UDC 396.65 DOI: 10.30748/nitps.2018.33.09

Radhwan Mohammed Jawad Kadhim

National Aerospace University named after M.E. Zhukovsky "Kharkiv Aviation Institute", Kharkiv

MULTILOOP TRACKING DISTANCE MEASURING DEVICE OF RADIO-TECHNICAL TRACKING SYSTEM OF HIGH-MANAVABLE AIRCRAFTS

One of the important parameters evaluated in radio-technical systems of trajectory measurements is the distance to the tracking object. In view of the emergence of highly maneuverable aircrafts, the existing range autoselectors cannot effectively track the distance to such objects. Therefore, the work solves the problem of synthesis of a multiloop distance measuring device based on the estimation of the higher derivatives of the distance to the object. The models of the monitored and controlled processes are considered, the algorithm and the structure of the quasioptimal meter are proposed.

Keywords: *highly maneuverable aircrafts, tracking distance measuring device, auto-range provider, controller design of distance measuring device. digital automatic tracking and ranging system.*

Introduction

One of the important parameters evaluated in radio-technical systems of trajectory measurements is the distance to the tracking object. Due to the fact that the operation of the distance measuring devices included in the RTS is subject to the influence of various kinds of interference (intentional and unintended), they usually work in the automatic selection mode by the delay time of the signal reflected from the object (range). Therefore, such measuring devices are often called auto-range providers. The essence of the range selection is to unlock the radar receiver only at the time of the expected arrival of the signal reflected from the desired object [1–2]. As a result of automatic selection, only the signal reflected from the tracking object comes to the channel of forming the range estimate. This leads to an increase in the efficiency of range estimation compared to measuring devices that do not use pre-selection.

Maneuvering of objects leads to an increase in dynamic errors, which in turn can lead to disruption of tracking [3]. For an auto-range provider, this means that the received signal goes beyond the strobe limits. The expansion of the strobe, as a possible solution to this problem is not an effective measure, since this reduces the signal-to-noise ratio at the input of the radar receiver, there is the possibility of hitting the strobe signals reflected from other objects, which, again, can lead to the disruption of the tracking.

The elimination of these drawbacks is possible when expanding the vector of estimated system state parameters and optimizing algorithms for controlling the RTS actuators based on the extended state vector [4–5].

Existing tracking meters are built on a single-loop principle, when a sensing element (discriminator), a command generator (regulator, controller) and actuators are connected in a loop in series.

With such a scheme for constructing a measuring device, the conditions for achieving high accuracy in estimating the parameters of the state of a system contradict the conditions of stability [6]. In addition, the basic parameters – range and speed in existing radar measuring devices – are estimated based on models of uniform or uniformly accelerated motion of an object, while modern aircraft can perform spatial evolutions leading to the appearance of significant components of the second, third, and fourth range derivatives [7] .

A promising direction to eliminate these disadvantages of single-loop meters is the synthesis of multi-loop tracking systems with an expanded composition of measured parameters. In a multi-loop meter, the processes of estimating measured values and generating a control signal are carried out separately, which increases the stability of the distance measuring device [1; 6].

Research Objective

The aim of the work is to synthesize an optimal multiloop regulator (ruler) of the range auto-selector to accompany highly maneuverable aircrafts. The subject of optimization is the process of generating gating pulses of the rangefinder.

Synthesis of the tracking measuring device will be performed by the state space method. At the same time, we believe that the evolution of the controlled (required) process of changing the range in the rangefinder controller being synthesized (the vector of required states $\vec{\mathbf{x}}_T$ and measurements $\vec{\mathbf{z}}_T(t)$) is given by general equations of the form:

$$\dot{\vec{\mathbf{x}}}_T(t) = \mathbf{A}_T(t)\vec{\mathbf{x}}_T(t) + \mathbf{C}_T(t)\vec{\xi}_{xT}(t)\,, \qquad (1)$$

$$\vec{\mathbf{z}}_T(t) = \mathbf{H}_T(t)\vec{\mathbf{x}}_T(t) + \vec{\xi}_{zT}(t)\,, \qquad (2)$$

where $\mathbf{A}_T(t)$ - dynamic matrix of the controlled process; $\mathbf{C}_T(t)$ - disturbance matrix of the controlled process; $\mathbf{H}_T(t)$ - measurement matrix; $\vec{\mathbf{z}}_T(t)$ - measurement vector of the controlled process; $\vec{\xi}_{xT}(t)$ and $\vec{\xi}_{zT}(t)$ - disturbance vectors of the controlled process and measurement noise, respectively.

The controlled process model is given by general equations of state. $\vec{\mathbf{x}}_y(t)$ and measurements $\vec{\mathbf{z}}_y(t)$ as:

$$\dot{\vec{\mathbf{x}}}_y(t) = \mathbf{A}_y(t)\vec{\mathbf{x}}_y(t) + \mathbf{B}_y(t)\vec{\mathbf{u}}(t) + \mathbf{C}_y(t)\vec{\xi}_{x_y}(t), \quad (3)$$

$$\vec{\mathbf{z}}_y(t) = \mathbf{H}_y(t)\vec{\mathbf{x}}_y(t) + \vec{\xi}_{\mathbf{z}_y}(t), \quad (4)$$

where $\mathbf{A}_y(t)$ - dynamic matrix of the controlled process; $\mathbf{B}_y(t)$ - control matrix; $\mathbf{C}_y(t)$ - disturbance matrix of the controlled process; $\vec{\mathbf{u}}(t)$ - control vector; $\mathbf{H}_y(t)$ - measurement matrix; $\vec{\xi}_{x_y}(t)$ and $\vec{\xi}_{\mathbf{z}_y}(t)$ - respectively, vectors of disturbances and noise measurements of a controlled process.

The task of synthesis is to determine the optimal algorithm for calculating the vector of control actions based on the results of observations $\vec{\mathbf{z}}_T(t)$ and $\vec{\mathbf{z}}_y(t)$ constituent vectors $\vec{\mathbf{x}}_T$ and $\vec{\mathbf{x}}_y(t)$, which would allow the best (optimal) way to form a controlled state $\vec{\mathbf{x}}_y(t)$ at the output of the controller (regulator).

The synthesis of the tracking part of the distance measuring device and its derivatives will be carried out based on the following assumptions and assumptions:

1) the tracking object is detected and the meter operates in the automatic tracking mode;

2) at the input of the optimal regulator from the temporal discriminator tracking measuring device, optimal estimates of higher derivatives of the range are received. Algorithms for the formation of such estimates are described in [5];

3) when describing the accelerated movement of the object of tracking, we restrict ourselves to the fourth derivative of the range [7].

Synthesis of optimal multiloop regulator

Process models: Limiting ourselves to considering the fourth derivative of the range in the synthesis of the optimal measuring device, the model of the controlled (required) process system can be represented by the equation of accelerated motion:

$$D_{\text{от}}(t) = D_{\text{от}}^{(1)}(t)\cdot t + D_{\text{от}}^{(2)}(t)\cdot\frac{t^2}{2!} + \\ = D_{\text{от}}^{(3)}(t)\cdot\frac{t^3}{3!} + D_{\text{от}}^{(4)}(t)\cdot\frac{t^4}{4!}, \quad (5)$$

where $D_{\text{от}}(t)$ – tracked distance; $D_{\text{от}}^{(1)}(t) = \dot{D}_{\text{от}}(t) = V_{\text{от}}(t)$ – controlled speed; $D_{\text{от}}^{(2)} = \ddot{D}_{\text{от}}(t) = \dot{V}_{\text{от}}(t) = a_{\text{от}}(t)$ – tracked acceleration; $D_{\text{от}}^{(3)}(t) = \dddot{D}_{\text{от}}(t) = \ddot{V}_{\text{от}}(t) = \dot{a}_{\text{от}}(t) = j_{\text{от}}(t)$ – tracked inversion (derivative of acceleration; rate of change of acceleration); $D_{\text{от}}^{(4)}(t) = \ddddot{D}_{\text{от}}(t) = \dot{j}_{\text{от}}(t) = w_{\text{от}}(t)$ – tracked rate of change of the inversion; $D_{\text{от}}^{(n)} = \frac{dD_{\text{от}}^n}{dt^n}$; $\dot{D}_{\text{от}}(t) = \frac{dD_{\text{от}}}{dt}$; $\ddot{D}_{\text{от}}(t) = \frac{dD_{\text{от}}^2}{dt^2}$; $\dddot{D}_{\text{от}}(t) = \frac{dD_{\text{от}}^3}{dt^3}$; $\ddddot{D}_{\text{от}}(t) = \frac{dD_{\text{от}}^4}{dt^4}$ - differentiation operators.

Let's rewrite equation (5) as:

$$\ddddot{Д}_{\text{от}}(t)\cdot\frac{t^4}{24} + \dddot{Д}_{\text{от}}(t)\cdot\frac{t^3}{6} + \ddot{Д}_{\text{от}}(t)\cdot\frac{t^2}{2} + \\ + \dot{Д}_{\text{от}}(t)\cdot t - Д_{\text{от}}(t) = 0 \quad (6)$$

and divide by $\frac{t^4}{24}$:

$$\ddddot{Д}_{\text{от}}(t) + \frac{4}{t}\dddot{Д}_{\text{от}}(t) + \frac{12}{t^2}\cdot\ddot{Д}_{\text{от}}(t) + \\ + \frac{24}{t^3}\cdot\dot{Д}_{\text{от}}(t) - \frac{24}{t^4}\cdot Д_{\text{от}}(t) = 0. \quad (7)$$

Equation (7) can be rewritten as:

$$\ddddot{Д}_{\text{от}}(t) + a_3(t)\dddot{Д}_{\text{от}}(t) + a_2(t)\cdot\ddot{Д}_{\text{от}}(t) + \\ + a_1(t)\cdot\dot{Д}_{\text{от}}(t) + a_0(t)\cdot Д_{\text{от}}(t) = 0, \quad (8)$$

where $a_0(t) = -\frac{24}{t^4}$, $a_1(t) = \frac{24}{t^3}$, $a_2(t) = \frac{12}{t^2}$, $a_3(t) = \frac{4}{t}$.

The equation (8), as normal, describes the model of the process being controlled. Let's transform the third-order differential equation into a form representable in the state space, that is, we reduce it to form (1). To do this, let's introduce the notations:

$Д_{\text{от}}(t) = Д_{\text{от}1}(t)$;

$\dot{Д}_{\text{от}1}(t) = Д_{\text{от}2}(t)$;

$\dot{Д}_{\text{от}2}(t) = Д_{\text{от}3}(t)$;

$\dot{Д}_{\text{от}3}(t) = Д_{\text{от}4}(t)$;

$\dot{Д}_{\text{от}4}(t) = -a_3(t)\cdot\dddot{Д}_{\text{от}}(t) - a_2(t)\cdot\ddot{Д}_{\text{от}}(t) - \\ -a_1(t)\cdot\dot{Д}_{\text{от}}(t) - a_0(t)\cdot Д_{\text{от}}(t).$

Taking into account the introduced notation, a fourth-order differential equation (8) can be represented as a system of first-order equations written in vector-matrix form:

$$\begin{Vmatrix} \dot{Д}_{\text{от}1}(t) \\ \dot{Д}_{\text{от}2}(t) \\ \dot{Д}_{\text{от}3}(t) \\ \dot{Д}_{\text{от}4}(t) \end{Vmatrix} = \begin{Vmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0(t) & -a_1(t) & -a_2(t) & -a_3(t) \end{Vmatrix} \cdot \begin{Vmatrix} Д_{\text{от}1}(t) \\ Д_{\text{от}2}(t) \\ Д_{\text{от}3}(t) \\ Д_{\text{от}4}(t) \end{Vmatrix} \quad (9)$$

or $$\dot{\vec{Д}}_{\text{от}}(t) = \mathbf{A}_{\text{от}}(t)\cdot\vec{Д}_{\text{от}}(t), \quad (10)$$

where $\vec{Д}_{от}(t)=[Д_{от}(t)\ \dot{Д}_{от}(t)\ \ddot{Д}_{от}(t)\ \dddot{Д}_{от}(t)]^T$ - state vector of the controlled process (vector of phase coordinates).

The controlled process takes place against the background of noise exposure (measurement noise, external disturbances affecting the aircraft), therefore, the noise component must be included in equation (10). Moreover, when solving a problem in a Gaussian formulation, (10) is converted to the form:

$$\dot{\vec{Д}}_{от}(t)=\mathbf{A}_{от}(t)\cdot\vec{Д}_{от}(t)+\mathbf{C}_{от}(t)\cdot\vec{\xi}_{Дот}(t), \quad (11)$$

where $\vec{\xi}_{Дот}(t)=[\xi_{от1}(t)\ \xi_{от2}(t)\ \xi_{от3}(t)\ \xi_{от4}(t)]^T$ - disturbance and noise vector of measurements of the controlled process, described by centered Gaussian noises with a known matrix of single-sided spectral densities $\mathbf{G}_{\xi от}$; $\mathbf{C}_{от}(t)=[1\ 1\ 1\ 1]^T$ - disturbance matrix of the controlled process $4x1$.

The model of the controlled process of the synthesized regulator must ensure the stable control of the actuators. For linear stationary systems or processes (3) in which control signals u_i $(i=\overline{1,r})$ do not exceed some acceptable values $U_{доп\ i}$ the criterion of controllability is determined by the relation [8]:

$$\mathrm{rank}\left[\mathbf{B}_y\left|\mathbf{A}_y\mathbf{B}_y\right|\mathbf{A}_y^2\mathbf{B}_y\left|...\right|\mathbf{A}_y^{n-1}\mathbf{B}_y\right]=n, \quad (12)$$

where n - dimension of the state vector $\vec{\mathbf{x}}_y$ systems (number of controlled phase coordinates).

Criterion (12) allows determining the minimum set of control signals for targeted change of all system state variable To fulfill condition (12), it is necessary that in all groups of functionally related phase coordinates at least the highest derivative be controlled [8]. In the future, the framework for using this assumption should be checked at the stage of modeling the operation of the synthesized controller.

For the range measurer, the control device is the gate arrangement device. The delay time of the strobe relative to the probe pulse is determined by the expected delay time of arrival of the reflected pulse. With these comments, the model of the controlled process can be represented by the equation:

$$\begin{aligned}Д_y(t)=Д_y^{(1)}(t)\cdot t+Д_y^{(2)}(t)\cdot\frac{t^2}{2!}+Д_y^{(3)}(t)\cdot\frac{t^3}{3!}+\\+Д_y^{(4)}(t)\cdot\frac{t^4}{4!}+b_j(t)\cdot u_j(t),\end{aligned} \quad (13)$$

where $u_j(t)$ - loop actuating signal; $b_j(t)$ - efficiency factor of control signal. Here, the index "y" denotes the controlled range and its derivatives.

By analogy with the controlled, the controlled process model can also be reduced to the form (3) state-space description:

$$\dot{\vec{Д}}_y(t)=\mathbf{A}_y(t)\cdot\vec{Д}_y(t)+\mathbf{B}_y(t)\cdot\vec{U}_{Ду}(t)+\mathbf{C}_y(t)\cdot\vec{\xi}_{Ду}(t), \quad (14)$$

where $\vec{Д}_y(t)=[Д_y(t)\ \dot{Д}_y(t)\ \ddot{Д}_y(t)\ \dddot{Д}_y(t)]^T$ - state vector of the controlled process;

$\mathbf{A}_y(t)=\begin{Vmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\-a_0(t)&-a_1(t)&-a_2(t)&-a_3(t)\end{Vmatrix}$ - dynamic matrix of the controlled process; $\vec{U}_{Ду}(t)=[0\ 0\ 0\ u_w(t)]^T$ - control vector; $\mathbf{B}_y(t)=\begin{Vmatrix}0\\0\\0\\b_w(t)\end{Vmatrix}$ - control matrix;

$\vec{\xi}_{Ду}(t)=[\xi_{y1}(t)\ \xi_{y2}(t)\ \xi_{y3}(t)\ \xi_{y4}(t)]^T$ - vector of disturbances and noise measurements of a controlled process, described by centered Gaussian noises with a known matrix of single-sided spectral densities $\mathbf{G}_{\xi y}$; $\mathbf{C}_y(t)=[1\ 1\ 1\ 1]^T$ - disturbance matrix of a controlled process $4x1$.

The general form of the equations of observation for monitored and controlled processes, in the case of Gaussian disturbances, corresponds to (2; 4). With the selected models of the state of the monitored and controlled processes, measurements should ensure observance of observability criteria [8–10], analysis of which shows [11] that, in general, with an increase in the number of gauges (observers), observability improves. Suppose that in both the controlled and the controlled processes all phase coordinates are observed independently. Then the processes are absolutely observable, and the measurement matrices in equations (2; 4) take the form of diagonal unit matrices:

$$\mathbf{H}_y(t)=\mathbf{H}_{от}(t)=\begin{Vmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{Vmatrix}. \quad (15)$$

Evaluation of the state vector of the controlled process $\vec{Д}_{от}(t)$ generates a discriminator, and information about the state vector of the controlled process $\vec{Д}_y(t)$ can be obtained at the output of the range finder.

The final form of the observation equations for the controlled process:

$$\vec{z}_{от}(t)=\mathbf{H}_{от}(t)\cdot\vec{Д}_{от}(t)+\mathbf{C}_{иот}(t)\cdot\vec{\xi}_{иот}(t), \quad (16)$$

and controlled process:

$$\vec{z}_y(t)=\mathbf{H}_y(t)\cdot\vec{Д}_y(t)+\mathbf{C}_{иу}(t)\cdot\vec{\xi}_{иу}(t), \quad (17)$$

where $\vec{\xi}_{иот}(t)=[\xi_{иот1}(t)\ \xi_{иот2}(t)\ \xi_{иот3}(t)\ \xi_{иот4}(t)]^T$, $\vec{\xi}_{иу}(t)=[\xi_{иу1}(t)\ \xi_{иу2}(t)\ \xi_{иу3}(t)\ \xi_{иу4}(t)]^T$ - the measurement noise vectors of the monitored and controlled processes described by centered Gaussian noises with known matrices of single-sided spectral densities $\mathbf{G}_{\xi\text{иот}}$ and $\mathbf{G}_{\xi\text{иу}}$, respectively; $\mathbf{C}_{\text{иот}}(t) = \mathbf{C}_{\text{иу}}(t) = [1\ 1\ 1\ 1]^{\text{T}}$ - disturbance matrix of the monitored and controlled processes $4\text{x}1$, respectively.

Compensator design.

Let's assume the state of the synthesized regulator as generalized state vector $\vec{\text{Д}}(t) = [\vec{\text{Д}}^{\text{T}}_{\text{от}}(t)\ \ \vec{\text{Д}}^{\text{T}}_{\text{у}}(t)]^{\text{T}}$. Then his model in the state space will be described by the matrix equation:

$$\dot{\vec{\text{Д}}}(t) = \mathbf{A}(t)\cdot\vec{\text{Д}}(t) + \mathbf{B}(t)\cdot\vec{\text{U}}(t) + \mathbf{C}(t)\cdot\vec{\xi}(t), \qquad (18)$$

where $\mathbf{A} = \begin{Vmatrix} \mathbf{A}_{\text{от}} & \mathbf{O}_1 \\ \mathbf{O}_2 & \mathbf{A}_{\text{у}} \end{Vmatrix}$, $\mathbf{B} = \begin{Vmatrix} \mathbf{O}_3 \\ \mathbf{B}_{\text{у}} \end{Vmatrix}$, $\xi = \begin{Vmatrix} \xi_{\text{от}} \\ \xi_{\text{у}} \end{Vmatrix}$, $\mathbf{C} = \begin{Vmatrix} \mathbf{C}_{\text{от}} & \mathbf{O}_4 \\ \mathbf{O}_5 & \mathbf{C}_{\text{у}} \end{Vmatrix}$, $\mathbf{O}_i$ - zero matrices of the corresponding dimensions $i = \overline{1,5}$. Hereinafter, to simplify recording, time dependence is omitted.

In [8], it was shown that for the system described by (18) when optimizing for the minimum of the local quadratic quality functional, the optimal control algorithm should give the following value of the control vector:

$$\vec{\text{U}} = \mathbf{K}^{-1}\cdot\mathbf{B}^{\text{T}}_{\text{у}}\cdot\mathbf{Q}\cdot[\hat{\mathbf{x}}_{\text{от}} - \hat{\mathbf{x}}_{\text{у}}]. \qquad (19)$$

where

$$\vec{\text{U}} = u_w,\ \mathbf{K} = k_u,\ \mathbf{Q} = \begin{Vmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \\ q_{41} & q_{42} & q_{43} & q_{44} \end{Vmatrix},$$

$q_{n\ m}$ - penalty coefficients for tracking accuracy on the corresponding phase coordinate ($n, m = \overline{1,4}$); k_u - penalty factor for the amount of control signal.

Given that $\hat{\mathbf{x}}_{\text{у}} = \vec{\text{Д}}_{\text{у}} = [\text{Д}_{\text{у}}\ \dot{\text{Д}}_{\text{у}}\ \ddot{\text{Д}}_{\text{у}}\ \dddot{\text{Д}}_{\text{у}}]^{\text{T}}$, $\hat{\mathbf{x}}_{\text{от}} = \vec{\text{Д}}_{\text{от}} = [\text{Д}_{\text{от}}\ \dot{\text{Д}}_{\text{от}}\ \ddot{\text{Д}}_{\text{от}}\ \dddot{\text{Д}}_{\text{от}}]^{\text{T}}$ and substituting everything in (19) we get:

$$u_w = \frac{b_w q_{41}}{k_u}[\hat{\text{Д}}_{\text{от}} - \hat{\text{Д}}_{\text{у}}] + \frac{b_w q_{42}}{k_u}[\hat{\dot{\text{Д}}}_{\text{от}} - \hat{\dot{\text{Д}}}_{\text{у}}] + \frac{b_w q_{43}}{k_u}[\hat{\ddot{\text{Д}}}_{\text{от}} - \hat{\ddot{\text{Д}}}_{\text{у}}] + \frac{b_w q_{44}}{k_u}[\hat{\dddot{\text{Д}}}_{\text{от}} - \hat{\dddot{\text{Д}}}_{\text{у}}] = K^{\text{Д}}\Delta\text{Д} + K^{\dot{\text{Д}}}\Delta\dot{\text{Д}} + K^{\ddot{\text{Д}}}\Delta\ddot{\text{Д}} + K^{\dddot{\text{Д}}}\Delta\dddot{\text{Д}}, \qquad (20)$$

where $\Delta\text{Д} = \hat{\text{Д}}_{\text{от}} - \hat{\text{Д}}_{\text{у}}$, $\Delta\dot{\text{Д}} = \hat{\dot{\text{Д}}}_{\text{от}} - \hat{\dot{\text{Д}}}_{\text{у}}$, $\Delta\ddot{\text{Д}} = \hat{\ddot{\text{Д}}}_{\text{от}} - \hat{\ddot{\text{Д}}}_{\text{у}}$, $\Delta\dddot{\text{Д}} = \hat{\dddot{\text{Д}}}_{\text{от}} - \hat{\dddot{\text{Д}}}_{\text{у}}$ - tracking error in range and corresponding range derivative; $K^{\text{Д}}$, $K^{\dot{\text{Д}}}$, $K^{\ddot{\text{Д}}}$, $K^{\dddot{\text{Д}}}$ - the gains of the corresponding errors.

From (20) it is clear that for the functioning of the synthesized regulator, optimal estimates of the vectors are needed $\vec{\text{Д}}_{\text{от}}$, $\vec{\text{Д}}_{\text{у}}$. The first vector estimates are generated by the discriminator measuring device. To obtain vector estimates $\vec{\text{Д}}_{\text{у}}$ need to synthesize a separate filter.

To evaluate the process given by equation (14) in the presence of observations (17), in practice, the Kalman estimator optimal linear filtering is often used.

Kalman estimator allows you to form an optimal estimate by the criterion of minimum variance $\text{M}\{(\vec{\text{Д}}_{\text{у}} - \hat{\vec{\text{Д}}}_{\text{у}})(\vec{\text{Д}}_{\text{у}} - \hat{\vec{\text{Д}}}_{\text{у}})^{\text{T}}\}$ according to the algorithm [8; 12]:

$$\dot{\hat{\vec{\text{Д}}}}_{\text{у}} = \mathbf{A}_{\text{у}}\cdot\hat{\vec{\text{Д}}}_{\text{у}} + \mathbf{B}_{\text{у}}\cdot\vec{\text{U}}_{\text{Ду}} + \mathbf{K}_{\text{у}}(\vec{z}_{\text{у}} - \mathbf{H}\cdot\hat{\vec{\text{Д}}}_{\text{у}}), \qquad (21)$$

$$\mathbf{K}_{\text{у}} = 2\mathbf{R}\mathbf{H}^{\text{T}}\mathbf{G}^{-1}_{\xi\text{иу}}, \qquad (22)$$

$$\dot{\mathbf{R}} = \mathbf{A}_{\text{у}}\mathbf{R} + \mathbf{R}\mathbf{A}^{\text{T}}_{\text{у}} - 2\mathbf{R}\mathbf{H}^{\text{T}}\mathbf{G}^{-1}_{\xi\text{иу}}\mathbf{H}\mathbf{R} + 0{,}5\mathbf{G}_{\xi\text{у}},\quad \mathbf{R}(0) = \mathbf{R}_0, \qquad (23)$$

where $\mathbf{R}$ - covariance matrix of filtering errors, which determines the potential accuracy of estimation.

The block diagram of the measuring device (fig. 1) is obtained on the basis of the initial equations of the monitored and controlled processes, the law of optimal control and the optimal estimation of phase coordinates during optimization by the quadratic criterion. In the picture: ПРМ – receiver; Д – discriminator; УРС – gate arrangement device.

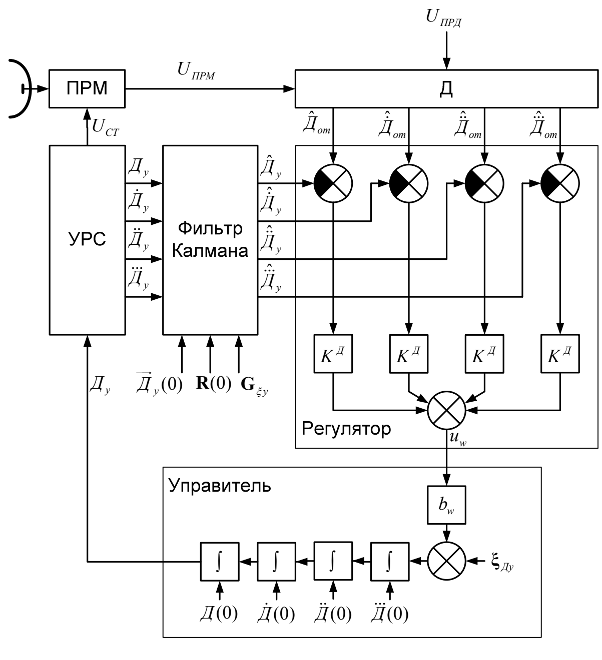

Fig. 1. Multiloop block diagram of a quasi-optimal tracking distance measuring device

The synthesized distance measuring device is a multidimensional non-stationary multiloop system. Multidimensionality is due to the use of several measured system state variables. Some state variables are passed to the user ($Д$, $\dot{Д}$), and part is used only to form the control signal ($\ddot{Д}$, $\dddot{Д}$, $\ddddot{Д}$). The nonstationarity of the system is due to the use of variable gain factors in the Kalman filter $\mathbf{K}_{у}$ of residuals $\vec{z}_{у} - \mathbf{H} \cdot \hat{\vec{Д}}_{у}$, the value of which can vary from the highest values (for testing the initial discrepancy) to the smallest (to ensure maximum accuracy of estimation), as well as the non-stationarity of the coefficients of dynamic matrices tracked $\mathbf{A}_{от}$ and controlled $\mathbf{A}_{у}$ processes.

Conclusion

A quasi-optimal distance measuring device was synthesized in the paper, which takes into account the appearance of higher derivatives of a range of intensively maneuvering aircraft.

To increase stability in the meter used multi-circuit design principle. Separately synthesized are the phase coordinate measurement loop (discriminator), the control loop (controller - ruler - gate device - Kalman estimator - regulator) and the loop of controlled phase coordinate estimation (Kalman estimator).

Список літератури

1. Авиационные системы радиоуправления. В 3-х томах. Т.2. Принципы построения систем радиоуправления. Основы синтеза и анализа / В.И. Меркулов, В.В. Дрогалин, А.И. Канащенков и др.; под ред. А.И. Канащенкова и В.И. Меркулова. – М.: Радиотехника, 2003. – 391 с.

2. Радиотехнические системы / Ю.П. Гришин, В.П. Ипатов, Ю.М. Казаринов и др.; под ред. Ю.М. Казаринова. – М.: Высш. шк., 1990. – 496 с.

3. Канащенков А.И. Облик перспективных бортовых радиолокационных систем. Возможности и ограничения / А.И. Канащенков, В.И. Меркулов, О.Ф. Самарин. – М.: ИПЖР, 2002. – 176 с.

4. Меркулов В.И. Обоснование состава информации, используемой в комплексе бортового оборудования при перехвате воздушных целей / В.И. Меркулов // Радиолокация и радиометрия. – 1999. – Вып. 1. – С. 9-11.

5. Барышев И.В. Измерение высших производных доплеровской частоты когерентной пачки импульсов, отраженной от высокоманевренного объекта / И.В. Барышев, М.Л. Усс, Радван М. Джавад // Радіоелектронні і комп’ютерні системи. – 2008. – № 1(28). – С. 43-55.

6. Максимов М.В. Радиоэлектронные следящие системы. (Синтез методами теории оптимального управления) / М.В. Максимов, В.И. Меркулов. – М.: Радио и связь, 1990. – 256 с.

7. Радван М. Джавад. Оценка высших производных дальности для сверхманевренных летательных аппаратов / Радван М. Джавад // Вісник Національного технічного університету «ХПІ». Збірник наукових праць. Тематичний випуск: Нові рішення в сучасних технологіях. – Харків: НТУ «ХПІ», 2010. – № 17. – С. 85-93.

8. Авиационные системы радиоуправления. В 3-х томах. Т.1. Принципы построения систем радиоуправления. Основы синтеза и анализа / Под ред. А.И. Канащенкова и В.И. Меркулова. – М.: Радиотехника, 2003. – 192 с.

9. Справочник по теории автоматического управления / Под ред. А.А. Красовского. - М.: Наука, 1987.

10. Мита Ц. Введение в цифровое управление: перев. с японск. / Ц. Мита, С. Хара, Р. Кондо. - М.: Мир, 1994.

11. Крутько И.Д. Алгоритмы и программы проектирования автоматических систем / И.Д. Крутько, А.И. Максимов, Л.М. Скворцов. – М.: Радио и связь, 1988.

12. Браммер К. Фильтр Калмана-Бьюси. Детерминированное наблюдение и стохастическая фильтрация / К. Браммер, Г. Зиффлинг. – М.: Наука, 1982. – 200 с.

References

1. Merkulov, V.I., Drogalin, V.V. and Kanashchenkov, A.I. (2003), “*Aviatsionnyye sistemy radioupravleniya. V 3-kh tomakh. T.2. Printsipy postroyeniya sistem radioupravleniya. Osnovy sinteza i analiza*” [*Aircraft radio control systems. In 3 volumes. Vol. 2. Principles of construction of radio control systems. Basics of synthesis and analysis*], Radiotekhnika, Moscow, 391 p.

2. Grishin, Yu.P., Ipatov, V.P. and Kazarinov, Yu.M. (1990), “*Radiotekhnicheskiye sistemy*” [*Radio systems*], Vysshaya shkola, Moscow, 496 p.

3. Kanashchenkov, A.I., Merkulov, V.I. and Samarin, O.F. (2002), “*Oblik perspektivnykh bortovykh radiolokatsionnykh sistem. Vozmozhnosti i ogranicheniya*” [*The appearance of promising airborne radar systems. Features and limitations*], IPZhR, Moscow, 176 p.

4. Merkulov, V.I. (1999), “Obosnovaniye sostava informatsii. ispolzuyemoy v komplekse bortovogo oborudovaniya pri perekhvate vozdushnykh tseley” [Justification of the composition of the information used in the complex onboard equipment in the interception of air targets], *Radiolokatsiya i Radiometriya*, No. 1, pp. 9-11.

5. Baryshev, I.V., Uss, M.L. and Radvan, M. Dzhavad (2008), “Izmereniye vysshikh proizvodnykh doplerovskoy chastoty kogerentnoy pachki impulsov. otrazhennoy ot vysokomanevrennogo obyekta” [Measurement of the higher derivatives of the Doppler frequency of a coherent burst of pulses reflected from a highly maneuverable object], *Radioyelektronni i komp’yuterni sistemi*, No. 1 (28), pp. 43-55.

6. Maksimov, M.V. and Merkulov, V.I. (1990), "*Radioelektronnyye sledyashchiye sistemy. (Sintez metodami teorii optimalnogo upravleniya)*" [*Radio-electronic tracking systems. (Synthesis by methods of optimal control theory)*], Radio i svyaz, Moscow, 256 p.

7. Radhwan M. Jawad (2010), "Otsenka vysshikh proizvodnykh dalnosti dlya sverkhmanevrennykh letatelnykh apparatov" [Evaluation of higher range derivatives for super-maneuverable aircraft], *Visnyk Natsionalnoho tekhnichnoho universytetu „KhPI",* No. 17, pp. 85-93.

8. Kanashchenkov, A.I. and Merkulov, V.I. (2003), "*Aviatsionnyye sistemy radioupravleniya. V 3-kh tomakh. T.1. Printsipy postroyeniya sistem radioupravleniya. Osnovy sinteza i analiza*" [*Aircraft radio control systems. In 3 volumes. Vol. 1. Principles of construction of radio control systems. Basics of synthesis and analysis*], Radiotekhnika, 192 p.

9. Krasovskiy, A.A. (1987), "*Spravochnik po teorii avtomaticheskogo upravleniya*" [*Handbook of Automatic Control Theory*], Nauka, Moscow.

10. Mita, Ts., Khara, S. and Kondo, R. (1994), "*Vvedeniye v tsifrovoye upravleniye*" [*Introduction to digital control*], Mir, Moscow.

11. Krutko, I.D., Maksimov, A.I. and Skvortsov, L.M. (1998), "*Algoritmy i programmy proyektirovaniya avtomaticheskikh sistem*" [*Algorithms and programs for designing automatic systems*], Radio i svyaz, Moscow.

12. Brammer, K. and Ziffling, G. (1982), "*Filtr Kalmana-Byusi. Determinirovannoye nablyudeniye i stokhasticheskaya filtratsiya*" [*Kalman-Bucy filter. Deterministic observation and stochastic filtering*], Nauka, Moscow, 200 p.

Received by Editorial Board 4.10.2018
Signed for printing 5.11.2018

Відомості про автора:

Радван Мухамед Жавад Кадім
аспірант Національного аерокосмічного університету
ім. М.Є. Жуковського «Харківський авіаційний інститут»,
Харків, Україна

Information about the author:

Radhwan Mohammed Jawad Kadhim
Doctoral Student of National Aerospace University
named after M.E. Zhukovsky "Kharkiv Aviation Institute",
Kharkiv, Ukraine

БАГАТОКОНТУРНИЙ СЛІДКУВАЛЬНИЙ ВИМІРЮВАЧ ДАЛЬНОСТІ РАДІОТЕХНІЧНОЇ СИСТЕМИ СУПРОВОДУ ВИСОКОМАНЕВРЕНИХ ЛІТАЛЬНИХ АПАРАТІВ

Радван Мухамед Жавад Кадім

Одним з важливих параметрів, які оцінюються в радіотехнічних системах траєкторних вимірювань, є дальність до супроводжуваного об'єкта. У зв'язку з появою високоманеврених літальних апаратів існуючі автоселектори дальності не можуть ефективно відстежувати дальність до таких об'єктів. Тому в роботі вирішується завдання синтезу багатоконтурного вимірювача дальності на основі оцінювання вищих похідних зміни дальності до об'єкта. Розглянуто моделі відслідковуємого і керованого процесів, запропонований алгоритм і структура квазіоптимального вимірювача.

Ключові слова: *високоманеврені літальні апарати, вимірювач дальності, що слідкує, автоселектор дальності, синтез регулятора вимірювача дальності.*

МНОГОКОНТУРНЫЙ СЛЕДЯЩИЙ ИЗМЕРИТЕЛЬ ДАЛЬНОСТИ РАДИОТЕХНИЧЕСКОЙ СИСТЕМЫ СОПРОВОЖДЕНИЯ ВЫСОКОМАНЕВРЕННЫХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ

Радван Мухамед Жавад Кадим

Одним из важных параметров, оцениваемых в радиотехнических системах траекторных измерений, является дальность до сопровождаемого объекта. В связи с появлением высокоманевренных летательных аппаратов существующие автоселекторы дальности не могут эффективно отслеживать дальность до таких объектов. Поэтому в работе решается задача синтеза многоконтурного измерителя дальности на основе оценивания высших производных изменения дальности до объекта. Рассмотрены модели отслеживаемого и управляемого процессов, предложен алгоритм и структура квазиоптимального измерителя.

Ключевые слова: *высокоманевренные летательные аппараты, следящий измеритель дальности, автоселектор дальности, синтез регулятора измерителя дальности.*