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ANALYTICAL MODELING EVALUATION AND MANAGEMENT OF OPERATIONAL STATE OF POWERFUL DRUM MILLS AS INTELLIGENT AGENTS

The use of intelligent multi-agent systems in the technological processes of mining and processing enterprises, taking into account the complexity and power of the units used here, requires research and analytical justification for the functioning of assessment and management systems in this environment. A promising approach is the ability to present each technological unit, namely a powerful drum mill with a control system, as an intelligent agent in the whole set of technological and technical processes actually existing here.

The aim *of the work is to study the possibility of analytical modeling of evaluation and management of the operational state of powerful drum mills as intelligent agents using an observer.*

The methodology *for ensuring the solution of the presented problem is to apply the reflection of the operational state of a powerful drum mill through the internal state of the agent in state variables, which to minimizes the resources for the formation of initial assessment and control solutions.*

The scientific novelty *is in the application of analytical modeling in state variables, using the principle of dynamic programming by R. Bellman to present the internal technical and technological state of the drum mill through the state of the agent, using a discrete observer for operational evaluation and control. This allows optimization according to a given criterion for the accuracy and energy consumption of the initial solutions that are formed in the system.*

Conclusions*. The justified application of equations in state variables written in the normal Koshi form to represent the internal state of the agent of a powerful drum mill presents an opportunity to more effectively work out the formation of optimal laws of decisions made according to a given criterion for accuracy and energy consumption.*

Key words: *multi-agent systems, intellectual agents, drum mill, dynamic programming, state variables, optimization of evaluation and management.*

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АНАЛІТИЧНЕ МОДЕЛЮВАННЯ ОЦІНЮВАННЯ ТА УПРАВЛІННЯ ОПЕРАТИВНИМ СТАНОМ ПОТУЖНИХ БАРАБАННИХ МЛИНІВ ЯК ІНТЕЛЕКТУАЛЬНИХ АГЕНТІВ

Застосування інтелектуальних мультиагентних систем в технологічних процесах гірничо-збагачувальних підприємств, враховуючи складність та потужність агрегатів, що тут використовуються, вимагає дослідження та аналітичного обґрунтування функціонування в цьому середовищі систем оцінювання та управління. Перспективним підходом при цьому виступає можливість представити кожний технологічний агрегат, а саме потужний барабанний млин з системою керування, як інтелектуальний агент у всій множині реально існуючих тут технологічних та технічних процесів.

Метою роботи *є дослідження можливості аналітичного моделювання оцінювання та управління оперативним станом потужних барабанних млинів як інтелектуальних агентів з використанням спостерігача.*

Методологія *забезпечення рішення представленого завдання складається в застосуванні відображення оперативного стану потужного барабанного млина через внутрішній стан агенту в змінних стану, що дозволяє мінімізувати ресурси формування вихідних рішень оцінювання та управління.*

Наукова новизна*. Складається в застосуванні аналітичного моделювання в змінних стану, з використанням принципу динамічного програмування Р. Беллмана до представлення внутрішнього техніко-технологічного стану барабанного млина через стан агенту, з використання дискретного спостерігача для оперативної оцінки і управління, що дозволяє здійснити оптимізацію відповідно заданого критерію по точності та енерговитратам вихідних рішень, які формуються в системі.*

Висновки*. Обґрунтоване застосування рівнянь в змінних стану, записаних в нормальній формі Коши, для представлення внутрішнього стану агенту потужного барабанного млина представляє можливість більш ефективно відпрацьовувати формування оптимальних відповідно заданого критерію по точності та енерговитратам закону рішень, що приймається.*

Ключові слова: *мультиагентні системи, інтелектуальні агенти, потужний барабанний млин, динамічне програмування, змінні стану, оптимізація оцінювання і управління.*

Urgency of the problem. If we consider every single powerful drum mill as an agent of mining and processing enterprise, and there are dozens of them located in the shops parallel to each other, then it is quite possible to introduce such an enterprise as a complex multi-agent system. Moreover, each drum mill that unites a whole stack of various technological, physical and chemical processes, taking into account automatic control systems is essentially an intellectual agent. Depending on the physical and chemical properties of the ore, which comes to the grinding, and the current technical condition of the mill units is carried out the operative intellectual adaptation of the control system according to the formed control criteria (is carried out). This is where application of analytical modeling to the estimation and management of the operational state of powerful drum mills as intellectual agents is a perspective approach with the purpose to increase the accuracy and reliability of functioning of technological process of grinding.

Analysis of recent research and publications. A wide study of existing sources revealed examples of the use of multi-agent systems for planning the work of various production complexes (Griffin, 2001; Meshcheriakov, 2018; Doudlya, 2004; Parunak, 1997; Karaboga, 2005). The main advantages of such systems are respectively: a clear formalization of decision-making points in the form of agents; basic scheduler, which accordingly operates in real time; the formed network of agents that is connected by specific relationships and independently coordinate their functional actions.

In general, the most significant practical results of the use of modern multi-agent systems include the solution of a number of problems of forming an apparatus of needs and capabilities (PM networks). Software-implemented in the form of MAGENTA technology, this apparatus of PM networks (developed by V.A. Vittikh, P.O. Skobelev, G.A. Rzhevsky (Meshcheriakov, 2018)) has found wide use in applied intelligent planning systems for various technological processes and distributed throughout network of objects.

The simulation modeling apparatus also uses a multi-agent approach to formalize the behavior of objects as agents. Currently, there are approaches and appropriate models of multi-agent planning on active and passive converters (developed by B.I. Klebanov and I.M. Moskalev (Parunak, 1997; Karaboga, 2005))), as well as approaches implemented in the AnyLogic environment and when modeling the technological processes of resource transformation (Meshcheriakov, 2018; Doudlya, 2004).

In the identified existing directions of application of modern multi-agent systems and, accordingly, intelligent agents, no significant attention has yet been paid to the operational internal state of powerful drum mills as agents, the assessment of this state and the management of the first on the basis of observers. Obviously, in the future this is one of the promising areas of consideration of generally complex powerful technological units as intelligent agents.

The purpose of the article is to explore the possibility of analytical modeling of evaluation and management of the operational state of powerful drum mills as intelligent agents using a discrete observer.

Presentation of the main material. Solving the problem of identification and optimal joint control of the technical and technological condition of powerful drum mills is an important task, and practice requires such a comprehensive approach. Therefore, considering the architecture of a powerful drum mill on the examples of a mill of the MMS 90 * 30 type, as a single closed technical and technological system, it is quite acceptable to carry out its presentation with a block diagram presented in fig.1, where typical links with unknown values of coefficients reflecting the actual inertia of the corresponding functional technological channels are taken (Meshcheriakov, 2009; Meshcheriakov, 2015).

The control algorithm is formed in the following form. It is necessary to form such control actions U_1, U_2, U_3, U_4, to ensure optimal stabilization at the specified levels of the total friction value in the support bearing units of the drum mill, the total friction value of the ore filling mass in the drum and the timely stop of the powerful drum mill before the emergency (on the supports and lining).

Based on Fig. 1, differential equations describing the operational dynamics of the state variables of a powerful drum mill will be presented in the technological state as following:

$$\dot{x}_1^* + \alpha_1 x_1^* = b_1 U_1, \qquad x_1 = x_1^* + x_1^{**} = x_1^* + k_1 U_2 \qquad (1)$$

$$\dot{x}_2^* + \alpha_2 x_2^* = b_2 U_3, \qquad x_2 = x_2^* + x_2^{**} = x_2^* + k_2 U_4,$$

$$y_1^* = x_1 + x_2.$$

And according to the technical condition

$$\dot{x}_3^* + \alpha_3 x_3^* = b_3 U_1, \quad x_3 = x_3^* + x_3^{**} = x_3^* + k_3 U_2,$$

$$\dot{x}_4^* + \alpha_4 x_4^* = b_4 U_3,$$

$$x_4 = x_4^* + x_4^{**} = x_4^* + k_4 U_4, , \qquad y_2^* = x_3 + x_4. .$$

After replacing x_i with z_i expressions (1) on the technological and technical conditions, respectively, will look like

$$\begin{cases} \dot{z}_1 + \alpha_1 z_1 = b_1 U_1 \\ \dot{z}_2 + \alpha_2 z_2 = b_2 U_3 \end{cases}, \qquad \begin{cases} \dot{z}_3 + \alpha_3 z_3 = b_3 U_1 \\ \dot{z}_4 + \alpha_4 z_4 = b_4 U_3 \end{cases}, \qquad (2)$$

$$y_1^* = z_1 + z_2 + k_1 U_2 + k_2 U_4, \ y_2^* = z_3 + z_4 + k_3 U_2 + k_4 U_4 .$$

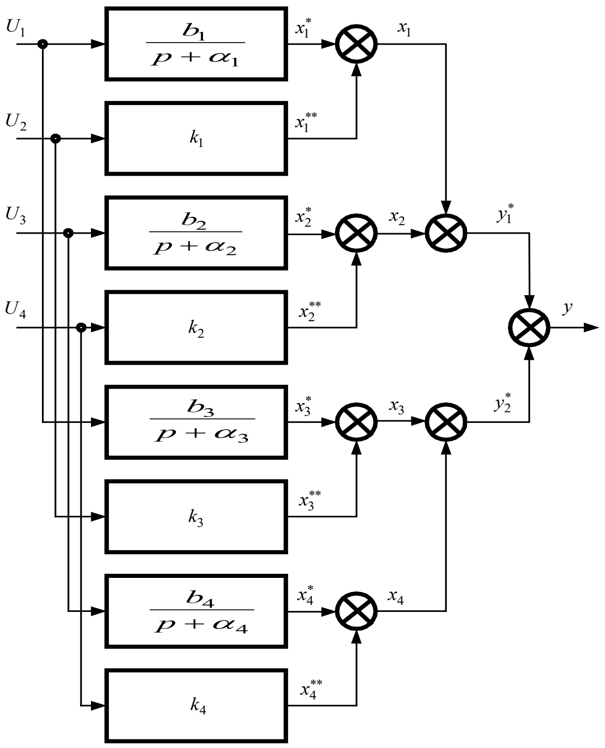

Fig. 1. Complex technical and technological architecture of a powerful drum mill in regular mode

As a result of combining the equations (1) and (2), the complete system for displaying a powerful drum mill in state variables with this representation will be presented in the following form

$$\begin{aligned} \dot{z}_1 &= -\alpha_1 z_1 + b_1 U_1, & z_1(0) &= z_{10}; \\ \dot{z}_2 &= -\alpha_2 z_2 + b_2 U_3, & z_2(0) &= z_{20}; \\ \dot{z}_3 &= -\alpha_3 z_3 + b_3 U_1, & z_3(0) &= z_{30}; \\ \dot{z}_4 &= -\alpha_4 z_4 + b_4 U_3, & z_4(0) &= z_{40}; \end{aligned} \qquad (3)$$

Accordingly, the output equations will have the form

$$y_1^* = z_1 + z_2 + k_1 U_2 + k_2 U_4, \ y_2^* = z_3 + z_4 + k_3 U_2 + k_4 U_4,$$

$$y = y_1^* + y_2^* = z_1 + z_2 + z_3 + z_4 + (k_1 + k_3) U_2 + (k_2 + k_4) U_4 \qquad (4)$$

Or in vector-matrix form

$$\frac{d}{dt}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} -\alpha_1 & 0 & 0 & 0 \\ 0 & -\alpha_2 & 0 & 0 \\ 0 & 0 & -\alpha_3 & 0 \\ 0 & 0 & 0 & -\alpha_4 \end{bmatrix} \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + \begin{bmatrix} b_1 & 0 & 0 & 0 \\ 0 & 0 & b_2 & 0 \\ b_3 & 0 & 0 & 0 \\ 0 & 0 & b_4 & 0 \end{bmatrix} \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix},$$

$$y = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + \begin{bmatrix} 0 & k_1 + k_3 & 0 & k_2 + k_4 \end{bmatrix} \times \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix}.$$

Transients in the mathematical model of the system for evaluating and controlling a powerful drum mill as an intelligent agent will be absent at the following values of controls

$$U_1 = U_{10}; \quad U_2 = U_{20}; \quad U_3 = U_{30}; \quad U_4 = U_{40},$$

where U_{10}, U_{20}, U_{30}, U_{40} – are constant values, and respectively

$$z_{10} = \frac{b_1 U_{10}}{\alpha_1}; \quad z_{20} = \frac{b_2 U_{30}}{\alpha_2}; \quad z_{30} = \frac{b_3 U_{10}}{\alpha_3}; \quad z_{40} = \frac{b_4 U_{30}}{\alpha_4}.$$

Because it is required to stabilize the values of controls $y_1^* = c_1$, $y_2^* = c_2$ and $y = c$, where c, c_1 i c_2 – are taken as constant values, then the initial control levels can be found from the relations

$$c_1 = z_{10} + z_{20} + k_1 U_{20} + k_2 U_{40} = \frac{b_1 U_{10}}{\alpha_1} + \frac{b_2 U_{30}}{\alpha_2} + k_1 U_{20} + k_2 U_{40},$$

$$c_2 = z_{30} + z_{40} + k_3 U_{20} + k_4 U_{40} = \frac{b_3 U_{10}}{\alpha_3} + \frac{b_4 U_{30}}{\alpha_4} + k_3 U_{20} + k_4 U_{40}, \qquad (5)$$

$$c_2 = \frac{b_1 U_{10}}{\alpha_1} + \frac{b_2 U_{30}}{\alpha_2} + \frac{b_3 U_{10}}{\alpha_3} + \frac{b_4 U_{30}}{\alpha_4} + (k_1 + k_3) U_{20} + (k_2 + k_4) U_{40}.$$

When changing control actions by the amount of magnification, the mathematical model of the system of equations (3) and (4) can be written as

$$\begin{cases} \dot{z}_1 = -\alpha_1 z_1 + b_1 (U_{10} + \Delta U_1) \\ \dot{z}_{10} = -\alpha_1 z_{10} + b_1 U_{10} \end{cases}, \qquad z_1(0) = z_{10},$$

$$z_{10}(0) = \frac{b_1 U_{10}}{\alpha_1};$$

$$\begin{cases} \dot{z}_2 = -\alpha_2 z_2 + b_2 (U_{30} + \Delta U_3) \\ \dot{z}_{20} = -\alpha_2 z_{20} + b_2 U_{30} \end{cases}, \qquad z_2(0) = z_{20}$$

$$z_{20}(0) = \frac{b_2 U_{30}}{\alpha_2}$$

$$\begin{cases} \dot{z}_3 = -\alpha_3 z_3 + b_3 (U_{10} + \Delta U_1) \\ \dot{z}_{30} = -\alpha_3 z_{30} + b_3 U_{10} \end{cases}, \qquad z_3(0) = z_{30},$$

$$z_{30}(0) = \frac{b_3 U_{10}}{\alpha_3}$$

$$\begin{cases} \dot{z}_4 = -\alpha_4 z_4 + b_4 (U_{30} + \Delta U_3) \\ \dot{z}_{40} = -\alpha_4 z_{40} + b_4 U_{30} \end{cases}, \qquad z_4(0) = z_{40},$$

$$z_{40}(0) = \frac{b_4 U_{30}}{\alpha_4}$$

$$\begin{cases} y_1 = z_1 + z_2 + k_1 (U_{20} + \Delta U_2) + k_2 (U_{40} + \Delta U_4) \\ y_{10} = z_{10} + z_{20} + k_1 U_{20} + k_2 U_{40} \end{cases}$$

$$\begin{cases} y_2 = z_3 + z_4 + k_3 (U_{20} + \Delta U_2) + k_4 (U_{40} + \Delta U_4) \\ y_{20} = z_{30} + z_{40} + k_3 U_{20} + k_4 U_{40} \end{cases} \qquad (6)$$

$$\begin{cases} y = z_1 + z_2 + z_3 + z_4 + (k_1 + k_3)(U_{20} + \Delta U_2) + (k_2 + k_4)(U_{40} + \Delta U_4) \\ y_0 = z_{10} + z_{20} + z_{30} + z_{40} + (k_1 + k_3) U_{20} + (k_2 + k_4) U_{40} \end{cases}$$

When subtracting from the upper equations of the lower equations of the systems (6), you can get the corresponding expressions

$$\dot{\varepsilon}_1 = -\alpha_1\varepsilon_1 + b_1\Delta U_1\,, \qquad {}_1(0) = {}_{10} - \frac{b_1U_{10}}{}\,;$$

$$\dot{\varepsilon}_2 = -\alpha_2\varepsilon_2 + b_2\Delta U_3\,, \qquad \varepsilon_2(0) = z_{20} - \frac{b_2U_{30}}{\alpha_2}\,;$$

$$\dot{\varepsilon}_3 = -\alpha_3\varepsilon_3 + b_3\Delta U_1\,, \qquad \varepsilon_3(0) = z_{30} - \frac{b_3U_{10}}{\alpha_3}\,; \qquad (7)$$

$$\dot{\varepsilon}_4 = -\alpha_4\varepsilon_4 + b_4\Delta U_3\,, \qquad \varepsilon_4(0) = z_{10} - \frac{b_4U_{30}}{\alpha_4}\,;$$

$$y_1 = \varepsilon_1 + \varepsilon_2 + k_1\Delta U_2 + k_2\Delta U_4\,,$$

$$y_2 = \varepsilon_3 + \varepsilon_4 + k_3\Delta U_2 + k_4\Delta U_4\,,$$

$$y = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + (k_1 + k_3)\Delta U_2 + (k_2 + k_4)\Delta U_4\,.$$

де $\varepsilon_i = z_i + z_{i0}\,, \quad (i = \overline{1,4})$.

To determine the unknown coefficients of the system (7), it is possible to conduct a comparative analysis of it with other normal systems of equations in state variables [2, 3, 5, 6, 8]. Then the systems in the state variables in general can be represented as follows:

– model of electromechanical system of powerful drum mill in vector-matrix form

$$\dot{x} = Ax + BU\,,$$
$$y = Cx + DU\,, \qquad x(0) = x_0\,; \qquad (8)$$

– adopted technical and technological model of a powerful drum mill in vector-matrix form

$$\varphi = M\varphi + NU\,,$$

$$y = S\varphi + RU\,, \qquad \varphi(0) = \overline{x}_0\,. \qquad (9)$$

Then using the Laplace transform we get for the system (8)

$$(pE - A)x(p) = BU(p) + x_0$$

$$x(p) = (pE - A)^{-1}BU(p) + (pE - A)^{-1}x \qquad (10)$$

$$Y(p) = Cx(p) + DU(p) =$$

$$= \left[C(pE - A)^{-1}B + D\right]U(p) + C(pE - A)^{-1}x_0\,.$$

And accordingly for the system (9)

$$(pE - M)\varphi(p) = NU(p) + \overline{x}_0$$

$$\varphi(p) = (pE - M)^{-1}NU(p) + (pE - M)^{-1}\overline{x}_0 \qquad (11)$$

$$Y(p) = S\varphi(p) + RU(p) =$$

$$= \left[S(pE - M)^{-1}N + R\right]U(p) + S(pE - M)^{-1}\overline{x}_0\,.$$

Based on the supposed identity of the systems considered in comparison, it can be assumed that

$$C(pE - A)^{-1}B + D = S(pE - M)^{-1}N + R \qquad (12)$$

$$C(pE - A)^{-1}x_0 = S(pE - M)^{-1}\overline{x}_0\,.$$

And then respectively

$$\begin{aligned}
&(k_{11} + k_{31} + k_{23} + k_{43})p^3 + \\
&[(k_{11} + k_{31} + k_{23})\alpha_{11} + k_{31}\alpha_{21} - k_{23}\alpha_{31} - \\
&-k_{11}\alpha_{41} - k_{31} - k_{23} - k_{43}]p^2 + \\
&+[(-k_{31} - k_{23})\alpha_{11} + (k_{23} + k_{11})\alpha_{21} + \\
&+(k_{31} + k_{23})\alpha_{31} + (k_{23} - k_{11})\alpha_{41} + k_{31} + k_{43}]p + \\
&+k_{31}\alpha_{11} + k_{23}\alpha_{21} + k_{11}\alpha_{31} + \left(k_{11} + k_{31} + k_{23}\right)\alpha_{41} - \\
&-k_{43} + k_{01} + k_{03} + k_{04} = \left(b_1 + b_2 + b_3 + b_4\right)p^3 + \\
&+[-\alpha_1\left(b_2 + b_3 + b_4\right) - \alpha_2\left(b_1 + b_3 + b_4\right) - \\
&-\alpha_3\left(b_1 + b_2 + b_4\right) + \alpha_4\left(b_1 + b_2 + b_3\right)]p^2 + \\
&+[\alpha_1\alpha_2\left(b_3 + b_4\right) + \alpha_1\alpha_3\left(b_3 + b_4\right) + \\
&+\alpha_1\alpha_4\left(b_2 + b_3\right) + \alpha_2\alpha_3\left(b_1 + b_4\right) + \\
&+\alpha_2\alpha_4\left(b_1 + b_3\right) + \alpha_3\alpha_4\left(b_1 + b_2\right)]p - \\
&-b_1\alpha_1\alpha_3\alpha_4 - b_3\alpha_1\alpha_2\alpha_3 - b_2\alpha_1\alpha_3\alpha_4 - b_4\alpha_1\alpha_2\alpha_3. \qquad (13)
\end{aligned}$$

By equating the coefficients at the same degrees of the complex variable, we obtain a system of nonlinear algebraic equations, the solution of which in this case the consideration leads to the following values of unknown coefficients

$$\alpha_1 = 0.7720389\cdot 10^{29} \quad b_1 = -6.286364\cdot 10^{-10}\,,$$

$$k_1' = 3.066031\cdot 10^{-11}$$

$$\alpha_2 = 0.741194\cdot 10^{11}\,,\ b_2 = 0.923272\cdot 10^{44}\,,$$

$$k_2' = 1.0203\cdot 10^{6}$$

$$\alpha_3 = 0.119998\cdot 10^{65}\,, \quad b_3 = 1.726575\cdot 10^{39}\,,$$

$$k_3' = 1.034001\cdot 10^{-11}$$

$$\alpha_4 = 0.0\,, \quad b_{13} = 0.207001\cdot 10^{75}\,,$$

$$k_4' = 0.2114031\cdot 10^{6}\,.$$

Checking at the obtained values of the condition of recoverability through the standard matrix of recoverability.

$$Q = \begin{bmatrix} C \\ CA \\ CA^2 \\ CA^3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -\alpha_1 & -\alpha_2 & -\alpha_3 & -\alpha_4 \\ -\alpha_1^2 & -\alpha_2^2 & -\alpha_3^2 & -\alpha_4^2 \\ -\alpha_1^3 & -\alpha_2^3 & -\alpha_3^3 & -\alpha_4^3 \end{bmatrix} =$$

$$= \begin{bmatrix} 1 & 1 & 1 & 1 \\ -0.77204\cdot 10^{29} & -0.7412\cdot 10^{11} & -0.11999\cdot 10^{65} & 0 \\ -0.596046\cdot 10^{58} & -0.549377\cdot 10^{22} & -0.0143976\cdot 10^{130} & 0 \\ -0.460171\cdot 10^{87} & -0.407199\cdot 10^{33} & -0.001627\cdot 10^{195} & 0 \end{bmatrix}$$

The matrix is not singular due to the fact that $\det Q = -0.7629752\cdot 10^{261} \neq 0$ and $rangQ = 4 = n.$ Therefore, in this case the object is renewable.

To ensure maximum accuracy of management and minimization of energy costs, management in the analytical design of the evaluation and management system uses the functionality of the form

$$I=\int_0^{\infty}\Big[q_1(y_1-y_{10})^2+q_2(y_2-y_{20})^2+q_3(U_1-U_{10})^2+$$
$$+q_4(U_2-U_{20})^2+q_5(U_3-U_{30})^2+q_6(U_4-U_{40})^2\Big]dt. \quad (14)$$

If the numerical values of controls and controlled variables are brought to standard unified signals, it is permissible to equate them

$$q_1=q_2=q_3=q_4=q_5=q_6=1.$$

Taking into account (7), the functional (14) will receive the following expression

$$I=\int_0^{\infty}\Big[\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2+\varepsilon_4^2+2(\varepsilon_1\varepsilon_2+\varepsilon_3\varepsilon_4)+$$
$$+\Delta U_1^2+2\Delta U_2(\varepsilon_1k_1+\varepsilon_2k_1+\varepsilon_3k_3+\varepsilon_4k_3)+$$
$$+\Delta U_2^2\left(k_1^2+k_3+1\right)+\Delta U_3^2+$$
$$+2\Delta U_4(\varepsilon_1k_2+\varepsilon_2k_2+\varepsilon_3k_4+\varepsilon_4k_4)+$$
$$+\Delta U_4^2\left(k_2^2+k_4+1\right)+$$
$$+2\Delta U_2\Delta U_4(k_1k_2+k_3k_4)\Big]dt \quad (15)$$

Drawing up the functional equation of R. Bellman

$$\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2+\varepsilon_4^2+2(\varepsilon_1\varepsilon_2+\varepsilon_3\varepsilon_4)+\Delta U_1^2+$$
$$+2\Delta U_2(\varepsilon_1k_1+\varepsilon_2k_1+\varepsilon_3k_3+\varepsilon_4k_3)+$$
$$+\Delta U_2^2\left(k_1^2+k_3+1\right)+\Delta U_3^2+$$
$$+2\Delta U_4(\varepsilon_1k_2+\varepsilon_2k_2+\varepsilon_3k_4+\varepsilon_4k_4)+$$
$$+\Delta U_4^2\left(k_2^2+k_4+1\right)+2\Delta U_2\Delta U_4(k_1k_2+k_3k_4)+$$
$$+(-\alpha_1\varepsilon_1+b_1\Delta U_1)\frac{dS}{d\varepsilon_1}+(-\alpha_2\varepsilon_2+b_2\Delta U_3)\frac{dS}{d\varepsilon_2}+$$
$$+(-\alpha_3\varepsilon_3+b_3\Delta U_1)\frac{dS}{d\varepsilon_3}+(-\alpha_4\varepsilon_4+b_4\Delta U_3)\frac{dS}{d\varepsilon_4}=0$$

$$2\Delta U_1+b_1\frac{dS}{d\varepsilon_1}+b_3\frac{dS}{d\varepsilon_3}=0 \quad (16)$$

$$k_1(\varepsilon_1+\varepsilon_2)+k_3(\varepsilon_3+\varepsilon_4)+\Delta U_2\left(k_1^2+k_3+1\right)+$$
$$+\Delta U_4(k_1k_2+k_3k_4)=0$$

$$2\Delta U_3+b_2\frac{dS}{d\varepsilon_2}+b_4\frac{dS}{d\varepsilon_4}=0$$

$$k_2(\varepsilon_1+\varepsilon_2)+k_4(\varepsilon_3+\varepsilon_4)+$$
$$+\Delta U_4\left(k_2^2+k_4+1\right)+\Delta U_2(k_1k_2+k_3k_4)=0$$

Denote accordingly

$\alpha=(k_1k_2+k_3k_4)$, $\beta=\left(k_1^2+k_3+1\right)$, $\sigma=\left(k_2^2+k_4+1\right)$.

From the second, third, fourth and fifth equations of the system (16) it turns out

$$\Delta U_1=-\frac{1}{2}\left(b_1\frac{dS}{d\varepsilon_1}+b_3\frac{dS}{d\varepsilon_3}\right)$$

$$\Delta U_2=\frac{\left[-k_1(\varepsilon_1+\varepsilon_2)-k_3(\varepsilon_3+\varepsilon_4)\right]\left(\alpha^2-\beta^2\right)}{\beta\left(\alpha^2-\beta^2\right)}-$$
$$-\frac{\alpha\left[(\varepsilon_1+\varepsilon_2)(\beta k_2-\alpha k_1)+(\varepsilon_3+\varepsilon_4)(\beta k_4-\alpha k_3)\right]}{\beta\left(\alpha^2-\beta^2\right)}$$

$$\Delta U_3=-\frac{1}{2}\left(b_2\frac{dS}{d\varepsilon_2}+b_4\frac{dS}{d\varepsilon_4}\right) \quad (17)$$

$$\Delta U_4=\frac{(\varepsilon_1+\varepsilon_2)(\beta k_2-\alpha k_1)+(\varepsilon_3+\varepsilon_4)(\beta k_4-\alpha k_3)}{\alpha^2-\beta^2}$$

Accordingly, from the first equation of the system (16) after substituting the expression (17) into it, it turns out

$$\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2+\varepsilon_4^2+2(\varepsilon_1\varepsilon_2+\varepsilon_3\varepsilon_4)+$$
$$+\frac{1}{4}\left(b_1\frac{dS}{d\varepsilon_1}+b_3\frac{dS}{d\varepsilon_3}\right)^2+$$
$$+2(\varepsilon_1k_1+\varepsilon_2k_1+\varepsilon_3k_3+\varepsilon_4k_3)G+$$
$$+\frac{1}{4}\left(b_2\frac{dS}{d\varepsilon_2}+b_4\frac{dS}{d\varepsilon_4}\right)^2+\beta G^2+$$
$$+2(\varepsilon_1k_2+\varepsilon_2k_2+\varepsilon_3k_4+\varepsilon_4k_4)K+$$
$$+\sigma K^2+2\alpha GK-\alpha_1\varepsilon_1\frac{dS}{d\varepsilon_1}-$$
$$-\frac{b_1}{2}\left(b_1\frac{dS}{d\varepsilon_1}+b_3\frac{dS}{d\varepsilon_3}\right)\frac{dS}{d\varepsilon_1}-\alpha_2\varepsilon_2\frac{dS}{d\varepsilon_2}-$$
$$-\frac{b_2}{2}\left(b_2\frac{dS}{d\varepsilon_2}+b_4\frac{dS}{d\varepsilon_4}\right)\frac{dS}{d\varepsilon_2}-\alpha_3\varepsilon_3\frac{dS}{d\varepsilon_3}-$$
$$-\frac{b_3}{2}\left(b_1\frac{dS}{d\varepsilon_1}+b_3\frac{dS}{d\varepsilon_3}\right)\frac{dS}{d\varepsilon_3}-\alpha_4\varepsilon_4\frac{dS}{d\varepsilon_4}-$$
$$-\frac{b_4}{2}\left(b_2\frac{dS}{d\varepsilon_2}+b_4\frac{dS}{d\varepsilon_4}\right)\frac{dS}{d\varepsilon_4}=0 \quad (18)$$

To find the laws of control (17), it is necessary to find a function S in the form of an expression (19)

$$S=[\alpha_1,\alpha_2,\alpha_3,\alpha_4]\times\begin{bmatrix} A_{11} & \frac{A_{12}}{2} & \frac{A_{13}}{2} & \frac{A_{14}}{2} \\ \frac{A_{12}}{2} & A_{22} & \frac{A_{23}}{2} & \frac{A_{24}}{2} \\ \frac{A_{13}}{2} & \frac{A_{23}}{2} & A_{33} & \frac{A_{34}}{2} \\ \frac{A_{14}}{2} & \frac{A_{24}}{2} & \frac{A_{34}}{2} & A_{44} \end{bmatrix}\times\begin{bmatrix}\alpha_1\\ \alpha_2\\ \alpha_3\\ \alpha_4\end{bmatrix} \quad (19)$$

From the expression (19) it is determined

$$\frac{dS}{d\alpha_1} = 2A_{11}\alpha_1 + A_{12}\alpha_2 + A_{13}\alpha_3 + A_{14}\alpha_4;$$

$$\frac{dS}{d\alpha_2} = A_{12}\alpha_1 + A_{22}\alpha_2 + A_{23}\alpha_3 + A_{24}\alpha_4;$$

$$\frac{dS}{d\alpha_4} = A_{14}\alpha_1 + A_{24}\alpha_2 + A_{34}\alpha_3 + A_{44}\alpha_4;$$

$$\frac{dS}{d\alpha_3} = A_{13}\alpha_1 + A_{23}\alpha_2 + A_{33}\alpha_3 + A_{34}\alpha_4. \quad (20)$$

The last equation substituting in (17) is obtained

$$\Delta U_1 = -\left(A_{11}b_1 + \frac{A_{13}b_3}{2}\right)\varepsilon_1 - \left(\frac{A_{12}b_1}{2} + \frac{A_{23}b_3}{2}\right)\varepsilon_2 - \left(\frac{A_{13}b_1}{2} + A_{33}b_3\right)\varepsilon_3 - \left(\frac{A_{14}b_1}{2} + \frac{A_{34}b_3}{2}\right)\varepsilon_4$$

$$\Delta U_2 = \frac{-\left[k_1\left(1-\gamma^2\right)+\left(\gamma k_2 - k_1\right)\right]\varepsilon_1 - \left[k_1\left(1-\gamma^2\right)+\left(\gamma k_2 - k_1\right)\right]\varepsilon_2 - \left[k_3\left(1-\gamma^2\right)+\left(\gamma k_4 - k_3\right)\right]\varepsilon_3 - \left[k_3\left(1-\gamma^2\right)+\left(\gamma k_4 - k_3\right)\right]\varepsilon_4}{\beta\left(\alpha^2-\beta^2\right)}$$

$$\Delta U_3 = -\left(\frac{A_{12}b_2}{2} + \frac{A_{14}b_4}{2}\right)\varepsilon_1 - \left(A_{22}b_2 + \frac{A_{24}b_4}{2}\right)\varepsilon_2 - \left(\frac{A_{23}b_2}{2} + \frac{A_{34}b_4}{2}\right)\varepsilon_3 - \left(\frac{A_{24}b_2}{2} + A_{44}b_4\right)\varepsilon_4$$

$$\Delta U_4 = \frac{\left(\gamma k_2 - k_1\right)\varepsilon_1 + \left(\gamma k_2 - k_1\right)\varepsilon_2 + \left(\gamma k_4 - k_3\right)\varepsilon_3 + \left(\gamma k_4 - k_3\right)\varepsilon_4}{\alpha\left(1-\gamma^2\right)}. \quad (21)$$

Substituting (20) in (18) and grouping the members with $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_1\varepsilon_2, \varepsilon_1\varepsilon_3, \varepsilon_1\varepsilon_4, \varepsilon_2\varepsilon_3, \varepsilon_2\varepsilon_4\varepsilon_3\varepsilon_4$ and equating the coefficients with zero for them, we get a system of nonlinear equations of the form

$$V_i\left(A_{11}, A_{12}, A_{13}, A_{14}, A_{22}, A_{23}, A_{24}, A_{33}, A_{34}, A_{44},\right) = 0,$$
$$i = 1,2,3,...10. \quad (22)$$

Solving a system of equations (22), we find the desired coefficients A_{ij}, which in this case are equal accordingly

$$A_{11} = 0.1533 \cdot 10^{-79} \qquad A_{14} = 0.1508 \cdot 10^{-79}$$
$$A_{24} = 0.2510 \qquad A_{44} = 0.2511$$
$$A_{12} = 0.1533 \cdot 10^{-79} \qquad A_{22} = 0.1510 \cdot 10^{-79}$$
$$A_{33} = 0.6091 \cdot 10^{11} \quad (23)$$
$$A_{13} = 0.1533 \cdot 10^{-79} \qquad A_{23} = 0.1496 \cdot 10^{-79}$$
$$A_{34} = 0.2510$$

Substituting their values into expressions (18) it can be obtained

$$\Delta U_1 = -0.1323491 \cdot 10^{-40}\varepsilon_1 - 0.1291547 \cdot 10^{-40}\varepsilon_2 + +0.105171 \cdot 10^{51}\varepsilon_3 - 0.2166968 \cdot 10^{39}\varepsilon_4$$
$$\Delta U_2 = -0.5082528 \cdot 10^{-41}\varepsilon_1 - 0.5182528 \cdot 10^{-41}\varepsilon_2 + +0.2499975 \cdot 10^{-25}\varepsilon_3 - 0.2499975 \cdot 10^{-25}\varepsilon_4$$
$$\Delta U_3 = -0.1560788 \cdot 10^{-5}\varepsilon_1 - 0.2597863 \cdot 10^{74}\varepsilon_2 + +0.2597863 \cdot 10^{74}\varepsilon_3 - 0.5195725 \cdot 10^{74}\varepsilon_4$$
$$\Delta U_4 = -0.4998983 \cdot 10^{-22}\varepsilon_1 - 0.4998983 \cdot 10^{-22}\varepsilon_2 + +0.4999995 \cdot 10^{-5}\varepsilon_3 - 0.4999995 \cdot 10^{-5}\varepsilon_4 \quad (24)$$

Replacing variables $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ with their values from (7) ΔU_i to $U_i - U_{i0}$ expressions of control actions have the form

$$U_1 = -0.1323491 \cdot 10^{-40}z_1 - 0.1291547 \cdot 10^{-40}z_2 + +0.105171 \cdot 10^{51}z_3 - 0.2166968 \cdot 10^{39}z_4 + + 0.1513307 \cdot 10^{24}U_{10} - 0.160182 \cdot 10^{-7}U_{30}$$

$$U_2 = -0.5082528 \cdot 10^{-41}z_1 - 0.5182528 \cdot 10^{-41}z_2 - -0.2499975 \cdot 10^{-25}z_3 - 0.2499975 \cdot 10^{-25}z_4 + +0.3597226 \cdot 10^{-52}U_{10} - 0.6331076 \cdot 10^{-8}U_{30} \quad (25)$$

$$U_3 = -0.1560788 \cdot 10^{-5}z_1 - 0.2597863 \cdot 10^{74}z_2 - - 0.2597863 \cdot 10^{74}z_3 - 0.5195725 \cdot 10^{74}z_4 + + 0.37380701 \cdot 10^{49}U_{10} - 0.323604 \cdot 10^{107}U_{30}$$

$$U_4 = 0.4998983 \cdot 10^{-22}z_1 + 0.4998983 \cdot 10^{-22}z_2 + +0.4999995 \cdot 10^{-5}z_3 + 0.4999995 \cdot 10^{-5}z_4 + +0.7194502 \cdot 10^{-30}U_{10} + 0.6227008 \cdot 10^{11}U_{30}$$

When using in the control circuit of the calculator and the expression of the law of control of the complex system in the state variables (25), it is advisable to restore the state vector of the drum mill with the help of a discrete observer. In this case, the structure of the control system will look like the one presented in Fig. 2, and the discrete description in the difference equations of state will get the following expression

$$z^+(i+1) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & n_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} z^+(i) + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ m_3 & 0 & 0 & 0 \\ 0 & 0 & m_4 & 0 \end{bmatrix} U^+(i). \quad (26)$$

With the corresponding replacement of $z(t)$ by $z(i)$, and accordingly $U(t)$ by $U(i)$ it turns out that the output variable $y(t)$, which is canted at

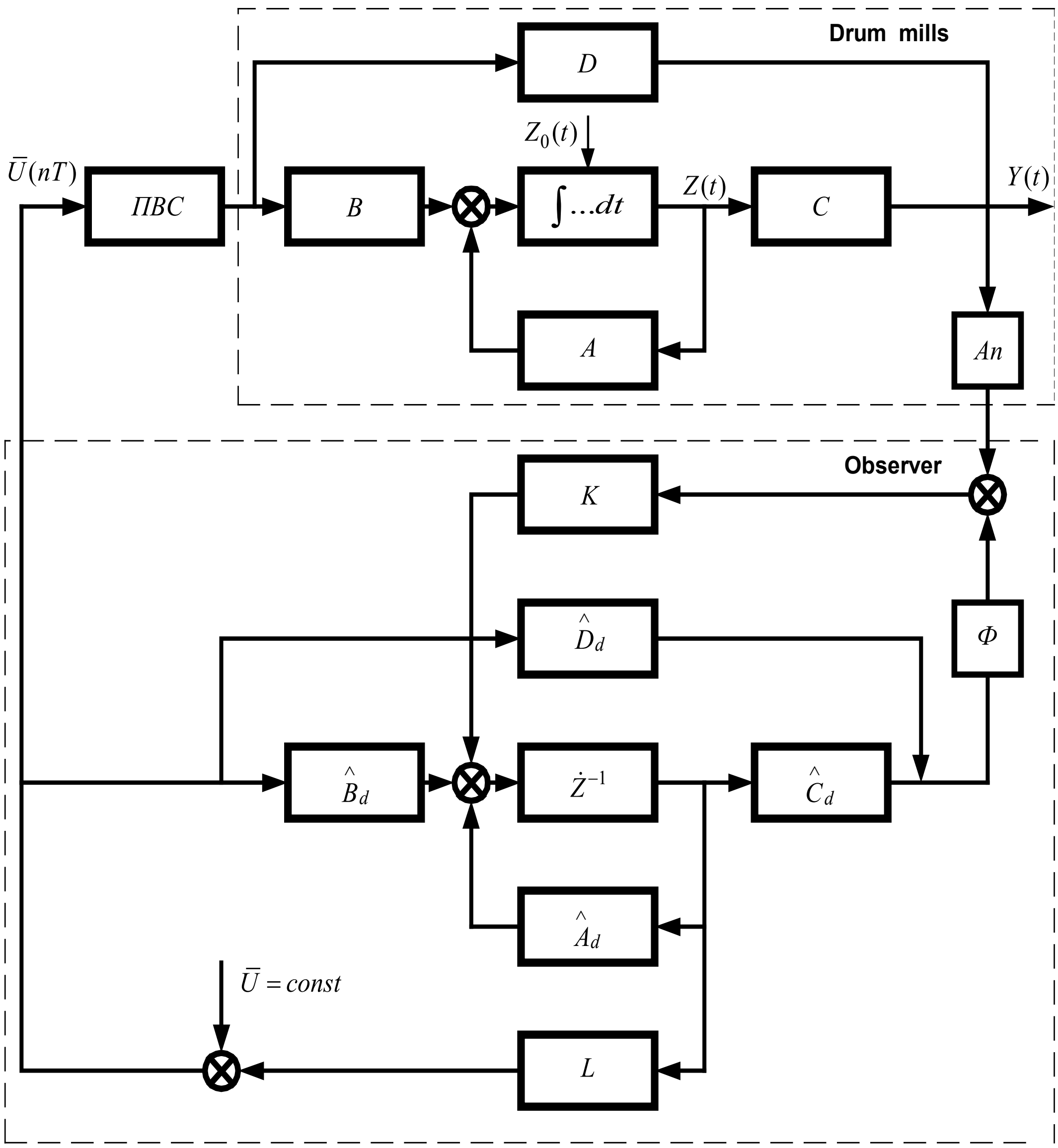

Fig. 2. Block diagram of a multidimensional optimal evaluation and control system with a discrete observer when operating a drum mill

moments of time t_i, where $i = 0.001, 0.002, 0.003, ...$ will be determined as

$$y^+(i) = [1 \quad 1 \quad n_3 \quad 1] z^+(i) + \\ + [m_3 \quad l_1 + l_3 \quad m_2 + m_3 \quad l_2 + l_4] U^+(i) \tag{27}$$

where $z^*(i+1)$ is replaced by $y^*(i)$ for numerical values

$n_3 = 0.4314 \cdot 10^{70}$, $m_3 = 0.1490 \cdot 10^{59}$,

$l_1 = k_1'$, $l_3 = k_3'$,

$m_2 = -0.9233 \cdot 10^{-6}$, $m_4 = 0.207 \cdot 10^{25}$,

$l_2 = k_2'$, $l_4 = k_4'$.

The given above proves that the formed evaluation and management system is fully renewable and we can find

$$A_\alpha - KC_\alpha = \begin{bmatrix} 1-k_1 & -k_1 & -k_1 & -k_1 \\ -k_2 & 1-k_2 & -k_2 & -k_2 \\ -k_3 & -k_3 & n_3(1-k_3) & -k_3 \\ -k_4 & -k_4 & -k_4 & 1-k_4 \end{bmatrix} \tag{28}$$

This matrix has the following characteristic polynomial

$$-3n_3k_2k_3k_4]p - n_3k_3^2 + 2n_3k_1k_3^2 + \\ + n_3k_1k_2k_3^2 - n_3k_1k_4k_3^2 + n_3k_4k_3^2 - n_3k_1 - \\ - n_3k_2 - n_3k_3 - n_3k_4 + n_3k_1k_3 + 2n_3k_1k_4 \\ + n_3k_2k_3 - n_3k_2k_4 + n_3k_1k_2k_3 - n_3k_1k_3k_4$$

$$-3n_3k_2k_3k_4\,\big]\,p - n_3k_3^2 + 2n_3k_1k_3^2 +$$
$$+n_3k_1k_2k_3^2 - n_3k_1k_4k_3^2 + n_3k_4k_3^2 - n_3k_1 -$$
$$-n_3k_2 - n_3k_3 - n_3k_4 + n_3k_1k_3 + 2n_3k_1k_4 +$$
$$+n_3k_2k_3 - n_3k_2k_4 + n_3k_1k_2k_3 - n_3k_1k_3k_4 +$$
$$+3n_3k_2k_3k_4 - 2n_3k_1k_2k_3k_4 + n_3 = 0 \qquad (29)$$

The corresponding discrete observer is found from a system of equations

$$k_1 + k_2 + n_3k_3 + k_4 - (n_3 + 3) = 0$$

$$n_3k_3^2 - (n_3+2)k_1 - 2k_2 - 4n_3k_3 - (n_3+2)k_4 +$$
$$+2k_1k_2 + (2n_3 - 1)k_1k_3 + 2k_1k_4 +$$
$$+n_3k_2k_3 + 3(n_3+1) = 0$$

$$n_3(2k_1 - k_4)k_3^2 + (2n_3+1)k_1 +$$
$$+(2n_3+1)k_2 + 3n_3k_3 + (2n_3+1)k_4 -$$
$$-(5n_3+1)k_1k_3 - 2n_3k_2k_3 + n_3k_2k_4 -$$
$$-(n_3-1)k_1k_2k_3 - k_1k_2k_4 -$$
$$-n_3k_1k_3k_4 - 3n_3k_2k_3k_4 = 0 \qquad (30)$$

$$-n_3k_3^2 - 2n_3k_1k_3^2 + n_3k_1k_2k_3^2 +$$
$$+n_3k_1k_4k_3^2 + n_3k_4k_3^2 - n_3k_1 -$$
$$-n_3k_2 - n_3k_3 - n_3k_4 + n_3k_1k_3 +$$
$$+2n_3k_1k_4 + n_3k_2k_3 - n_3k_2k_4 +$$
$$+n_3k_1k_2k_3 - n_3k_1k_3k_4 + 3n_3k_2k_3k_4 -$$
$$-2n_3k_1k_2k_3k_4 + n_3 = 0$$

where $n_3 = 0.4314$

The solution of the system (27) determines the matrix of observer coefficients

$$K = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{bmatrix} = \begin{bmatrix} -3.4314 \\ 12.6373 \\ 141.29 \\ -0.443307 \cdot 10^6 \end{bmatrix} \qquad (31)$$

The resulting discrete observer reduces any initial recovery error to zero value in a maximum of four steps.

Conclusions. The presentation of technological units, namely powerful drum mills, in conjunction with optimal control systems as individual intelligent agents can be analytically justified in structure. Accordingly, modeling through the variables of the state of the complex internal operational state of the mill as an agent of a multi-agent system presents an opportunity to more effectively work out the formation of optimal decisions according to a given criterion for accuracy and energy consumption of the law of decisions made. The use of a discrete observer in this structure increases positive outcomes of evaluation and management.

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