Development of an Operator's Mathematical Model in a Man-Machine Control System

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Abstract. The human-operator performs important functions related to the control of manufacturing human-machine systems. Human-operator can be considered as a nonlinear dynamic link in a closed loop of industrial control process. The operator's control actions are of a complex nature and consist of deterministic and random components. Accordingly, there are two main components to the operator's response – deterministic part and stochastic part, referred to as the remnant part. To identify the dynamic operator model, experimental studies of operator actions during SISO-type operation were performed. As a result of processing the obtained experimental data using the functions of System Identification Toolbox® library in MATLAB, it was established, that the deterministic part of the human operator's reaction can be represented by an aperiodic link of the first order with a delay (P1D model). The remnant part of the human-operator reaction is proposed to be identified in the form of a second-order oscillating link and a differentiating link connected in series. The adequacy of the proposed mathematical model of the human operator is confirmed.

Keywords: Ergatic system · Operator's model · Remnant part · Identification

1 Introduction

The rapid advancement of technology has transformed a person from a direct executor into an operator, whose main responsibility is to control and manage work processes in industry, transport, and energetics. Industrial systems with human operators are referred to ergatic ones [1].

Ergatic systems are widespread in modern industrial production. Examples of such systems are aviation transportation systems [2], crane mechanisms, various mining machines and production units, the work of which is controlled by a human operator [3].

Z. Hu et al. (Eds.): ICCSEEA 2024, LNDECT 242, pp. 229–238, 2025.
https://doi.org/10.1007/978-3-031-84228-3_19

The presence of the "human factor" in ergatic systems is often interpreted as their disadvantage, which has certain evidence. The number of accidents and disasters associated with operator errors is constantly growing, and their consequences are becoming more widespread and tragic [4–6]. However, it should be noted that the influence of the same "human factor" provides a number of advantages, such as continuous adaptation of ergatic systems, the ability to make decisions in non-standard situations [7].

Currently, due to the insufficient development of intelligent control systems capable of operating effectively in conditions of significant changes in the production scene, ergatic systems remain in demand and widespread. In the modern mining industry, excavator mechanisms of various types are a typical representative of ergatic systems. The influence of the human operator of excavator mechanisms does not lead to emergency situations with catastrophic consequences, as in the case of aircraft pilots. In ergatic systems of the mining industry, the negative impact of the human operator is manifested in a decrease in the technical and economic indicators of production processes. A low level of qualification of an excavator operator can lead to an increase in specific energy consumption by 30–40% [8].

A human operator performs a sequence of actions aimed at achieving certain goals and objectives. He is an important part of the control system and functions as a complex mechanism that processes information from various sources. He filters external data, analyzes it, and transforms it into control commands based on skills and knowledge. Through the controls, he executes commands and reacts to the feedback of the controlled object, similar to a link in a closed control loop, Fig. 1.

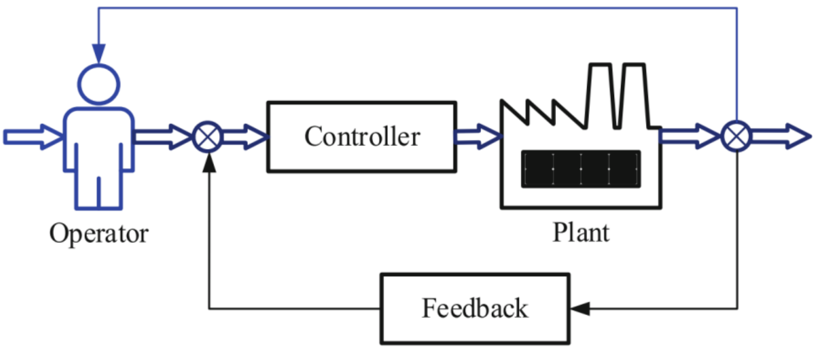

Fig. 1. Block diagram of an ergatic system with a closed-loop production process control system

So, the human operator can be considered as a nonlinear dynamic link in a closed loop of industrial control process.

Thus, in order to improve the accuracy of mathematical modeling of production mechanisms in the mining industry, it is necessary to take into account the peculiarities of the work of a human operator. Therefore, the scientific and practical task of developing a mathematical model of a human operator in a man-machine control system for mining equipment is an important and urgent task.

Goal of the work is the determination of features of the operator's work; the implementation of an experimental study of the operator's actions and the structural and parametric identification of the corresponding transfer function.

To achieve the set goal, the following tasks must be completed:

1) to perform experimental studies of the operator's actions and obtain generalizing numerical characteristics of the obtained results;
2) to perform structural and parametric identification of the transfer function of the operator.

2 Features of Human Operator in Man-Machine Systems

The objective of the ergatic system's human operator is to determine the current value of the system error and reduce it using appropriate control actions [9].

The simplest and most common situation is when the operator controls one input value. However, in the case of controlling the spatial movements of a working machine, the operator must evaluate and control at least three characteristics. A similar situation occurs not only in aviation, but also in the mining industry with a wide range of use of excavator equipment of various designs and complexity.

In [10], the kinematic diagram of the interconnected mechanical system of the "front shovel" excavator was considered; in [11], the issues of controlling the spatial position of the excavator bucket when controlling the electric drives of the main mechanisms of the "front shovel" excavator were considered. However, the mentioned works did not take into account the influence of the dynamic properties of the operator on the technical and economic performance of the excavator.

The primary question is how exactly the operator stabilizes the system. In the stabilization task, the following psycho-physiological features of the human operator behavior are noted [12]:

- presence of reaction delay;
- dependence on the task (the ability to change characteristics depending on the control objectives, dynamics of the controlled object, the type of information used);
- time dependence (manifests itself in two forms: firstly, the operator's characteristics change over time as he learns; secondly, the operator senses changes in the parameters of the external environment and the controlled object and changes his characteristics accordingly);
- prediction (the ability to foresee the future position of a goal based on knowledge of previous ones);
- significant nonlinearity;
- stochasticity (operator characteristics in the same experiment differs from trial to trial, but this variability is small if the training time is sufficient and the task is not complex, so the deterministic model can be used in a statistical sense);
- discreteness (in some cases the operator behaves like a discrete system).

The operator's control actions are of a complex nature and consist of deterministic and random components [13]:

- deterministic component, represents the reaction of a dynamic element of a constant structure equivalent to a human operator;
- stochastic component, depending on the functional state of the operator, due to the finite controllability of the human neuromuscular system, limited accuracy and subjectivity of perception of input information.

The statistical parameters of this component significantly depend on the type of input signal, the complexity of the task, the ergonomic characteristics of the workplace (operator fatigue) and can change significantly over time.

Consequently, two main components are distinguished in the operator's response:

- the first one, deterministic, which corresponds to the response to the input signal of a dynamic element equivalent to a human operator;
- the second one, which is called remnant, and is the difference between the actual output signal of the operator and the reaction of the linear model.

The presence of remnant is influenced by the following factors:

- Presence of noise. There are quite a lot of reasons for the occurrence of noise and erroneous actions of the operator when perceiving movement, analyzing it, dosing deviations of controls, etc.;
- Instability of operator characteristics. In the process of stabilizing the object, the characteristics of the operator change relative to a certain average value, which also contributes to the remnant.
- Finite controllability of the human neuromuscular system;
- Limited accuracy and subjectivity of perception of input information.

Researchers note the presence of a significant correlation between the complexity of the task, the operator's assessment of the object's controllability and the power of the remnant in the operator's signal [14]. Therefore, reproducing the remnant is an extremely important component in modeling operator behavior.

The mathematical model of the operator of the ergatic system must combine a whole range of biomechanical, physical, psychophysical and psychological parameters inherent in a person, his reaction and interaction with the environment.

Considering the described behavioral characteristics of the operator, it may not be about a comprehensive model designed for all operator activities, but only about a model for performing a specific operation. It is assumed that the operator is sufficiently trained to perform this operation, and the dynamics of the control object and the external conditions of the operator's activity are unchanged.

Physical modeling of ergatic systems has limited use due to its complexity and high cost. Therefore, the main means of obtaining data for building models are training complexes. Experimental data exhibit significant variability due to random deviations in human activity, caused by many reasons: from changes in emotional state to loss of attention and fatigue. Therefore, experiments are performed repeatedly, and their results are subjected to statistical processing.

Identifying of an equivalent dynamic model of a human operator can be performed by parametric identification of a set of models with a given structure, selecting the best model based on the known criteria.

For each experiment, the transfer function parameters and the coefficient of determination were determined for each dynamic operator model according to Table 1. The coefficients of determination of individual models were averaged over the data of the entire series. The obtained result is shown in Fig. 4.

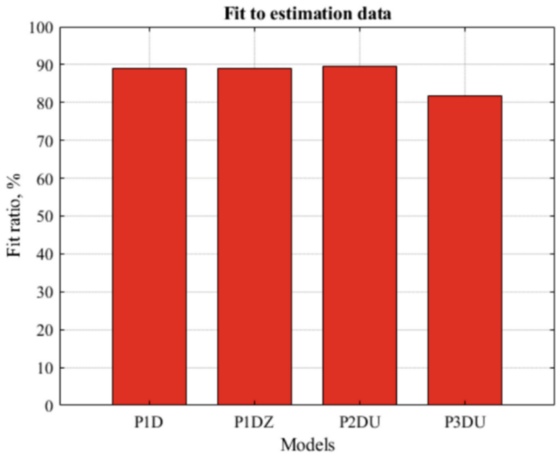

Fig. 4. Average values of the determination coefficients of the operator's dynamic models in the second series of experiments

As the obtained results show, the coefficients of determination of all the models considered are quite high (about 90%) and differ slightly in absolute value, which coincides with the results of the first series of experiments.

As a result of the experimental study, the following hypothesis can be put forward. The deterministic part of the dynamic model of the operator when performing SISO operations with sufficiently high accuracy is represented by a P1D model:

$$G(s) = \frac{K_P}{1 + T_{P1} \cdot s} \cdot e^{-T_d \cdot s} \tag{1}$$

4 Modeling of the Remant Component of the Operator's Response

Knowing the transfer function of the deterministic component of the human operator reaction, expressed by Eq. (1), it is easy to determine the remnant component of the operator reaction as the instantaneous value of the deviation of the real operator reaction from the reaction of the deterministic component of the operator model reaction, Fig. 5.

As can be seen from Fig. 5, the remnant component of the operator's reaction consists of two parts. The first part of the remnant component is associated with the operator's reaction to rapid, significant changes in the input signal; the second part is a random signal of insignificant amplitude, associated with the final sensitivity of the human neuromuscular system and control organs.

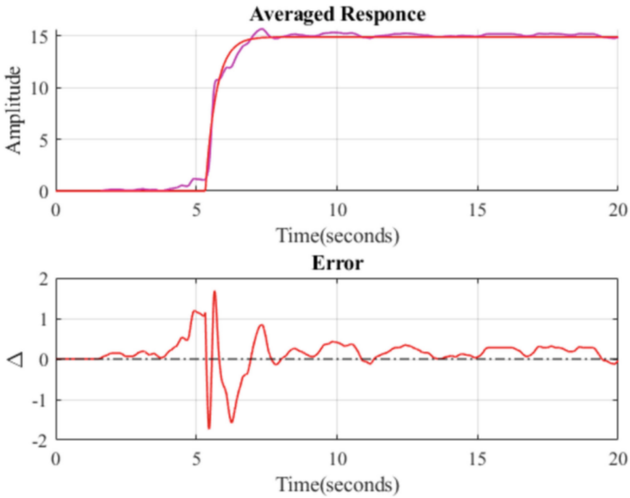

Fig. 5. Time diagram of the remnant component of the operator's reaction

The transfer function of the first part of the remnant component can be presented in the following form:

$$W_R(s) = \frac{-k_1 \cdot \omega_1^2 \cdot s}{s^2 + 2\zeta \cdot \omega_1 \cdot s + \omega_1^2} \cdot e^{-T_d \cdot s} \tag{3}$$

The structure and parameters of this transfer function were selected using empirical methods.

Combining Eqs. (1) and (2) we finally obtain the following transfer function for the deterministic part of the operator's response:

$$G(s) = \left(\frac{K_P}{1 + T_{P1} \cdot s} - \frac{k_1 \cdot \omega_1^2 \cdot s}{s^2 + 2\zeta \cdot \omega_1 \cdot s + \omega_1^2} \right) \cdot e^{-T_d \cdot s} \tag{4}$$

Figure 6 shows comparative diagrams of the real operator response in the experimental study and the operator model response obtained from Eq. (4) taking into account the stochastic part of the remnant component of the operator reaction.

Obtained diagrams show a high relevance between the proposed operator model and the results of the experimental study.

The disadvantages of the resulting mathematical model include the complete absence of elements reflecting the operator's anticipatory actions.

Also, additional research is needed to justify the applicability of the proposed operator model when performing MISO operations; when the excavator's operator needs to monitor changes and simultaneously manage three variables –coordinates of the spatial position of the excavator bucket.

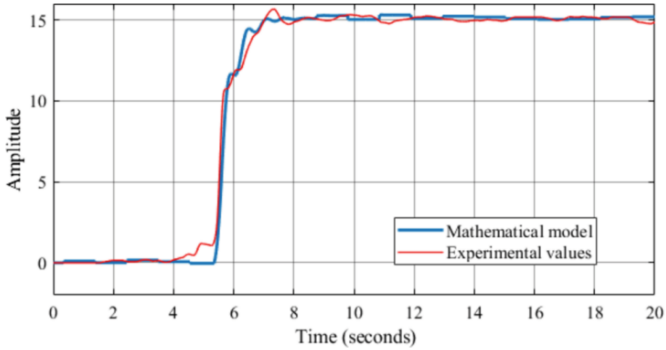

Fig. 6. Comparative results of the experimental data with the work of the proposed dynamic operator model

5 Summary and Conclusion

The paper presents the results of experimental studies of operator actions in a SISO system. The possibility of representing the operator as aperiodic first-order link with time-delay has been justified. The coefficient of determination of this model was approximately 90%. In order to describe the remnant component of the operator's reaction, it was proposed to use a combination of a differentiating link with a second-order oscillatory link. The suggested mathematical model of the operator can be used to determine the technical and economic indicators of mining excavators with a man-machine control system.

References

1. Korobiichuk, I., Tokar, A., Danik, Y., Katuha, V.: Evaluation methods for the ergatic system reliability operator. In: Szewczyk, R., Zieliński, C., Kaliczyńska, M. (eds.) AUTOMATION 2019. AISC, vol. 920, pp. 560–570. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-13273-6_52
2. Tan, Y., Feng, D., Shen H.: Research for Unmanned Aerial Vehicle components reliability evaluation model considering the influences of human factors. In: 3rd International Conference on Mechanical, Electronic and Information Technology Engineering, ICMITE 2017, vol. 139 (2017). https://doi.org/10.1051/matecconf/201713900221
3. Zhu, H.: fundamental models for missions of engineered systems. In: IEEE International Systems Conference (SysCon), pp. 1–6 (2019). https://doi.org/10.1109/syscon.2019.8836714
4. Che, H., Zeng, S., Guo, J.: Reliability assessment of man-machine systems subject to mutually dependent machine degradation and human errors. Reliab. Eng. Syst. **190**, 106504 (2019). https://doi.org/10.1016/j.ress.2019.106504
5. Kletz, T., Amyotte, P.: Accidents said to be due to human error. In: What Went Wrong? 6th edn., pp. 53–172. Butterworth-Heinemann (2019). https://doi.org/10.1016/B978-0-12-810539-9.00007-0
6. Strauch, B.: Investigating Human Error: Incidents, Accidents, and Complex Systems, 1st edn. Routledge, Milton Park (2018). https://doi.org/10.4324/9781315251851