Kupin, A., Ruban, S., & Kurganov, I. (2023). Optimal control of the drive drum of a belt conveyor with thermographic classification of operating modes using artificial neural networks. *Actual Issues of Modern Science. European Scientific e-Journal, 26*, 26-35. Ostrava: Tuculart Edition, European Institute for Innovation Development.

DOI: 10.47451/inn2023-12-01

The paper is published in Crossref, ICI Copernicus, BASE, Zenodo, OpenAIRE, LORY, Academic Resource Index ResearchBib, J-Gate, ISI International Scientific Indexing, ADL, JournalsPedia, Scilit, EBSCO, Mendeley, and WebArchive databases.

Andrii Kupin, Doctor of Technical Sciences, Department Professor, Department of Computer Systems and Networks, Kryvyi Rih National University. Kryvyi Rih, Ukraine.
Scopus 24722874000. ORCID 0000-0001-7569-1721

Serhii Ruban, Candidate of Technical Sciences (Ph.D.), Associate Professor, Department Head, Department of Automation, Computer Sciences and Technology, Kryvyi Rih National University. Kryvyi Rih, Ukraine. Scopus 56830582800. ORCID 0000-0002-4495-6667

Igor Kurganov, Candidate of Technical Sciences (Ph.D.), Senior Lecturer, Department of Automation, Computer Sciences and Technology, Kryvyi Rih National University. Kryvyi Rih, Ukraine.

Optimal control of the drive drum of a belt conveyor with thermographic classification of operating modes using artificial neural networks

Abstract: Optimum control of the drive drum of the belt conveyor in the transport flow by changing the belt tension is proposed in order to reduce the cost of transporting goods, increase the life of the belt, and reduce energy consumption due to the control of temperature and its distribution in the zone of frictional interaction between the belt and the drum. It is suggested to use belt tension control to eliminate the accidental slipping of the belt on the drum and its excessive abrasion during the transportation of the ore mass. To implement the control method being developed, it is necessary to use a mathematical model with distributed parameters, on the basis of which the optimal control system will be formed. Control of this kind of objects is determined by the technological need to compensate for the slippage of the belt on the drive drum of the conveyor, which is based on the process of transmission of motion using friction, and is implemented by changing the thermal field on the arc of the girth by changing the tension of the conveyor belt or the speed of rotation of the drum. Thus, from the point of view of the theory of control of systems with distributed parameters in the process of controlling the thermal field of the drive drum and the conveyor belt, the controlled coordinate is the temperature and its distribution on the girth arc. As a result of physical processes, both the size of the source of the heat flux and the size of the surface of its radiation change during the control of the tape tension. Thus, the problem of optimal control acquires a new character and turns into a problem of moving optimal control, where the source of the heat flow, just like its distribution, is considered as a moving element that changes its position during the control process. The use of an artificial neural network allows you to determine the modes of operation of the friction pair by analyzing thermograms from the obtained calculation models and obtained by thermal imaging control, to combine problems with distributed parameters, which are partial solutions to the problem of moving optimal control, where the source of heat flow and its distribution is considered as a moving element, which changes its position during the control.

Keywords: belt conveyor, friction pair, working slip angle, thermal field, thermograms, artificial neural networks, optimal control.

Introduction

One of the most frequent emergency situations that leads to the stoppage of the conveyor line is the skidding of the drive station of one of the belt conveyors of the supply path of the transported ore mass. As a result, the entire conveyor path has to be stopped and the already loaded conveyors have to be restarted, which can lead to slippage of the friction transmission of belt conveyors. In the technological operation of belt conveyors, situations often arise when the tension of the conveyor belt is weakened, which causes an increase in the resistance of the belt movement. As a result, the cost of power consumed by the conveyor drive station increases and the efficiency ratio of the drum-belt friction pair decreases, which increases the abrasion of the working surfaces of the belt and the lining of the drum, and as a result of their friction, heating occurs, which can lead to a fire situation.

The study of this problem was carried out by the authors of works (*Andreev, 1963, p. 5*; *Malyutin & Popov, 1972, p. 115*; *Troshchilo & Piletsky, 1999, p. 200*), who performed simulations of thermal processes in the zone of contact between the belt and the drum and conducted experimental studies that confirm the results of the simulation and the need to apply measures to eliminate the causes.

Thus, in the work performed by V.S. Volotkovsky, the following results were obtained. On belt conveyors with a long length from 467 to 1870 m, the area of the torn lower cover varies from 15 to 25%, which is caused by the occurrence of slippage of the belt and large values of tension in the lower cover of the belt during its interaction with the drive drum.

In the event of slippage, the temperature in the area of the belt and drum coupling rises to 300-350°C during 15 minutes of conveyor operation (*Troshchilo & Piletsky, 1999, p. 200*). In his works, V.G. Piletsky performed a simulation of a friction pair and investigated the thermal regimes of the drive drum when the belt slips on it for different speeds of its movement and the effect of the angle of the drum's grip by the belt on the rate of increase in the heating temperature.

In the work (*Malyutin & Popov, 1972, p. 115*), the authors M.O. Malyutin and L.I. Popov performed a mathematical modeling of the friction pair considering the Fourier heat conduction equation. Experimental studies of the friction temperature in the belt-drum contact were carried out on the conveyors of the "Apatit" plant, using the thermocouple method with recording on an oscilloscope. Here, the results showed that the temperature in the friction contact zone per shift (5 hours of continuous work) increases from 79.5°C to 127°C.

The authors of the paper propose to perform a digital simulation of a friction pair as a model with distributed parameters for its further use as a set of typical models for various operating modes and the formation of a knowledge base for further training of an artificial neural network, which is a component in the development of an optimal automatic control system with thermal imaging control of the friction pair of the conveyor drive drum-belt. Optimal control of the technological process of cargo transportation is based on the thermal imaging control of thermal radiation of the operation of the friction pair of the conveyor, while the artificial neural network, thanks to a set of typical models for various boundary conditions, is determined with the class, that is, the mode of operation of the friction pair of the conveyor, and according to the algorithm, it is performed by controlling the influences to create optimal mode of operation of the friction pair of the conveyor drive drum-belt.

Presentation of the material and results

The solution to the problem of control of the drive drum-belt friction pair is based on the construction of a mathematical model of temperature distribution on the girth arc. This model is considered as an element of the control object, which is represented by a belt conveyor at the lower level of the ASK TP. The need to control such objects is determined by the technological need to compensate for the slippage of the belt on the drive drum of the conveyor. An automatic control system is used to control the conveyor. The control signals are the belt tension and the speed of rotation of the drive drum, and the controlled parameter is the heating temperature of the lining in the coupling zone. It is advisable to use the principles of forming mathematical models with distributed parameters as a basis for defining the control task. The choice of such a class of systems is based on the physics of the friction transmission interaction process. To determine the heating temperature of the lining of the drum, its distribution on the working sliding arc, the solution of the boundary value problem is required, i.e., the solution of the Fourier heat conduction equation under the given initial and final conditions.

The magnitude of the radiated heat source depends on the angle (arc) of the working slip, the value of which changes when the tension of the conveyor belt changes, i.e., the heat source is distributed along the arc and its position and distribution on the arc of engagement of the drum with the conveyor belt depends on the magnitude of the angle of the working slip. From the point of view of the theory of heat conduction tasks, the arc (angle) of working slip is the limiting area of the radiated heat flow.

Thus, a change in the magnitude of the arc (angle) of the working slide changes the specific value of the heat flux emitted as a result of friction, which is an indirect manifestation of the control influence distributed in the space of interaction between the belt and the lining of the drive drum.

Let us consider the main components of the girth angle when using a flexible drum- belt connection. As we know, when the movement is transmitted by friction, the angle on the drive drum will be divided into two components (*Figure 1*). One of them is the working sliding angle $\alpha_{кв}$, where the movement is transmitted to the belt and its value on the drive drum determines the traction capacity of the conveyor. The second component is the angle of relative rest $\alpha_{вп}$, the value of which allows to exclude slippage of the belt on the drive drum of the conveyor.

The physical basis is the process of transmission of motion in the form of friction. The control implements a change in the thermal field on the arc of the girth by changing the tension of the conveyor belt or the speed of rotation of the drum.

Solving this problem allows to fulfill one of the main requirements for the conveyor line – the elimination of emergency slippage of the conveyor belt, which means preventing interruption of the technological process.

The control problem is perceived as an optimal control problem with distributed parameters.

As the mathematical model of the drive drum-belt friction pair, let us consider the thermal field $\tau 1(x, y\, z, t)$, where $(x, y\, z)$ are the Cartesian coordinates of a point on the drive drum or τ_1 (R,φ,z,t), where (R, φ, z) – cylindrical coordinates of the point, t – time.

Preliminarily, we assume that the temperature is evenly distributed across the width of the drum. In this case, the task is considered only in one Cartesian (x, y) or cylindrical (R, φ) spatial plane. The boundary value problem is reduced to a class of two-dimensional heat conduction equations with constant coefficients.

Thermal calculation of the drum-belt friction pair, based on the solution of the heat conduction equation, which describes the heat exchange in the drum lining system – working sliding arc – conveyor belt

$$\frac{d\tau_1}{dt} = \zeta\left(\frac{d^2\tau_1}{dx^2} + \frac{d^2\tau_1}{dy^2} + \frac{d^2\tau_1}{dz^2}\right)$$

$$\frac{d\tau_1}{dt} = \zeta\left(\frac{d^2\tau_1}{dR^2} + \frac{1}{R}\cdot\frac{d\tau_1}{dR} + \frac{1}{R^2}\cdot\frac{d^2\tau_1}{d\phi^2} + \frac{d^2\tau_1}{dz^2}\right),$$

where $\tau 1$ is the overheating temperature (above the ambient air temperature), °C; ζ – thermal conductivity coefficient, m^2/sec.

Let us consider in detail the formation of the boundary value problem, which includes the heat conduction equation, as well as the initial and boundary conditions.

Similar boundary value problems were previously performed by the authors (*Malyutin & Popov, 1972, p. 115*; *Troshchilo & Piletsky, 1999, p. 200*) when modeling the thermal processes of the interaction between the drive drum and the belt.

The equation of thermal conductivity is a parabolic equation characterizing non-stationary processes of temperature distribution:

$$\frac{d\tau_1}{dt} = \zeta\left(\frac{d^2\tau_1}{dR^2} + \frac{1}{R}\cdot\frac{d\tau_1}{dR} + \frac{1}{R^2}\cdot\frac{d^2\tau_1}{d\phi^2} + \frac{d^2\tau_1}{dz^2}\right) + q(t), \quad t > 0;\ R1 \le R \le R2;\ 0 \le \varphi \le 2\pi, \tag{1}$$

$$\frac{d\tau_2}{dt} = \zeta\left(\frac{d^2\tau_2}{dR^2} + \frac{1}{R}\cdot\frac{d\tau_2}{dR} + \frac{1}{R^2}\cdot\frac{d^2\tau_2}{d\phi^2} + \frac{d^2\tau_2}{dz^2}\right) + q(t), \quad t > 0;\ R2 \le R \le R3;\ 0 \le \varphi \le \pi, \tag{2}$$

where $\tau 2$ is the belt temperature, degrees; $R1$, $R2$ – inner and outer radii of the drum, including lining, m; $R3$ – the outer radius of the belt surrounding the drum, m (*Figure 2*); $q(t)$ is the heat flow source, J.

As initial conditions, we set the temperature distribution at the initial moment of time

$$\tau 1(R, \varphi, 0) = \tau 10. \tag{3}$$

Boundary conditions are conditions of the 3rd type, for describing the heat exchange processes of the drum lining and the conveyor belt, as well as the heat exchange of the belt with the environment. At the same time, we do not consider the heat exchange with the environment of the end surfaces of the belt and drum, as well as the inner surface of the drum and the outer surface of the belt. We consider the mentioned bodies to be homogeneous isotropic with constant thermophysical characteristics. We assume that the temperature is distributed uniformly across the width of the drum, in this case the task is considered only in one spatial plane, cylindrical (R, φ).

Boundary conditions are presented in the form:

$$\lambda\cdot\frac{\partial\tau_1}{\partial R}|_{R=R1} = \alpha_2\cdot[\tau_1(R1,\phi,t) - t_0],\ \ 0 \le \varphi \le 2\pi \tag{4}$$

$$\lambda\cdot\frac{\partial\tau_2}{\partial R}|_{R=R2} = \alpha_1\cdot[\tau_1(R2,\phi,t) - t_0],\ \ 0 \le \varphi \le \pi \tag{5}$$

$$\lambda\cdot\frac{\partial\tau_2}{\partial R}|_{R=R3} = \alpha_2\cdot[\tau_2(R3,\phi,t) - t_0],\ \ 0 \le \varphi \le 2\pi \tag{6}$$

$$\lambda\cdot\frac{\partial\tau_1}{\partial R}|_{R=R2} = \alpha_2\cdot[\tau_1(R2,\phi,t) - t_0],\ \ \pi \le \varphi \le 2\pi \tag{7}$$

$$\tau 1(R, \varphi, t) = \tau 1(R, \varphi + 2\pi n, t), \tag{8}$$

$$\frac{\partial\tau_1}{\partial\phi}|_{\phi=\phi'} = \frac{\partial\tau_1}{\partial\phi}|\phi = \phi' + 2\cdot\pi\cdot n, \quad \text{n=0,1,2, …}, \tag{9}$$

$$\frac{\partial\tau_2}{\partial\phi}|_{\phi=0} = \frac{\partial\tau_2}{\partial\phi}|\phi = \pi = 0,$$

where λ – coefficient of thermal conductivity of the material of the drum and belt, W/m·°C; α_1 – coefficient of heat exchange between the surfaces of the drum and the belt, W/m^2·°C; α_2 – coefficient of heat exchange with air of the outer surface of the drum, W/m^2·°C (*Troshchilo & Piletsky, 1999, p. 202*).

The coefficients ζ and λ are related by the ratio $\zeta = \lambda/c \cdot p$, where ρ is the density of the heated body, kg/m^3; c – heat capacity, J/kg·°C.

Thus, the presented mathematical model of the drive drum - belt friction pair is a boundary value problem at the basis of which is the solution of the heat conduction equation of the considered technological system and is a component of the optimal control problem.

The temperature value was obtained at the output of the system in the form of a thermal field, which for emergency operation of the conveyor drive is presented in Appendix (*Figure 3a*). The temperature distribution on the friction pair of the drive drum – belt during steady-state operation of the conveyor is shown in Appendix (*Figure 3b*).

The automatic control system with distributed parameters, which is being developed, is not only reduced to the problem of optimal control, but has a broader consideration. This is due to the fact that as a result of physical processes during control of the belt tension, both the size of the heat flux source (q) and the size of the surface where its radiation occurs ($\alpha_{кв}$) changes.

Thus, the task of optimal control acquires a new character and turns into a task of mobile optimal control, where the source of the heat flow and its distribution are considered as a moving element that changes its position during the control process. Accordingly, we will call the law or algorithm of source motion a mobile control influence or mobile control.

Let us consider the mathematical description of the problem of motion control.

The classical (fixed) control q(x, y, t) is replaced by

$$q[x, y, t, x - \phi(t), y - \phi(t)],$$

where φ(t) is the location of the changing source (φ(t)= v(t), v(t) is the velocity), and appears now as a special case of a more general effect. Here x, y and φ are also vectors (*Butkovsky & Pustylnikov, 1980, p. 35*).

To consider the problem of moving control, it is enough to put it as a fixed one

$$\varphi(t) \;=\; k \; for \; all \; t \in [t0, tn],$$

where k is a fixed value considered on a time interval.

Thus, the boundary value problem (*Troshchilo & Piletsky, 1999, p. 200*) will be presented in the following form:

$$\frac{d\tau_1}{dt} = \zeta\left(\frac{d^2\tau_1}{dR^2} + \frac{1}{R}\cdot\frac{d\tau_1}{dR} + \frac{1}{R^2}\cdot\frac{d^2\tau_1}{d\phi^2} + \frac{d^2\tau_1}{dz^2}\right) + q(R, \phi, z, t)\cdot\delta\big(\phi - \phi(t)\big),$$

$$t > 0;\; R1 \leq R \leq R2;\; 0 \leq \varphi \leq 2\,\pi,$$

$$\frac{d\tau_2}{dt} = \zeta\left(\frac{d^2\tau_2}{dR^2} + \frac{1}{R}\cdot\frac{d\tau_2}{dR} + \frac{1}{R^2}\cdot\frac{d^2\tau_2}{d\phi^2} + \frac{d^2\tau_2}{dz^2}\right) + q(R, \phi, z, t)\cdot\delta\big(\phi - \phi(t)\big),$$

$$t > 0;\; R2 \leq R \leq R3;\; 0 \leq \varphi \leq \pi,$$

and the task of optimal control is formed on the basis of a functional that will allow optimal control of the temperature distribution on the arc of the drive drum girth in the time domain. The value of the temperature distribution is determined for several points of the studied space of the girth arc. The functional is represented by the following expression

$$J = \int_0^T [\tau_1{}^*(x,y,z) - \tau_1(x,y,z,t)]^2 dt \rightarrow \delta.$$

As a result, the motion control problem can be formulated as follows. From all possible control programs q, it is necessary to determine the one in which the functional J satisfied the condition J→δ (where δ is some positive number characterizing the accuracy of the approach to the desired distribution) in the minimum possible time T.

To further investigate the problem of moving optimal control, the authors propose to apply the existing experience of using systems based on neural networks to recognize the thermograms of the controlled object.

The use of an artificial neural network (ANN) in an information and measurement system (IMS) that processes visual and graphic images is promising. It is obvious that the thermogram registered during the control process of any technical object can be interpreted and processed as a raster image (*Nazarenko, 2021, p. 17*). As noted in many studies, convolutional neural networks (ANNs) of various modifications are an effective tool for classifying raster images according to the content of various features in them (*Przystałka et al., 2017, p. 145*).

The intelligent method of increasing classification accuracy is implemented using three main procedures (*Chernyak & Zakharchenko, 2010, p. 228*):

1. Obtaining thermograms, as a result of the solution of thermal conductivity equations, considering the additionally measured parameters of the control object to obtain an exact correspondence to the operating mode of the object, as well as the formation of a database based on them for further classification.
2. The use of a neural network software analyzer in the form of a deep two-branch neural network (DNM) as part of the IMS, consisting of a multilayer convolutional network for processing thermograms and a fully connected neural network for processing additional parameters of the control object (*Nazarenko, 2021, p. 36*).
3. Training of a two-branch neural network on a set of complex thermograms and further performance of the classification of the operating modes of the controlled object in the process of thermal imaging measurement to make decisions about the determination of the operating mode (emergency or working).

It is known that artificial neural networks (ANNs) effectively recognize complex images (*Przystałka et al., 2017, p. 143*). There are a large number of ANN applications where information analysis is performed under conditions of uncertainty. This article proposes an approach based on the application of a special neural network architecture for the inverse problem of thermogram recognition when determining the mode of operation of the drive drum of a belt conveyor. The proposed ANN represents two branches (two neural networks) combined into one complex neural network (*Nazarenko, 2021, p. 43*). As shown in Appendix (*Figure 4*), IIMS TIC is part of the information and control system, which provides analysis and determination of the operating mode of the drive drum and control of the belt conveyor in the technological process of cargo transportation.

The system includes a measurement system that includes channels for measuring thermograms and an additional set of conveyor parameters (drum rotation speed, belt movement speed, conveyor belt tension, etc.); DMS – a decision-making system for determining the mode of operation of the drive drum and the conveyor as a whole based on the results of the functioning of the neural network; Y – control influences based on the results of thermal imaging control of the operating modes of the drive drum; V is the value of the parameters that change during the operation of the drive drum; $\tau(x, y)$ is the established temperature distribution in the zone of frictional interaction of the drum-conveyor belt; P – a set of thermophysical and structural parameters of the device, taken into account when building mathematical models in the form of a heat conduction equation; $\tau n\,(x, y)$ – temperature distribution on the face of the device; $\{\tau kj(x, y)\}$ is the set of thermograms of the kth class in the knowledge base used in the training of ANNs, $j = 1, Jk$; Jk is the volume of the training sample for the kth class of operation modes of the drum friction pair-belt; $Vkj, j = 1, Jk$ – a set of values of additional object parameters for the kth class of the operating mode; $\tau_{ВИМ}(x, y)$ is a measured thermogram of a stable temperature distribution, obtained using a measuring channel that includes a thermal imager; $V_{ВИМ}$ is a vector of actually measured values of additional parameters; d_0, d_1, d_K , ,…, are the outputs of the ANN corresponding to the classes of conveyor operating modes, while d_0 is the operational state according to the main indicators, and the other outputs correspond to the classes of operating modes corresponding to deviations from the norm.

In the process of current control of the frictional interaction between the drive drum and the conveyor belt, the results of the ANN work are recorded in the knowledge base and are further used to correct the parameters of the mathematical models of heat exchange in the object under investigation. This allows to refine (training) model thermograms and increase the reliability of object control parameters by retraining the neural network.

Classes of educational thermograms. The basis of the neural network software analyzer is a two-branch neural network (*Nazarenko, 2021, p. 43*).

Obtaining educational thermograms is the solution of a number of direct thermal conductivity problems of a certain class, which differ in the location of internal heat sources and their power. That allows us to consider the solution of mobile control problems as a set of partial cases under different boundary conditions of the thermal conductivity problem and additional parameters that are an integral part of the object.

As a result, we get a set of educational thermograms for possible modes of operation of the conveyor drum-belt friction pair, which consider changes in boundary conditions (sliding arc, amount of thermal radiation), technological parameters (belt speed, conveyor belt tension).

In the next step, the task of matching each training thermogram to the corresponding mode of operation of the conveyor belt appears.

All thermograms related to the operating mode of the conveyor are combined into one class D_0. Other thermograms, which characterize the emergency operation mode or operation modes with significant deviations, are divided into k classes D_1, D_2, …, D_k, each of which corresponds to one and only one conveyor operation mode.

According to each class, the system has reference values for control influences, the use of which allows to transfer the control object from one mode to another, falling from one class to another, until it reaches the given class D_0.

Conclusions and direction of further research

Thus, the friction pair of the conveyor drive includes a rather complex task of researching physical processes. Solving this problem gives the results of determining the operation modes of the drive drum.

The use of an artificial neural network allows to combine a problem with distributed parameters, which is a partial solution to the problem of moving optimal control, where the source of heat flow and its distribution are considered as a moving element that changes its position during the control process. This allows to bypass the difficulties in modeling, because each operating mode of the friction pair needs to set the boundary conditions that belong only to it. Classification of a set of thermogram models for each mode using a neural network allows the system to determine the current mode and adjust the controlling influences for the transition of the control object to optimal parameters.

References:

Andreev, A. V. (1963). *Transmission by friction*. Moscow: Mashinostroenie. (In Russian)

Błażej, R., Sawicki, M., Konieczna, M., Kozłowski, T., & Kirjanów, A. (2016). Automatic analysis of thermograms as a means for estimating technical of a gear system. *Diagnostyka*, *17*(2), 43-48.

Butkovsky, A. G., & Pustylnikov, L. M. (1980). *The theory of mobile control systems with distributed parameters*. Moscow. (In Russian)

Chernyak, O. I., & Zakharchenko, P. V. (2010). *Intelligent data analysis: Textbook*. Kyiv: Ministry of Education and Science of Ukraine. (In Russian)

Dabek, P., Szrek, J., Zimroz, R., & Wodecki, J. (2022). An automatic procedure for overheated Idler detection in belt conveyors using fusion of infrared and RGB images acquired during UGV robot inspection. *Energies*, *15*.

Malyutin, M. A., & Popov, L. I. (1972). Study of contact temperature in belt conveyor drives. *Mining Journal*, *2*, 115-119. Izvestia Vuzov. (In Russian)

Nazarenko, D. A. (2021). The system of thermal imaging diagnostics using an intelligent information and measurement system. [Bachelor's thesis]. National Aviation University (NAU). Kyiv. https://er.nau.edu.ua/handle/NAU/52204 (In Ukrainian)

Przystałka, P., Kalisch, M., & Timofiejczuk, A. (2017). Genetic optimization of meta-learning schemes for context-based fault detection. *Advances in Technical Diagnostics*. *Proceedings of the 6th International Congress on Technical Diagnostic*, 287-297. 12-16 September 2016. Gliwice, Poland.

Rapoport, E. Ya. (2003). *Structural modelling of objects and control systems with distributed parameters*. Moscow. (In Russian)

Siami, M., Barszcz, T., Wodecki, J., & Zimroz, R. (2022). Automated identification of overheated belt conveyor idlers in thermal images with complex backgrounds using binary classification with CNN. *Sensors*, *22*, 10004. https:// doi.org/10.3390/s222410004

Troshchilo, V. S., & Piletsky, V. G. (1999). Investigation of the heating of the conveyor belt during slipping of the drive drum. *Mining Electromechanics and Automation*, *2*, 200-204. (In Russian)

Appendix

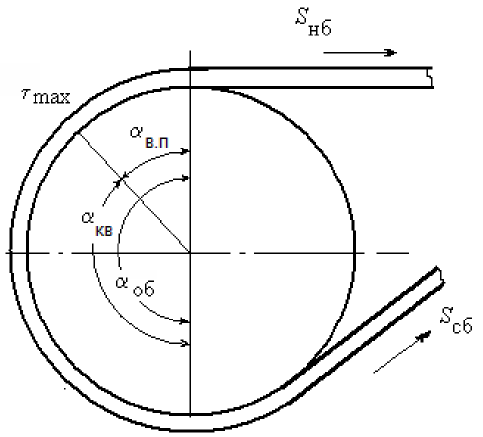

Figure 1. Scheme of determining the traction force transmitted by the drive drum of the belt conveyor

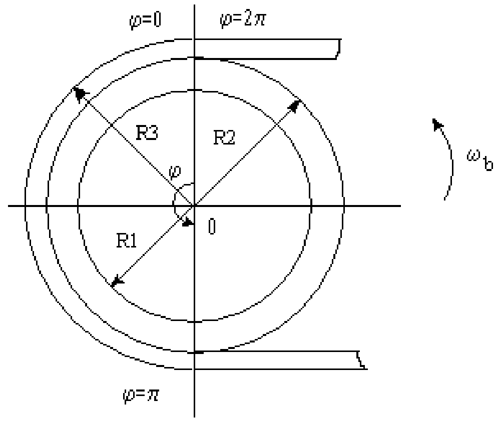

Figure 2. Friction pair drum – conveyor belt

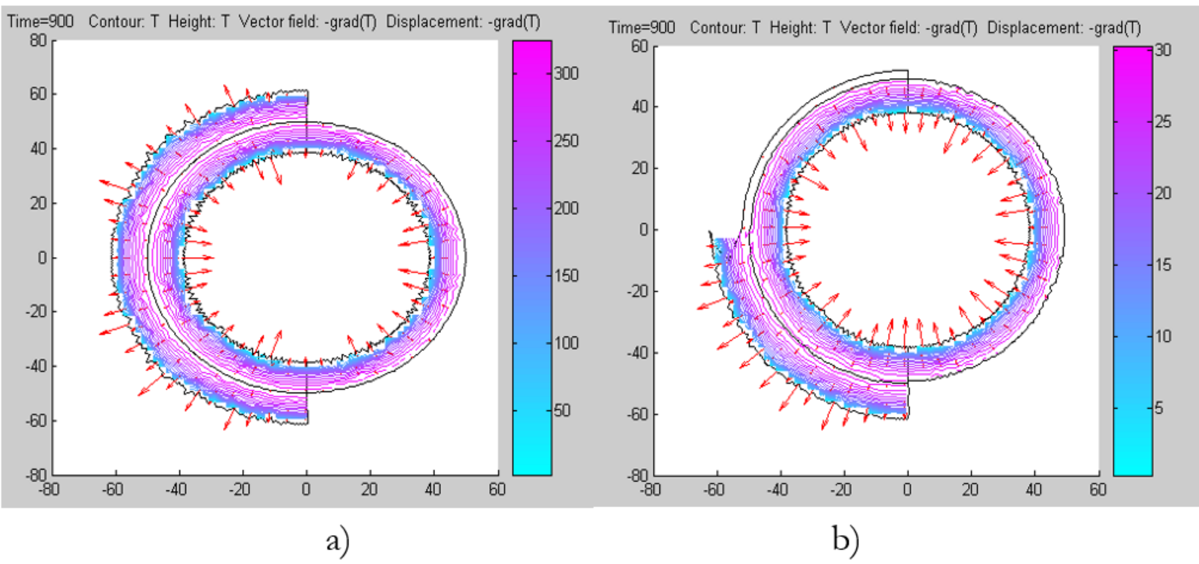

Figure 3. Temperature distribution in a two-dimensional spatial plane: a) during emergency slipping; b) at a steady state of operation of the conveyor at its maximum traction capacity

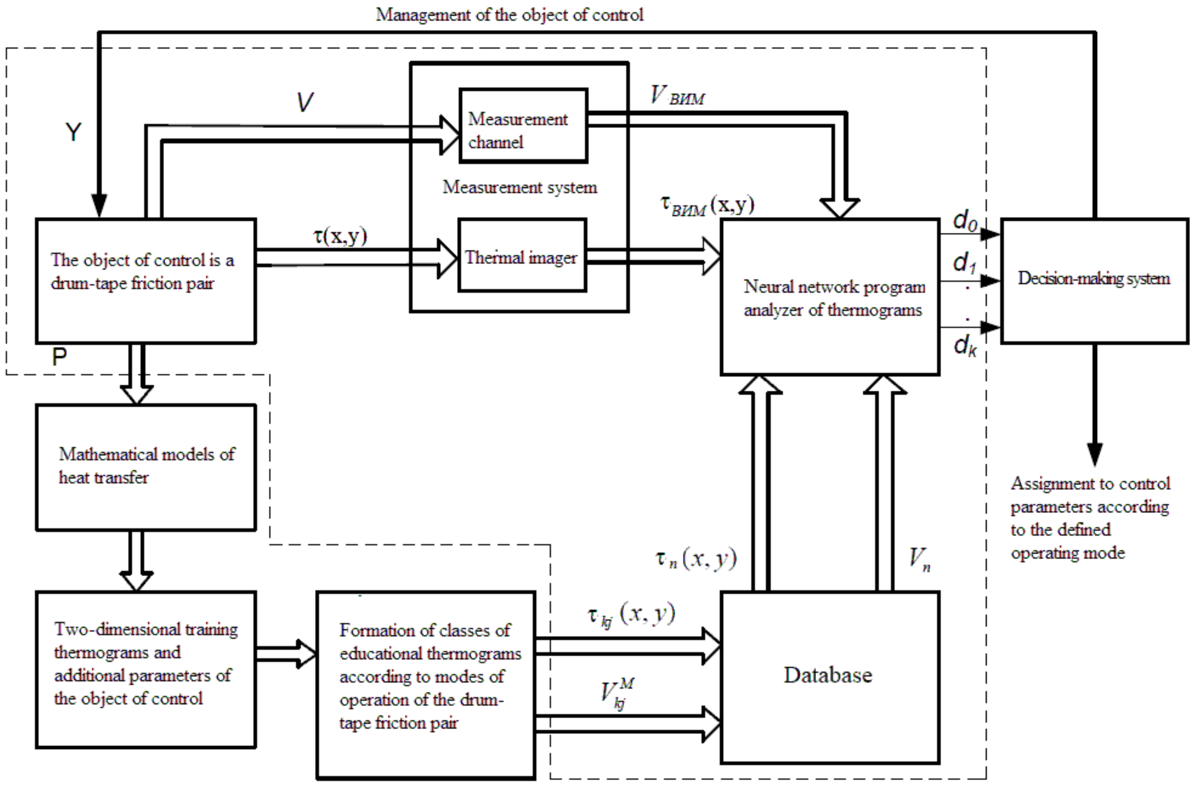

Figure 4. An intelligent information and measurement system of thermal imaging control with a neural network software analyzer of thermograms and additionally measured values of the object (*Nazarenko, 2021, p. 43*)