values ξ_i are set to the large numbers because the previous behaviour of the object is unknown. The value r_{11} represents measurement noise derived from the measurement error matrix $\boldsymbol{R}$.

$$\boldsymbol{P} = \begin{bmatrix} r_{11} & 0 & 0 \\ 0 & \xi_1 & 0 \\ 0 & 0 & \xi_2 \end{bmatrix}, \tag{10}$$

$$\boldsymbol{R} = [r_{11}] = [u^2], \tag{11}$$

where u is measurement deviation.

The calculation of gain K is expressed by the following equation:

$$K = \boldsymbol{P}^{-}\boldsymbol{H}^{T}\left(\boldsymbol{H}\boldsymbol{P}^{-}\boldsymbol{H}^{\mathrm{T}} + \boldsymbol{R}\right)^{-1}, \tag{12}$$

where $\boldsymbol{P}^{-}$ is the extrapolated covariance matrix, $\boldsymbol{H} = [1\ 0\ 0]^{\mathrm{T}}$ is the measurement matrix. The measurement matrix reflects the fact that there is only information about the target location, because the speed and acceleration are not measured. To the calculation of the extrapolated state vector $\boldsymbol{X}^{-}$ and the extrapolated covariance matrix $\boldsymbol{P}^{-}$, following equations are used:

$$\boldsymbol{X}^{-} = \boldsymbol{\Phi}\boldsymbol{X}_{P}, \tag{13}$$

$$\boldsymbol{P}^{-} = \boldsymbol{\Phi}\boldsymbol{P}_{P}\boldsymbol{\Phi}^{\mathrm{T}}, \tag{14}$$

where $\boldsymbol{X}_P$ is the state vector from the previous step and $\boldsymbol{P}_P$ is the covariance matrix from the previous step.

To obtain new values of state vector $\boldsymbol{X}^{+}$ and covariance matrix $\boldsymbol{P}^{+}$, following equations are used:

$$\boldsymbol{X}^{+} = \boldsymbol{X}^{-} + \boldsymbol{K}\left(\boldsymbol{Z} - \boldsymbol{H}\boldsymbol{X}^{-}\right), \tag{15}$$

$$\boldsymbol{P}^{+} = \left(\boldsymbol{I} - \boldsymbol{K}\boldsymbol{H}\right)\boldsymbol{P}^{-}, \tag{16}$$

where $\boldsymbol{Z}$ is a new measurement value and $\boldsymbol{I}$ is identity matrix.

To determine the area of uncertainty which the object must be located in so that the object was regarded as the true target, values of the covariance matrix or the value reflecting the uncertainty of the position determination (P [1,1]) can be used. The value P [1,1] is multiplied with experimentally determined constant to increase the uncertainty area so that it exceeds the maximum deviation of the predicted target position from the actual one during the observation. In general, the area of uncertainty is an ellipse in shape.

3.2. Methods of Target Discrimination

One way to distinguish individual objects is the utilization of the object position prediction and the uncertainty ellipse mentioned above. Objects that are outside the ellipse of uncertainty are ignored and the object (target) located inside the ellipse is observed only. Its position is used to update the Kalman filter. However, it may be the case that the area of uncertainty will identify true target as a false one (flare). This may happen if the false target is ignited immediately after the fling or the missile approaches the target at an angle when the true target image overlaps the false target image. In this case, it has to be decided which position is correct and can be used to the Kalman filter update. One possibility is to compare the distance of two (or more) objects from the predicted position and the object which is closer is considered a true target. With this method, however, the risk of confusion true and false targets is very high because of the principle of determining the predicted position where we cannot guarantee that the true target will be closer to the predicted position than the false target. In Fig. 5, there is a frame from video camera which shows the object. The figure is accompanied by a sign indicating the measured position, predicted position and uncertainty ellipse.

Another method based on the assumption that the true target is moving with less angular velocity than the false target within the seeker field of view allows to increase the probability of tracking the true target in the event that there are more objects in uncertainty area. If there are more objects within the uncertainty area, the Kalman filter is updated only by predicted values for a period of N cycles (frames). The N value depends on the parameters of the guidance system and on missile – target distance as well. The number N can be determined also experimentally. If the above-mentioned conditions are true, the true target, after N cycles, is still located in the area of uncertainty, while other objects (flares) are outside this area. After N cycles, it restores the original procedure and the Kalman filter will be again updated by values of the position of the object located within the area of uncertainty.

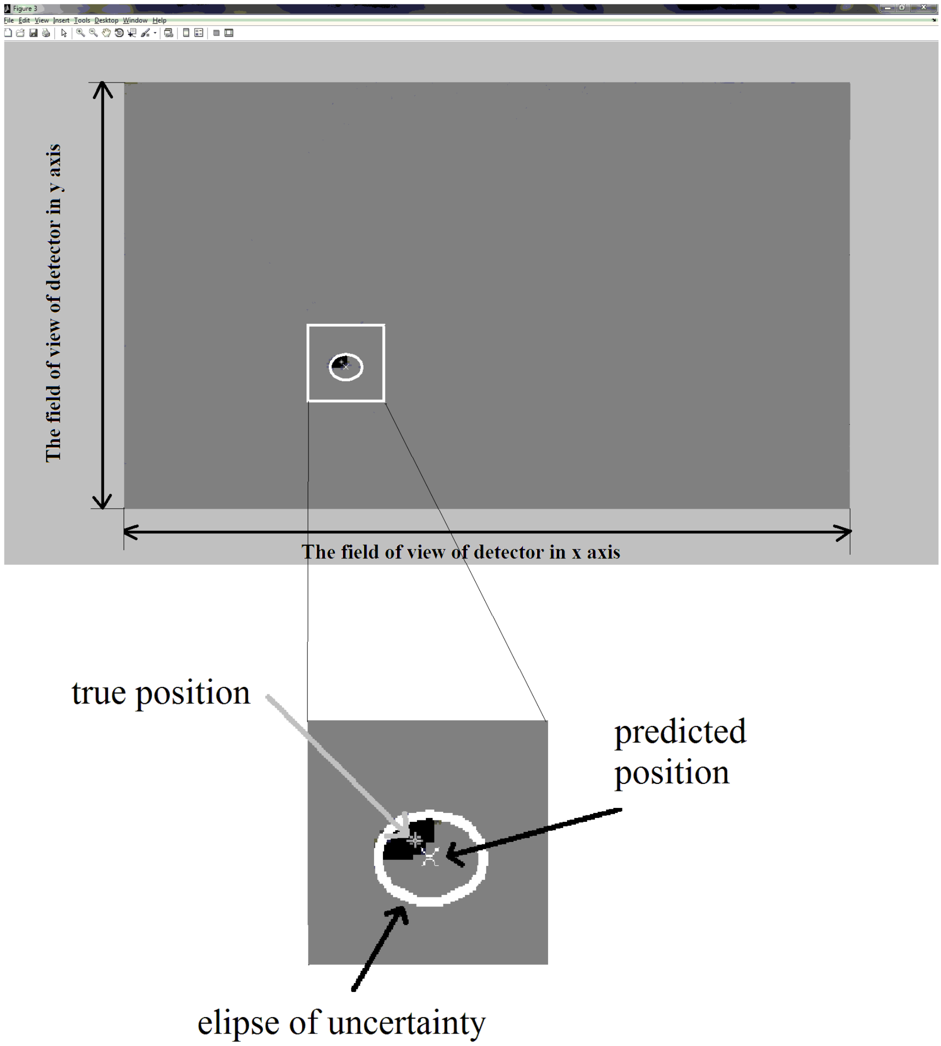

Fig. 5 Predicted position and ellipse of uncertainty

4. Conclusion

Electronic reduction of the field of view of the optoelectronic systems which serves for the measurement of the location of the optical radiation sources is one of possible precautions which can be implemented when the pulse position modulation is used. Together with other methods such as multicolour detection and tracking of useful object in accordance with level of radiant flux, it represents the effective instrument of high level of the protection against jamming.

In the processing of information from IIR missile seeker, the selection of targets is based on theirs motion prediction. It is one of methods for enhancing immunity against jamming. For predicting the motion, Kalman filter is appropriate. It allows changing the coefficients of gain on the basis of actual measured data. This is useful for tracking objects that manoeuvre.

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