Adaptive control methods

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EFFICIENCY AND RELIABILITY OF MULTI-OBJECT CONTROL METHODS IN COMPLEX NETWORKS

Abstract. Topicality. Efficient multi-object control in network environments ensures optimal performance and reliability. Due to delays and errors, traditional control methods often face challenges in managing complex, large-scale networks. **The aim of the research.** This study aims to evaluate and compare the efficiency and reliability of three distinct multi-object control methods: independent control, sequential control with error correction, and simultaneous control with global error correction. **Research methods.** The research employs mathematical modelling, probabilistic time graphs, and generating functions to develop and analyze the three control methods. **Research results.** To determine each method's performance, the study considers various factors such as network size, control distance, and error probability. Control distances are categorized into local, adjacent, and distant groups to assess their impact on control efficiency. Independent control, while simple and autonomous, becomes inefficient in larger networks due to insufficient coordination between objects. Sequential control enhances accuracy and reliability through stage-wise verification but faces increased control times in larger networks. Simultaneous control significantly reduces control time by managing all objects concurrently but is sensitive to error frequency, leading to potential delays in high-error environments. The study finds that control distance and network size significantly affect the performance of these methods, with simultaneous control maintaining stable control times in extensive networks, provided error rates are low. **Conclusions.** Independent control is most suitable for small, localized networks, sequential control is ideal for accuracy-critical applications, and simultaneous control is recommended for large-scale networks requiring rapid control and low error rates. Future research should explore hybrid approaches and the impact of emerging technologies like machine learning and artificial intelligence to further enhance multi-object control efficiency and reliability. This study provides a foundation for optimizing control strategies in increasingly complex network environments.

Keywords: multi-object control; control efficiency; network; control strategies.

Introduction

The advent of complex systems in various domains necessitates the development of efficient multi-object control strategies [1]. Multi-object control involves regulating and verifying numerous interconnected entities within a network. This field has gained significant attention due to its applications in various areas, such as industrial automation, telecommunications, and network control [2]. The efficiency of these control strategies directly impacts the overall performance and reliability of the systems involved. Ensuring accurate and timely regulation over multiple objects is critical in network control. The complexity of these tasks arises from the need to manage numerous interconnected nodes, each potentially affecting the others [3]. Traditional network control methods, which often rely on sequential control processes, may not suffice for large-scale networks where delays and errors can propagate through the system, leading to inefficiencies and increased risk of failures [4].

Recent research has focused on optimizing multi-object control through various methodologies [5]. These methods generally fall into three categories: independent control, sequential control with error correction, and simultaneous control with global error correction [6]. Independent control allows for autonomy by managing each object separately, potentially reducing system complexity but often leading to inefficiencies due to insufficient coordination between objects [7]. Sequential control involves a step-by-step process where each stage is verified and corrected as necessary, optimizing control through the results achieved at each stage but potentially slowing down due to its sequential nature [8]. Simultaneous control, on the other hand, involves all objects undergoing the control process at the same time, with global error correction [9]. If an error is detected in any object, the entire process is repeated, which aims to minimize control time through parallelization but can cause significant delays if errors are frequent.

The primary objective of this study is to develop and analyze mathematical models for these three multi-object control methods. The study aims to determine the most effective strategy by evaluating their performance under various conditions. Factors such as control distance, probability of error detection, and the time required for control processes are considered in this evaluation.

The methodology employed in this study is based on the Work Breakdown Structure (WBS), a proven approach for modelling sequentially performed operations. Probabilistic time graphs and generating functions represent the control processes and evaluate their efficiency. The study involves categorizing control distances, analyzing probabilistic characteristics, and assessing the impact of network size and error probabilities on control performance.

This research is significant because it has the potential to enhance the efficiency and reliability of multi-object control systems. By providing a comparative analysis of different control methods, the study aims to offer valuable insights into their applicability in various network configurations. The findings can guide the design and implementation of more robust and efficient control systems, particularly in large and complex networks where traditional methods may fall short.

This paper is structured to first detail the development of mathematical models for the three multi-object control methods, describing the scenarios considered for distance distribution between controlling and controlled objects. Following this, the results of the model analyses are presented, highlighting the performance of each control method under different conditions. The discussion interprets these results, comparing the effectiveness of the control methods and discussing their implications for network control. Based on the findings, the paper concludes with recommendations for the most efficient control method, considering various network sizes and error probabilities. By addressing these aspects, this research aims to contribute to the network control field and provide a foundation for future studies in multi-object control optimization.

Materials and Methods

Let us consider the most general version of multi-object control, where each object is controlled by a single center with subsequent verification of the results at the control center and, if necessary, repetition of the control process. In this case, three methods of multi-object control can be used. The first method involves organizing the control process for each object separately. Here, the control processes of many objects are independent of each other. The control systems of the objects are autonomous. The second method involves sequential control and monitoring of the correctness of this control of network objects, with the correction of detected errors. In the third method, all objects carry out the control process simultaneously. If a control error is detected in any object, the control process is repeated for all objects. The second and third methods allow for optimizing network control tasks considering the results achieved at each object.

We will develop models and examine the effectiveness of these three methods. The control system's topology is represented by a vector h of dimension $1 \times N$, where N is the number of controlled objects. Each element of the h_i vector characterizes the distance to the i-th object. In this case, distance is measured in kilometers or by the number of transit nodes to the controlled object. If the distances are short, the control process is faster. As the distance to the controlled object increases, the effectiveness of control decreases.

We will categorize the distances between objects into three groups for further analysis. The first group consists of objects for local control (i.e., control of neighboring objects). The second group includes objects in adjacent segments (at a distance of 2-3 transit nodes). The third group consists of objects located more than three transit nodes away. We will represent the probability distribution of controlled objects across these groups with a vector (p_1; p_2; p_3), where the numbers indicate the probabilities of an object belonging to the first, second, or third group, respectively.

In subsequent research, we will consider the following scenarios for the distribution of distances between the controlling and controlled objects:

1. Predominant control of local objects: (0.9; 0.05; 0.05).
2. Uniform distribution: (0.33; 0.34; 0.33).
3. Predominant control of distant objects: (0.1; 0.2; 0.7).

First and foremost, it is necessary to determine the methodology for developing the mathematical model. As demonstrated above, the method based on the Work Breakdown Structure (WBS) has proven fruitful in the development of mathematical models describing sequentially performed operations. According to this method, the probabilities are multiplied sequentially, and the time taken for their completion is summed. With many objects, the control processes for each are carried out similarly. However, these processes are performed in parallel in the tracks. Consequently, some particularities arise in model development, which include:

- The control time for objects is equal to the control time of the slowest among them;
- The condition for successful control is the correct resolution of the control task for all objects. This condition is analogous to the condition for correct control using the sequential method.

If individual operations result in cycles with varying durations, calculating the average time to solve the task must consider the longest average time of any cycle in any operation. In the other cycles, only the probabilities of performing individual operations should be considered.

From the above, it is evident that the WBS can be used to develop a model of multi-object control. Each arc, representing the control process of an individual object, accounts for both the time and the probability of operation execution. Arcs that consider the control process of individual operations are characterized only by the probability of completing a specific stage.

In this case, the mathematical model of the multi-object control problem-solving process will be equivalent to a similar model using the sequential method.

Assume that the network has M controlled objects. In the absence of interfering factors, we denote the duration of the control cycle for any of the objects as T_{cntr}. The duration of the control cycle in the presence of interfering factors is T_{ncntr}. The time to monitor the results of solving the network control task is denoted by τ_k. Thus, the relative speed of solving the control task will be

$$C = T_{cntr}/(max\ (T_{ncntri}) + \tau_k). \quad (1)$$

Results

Based on the methodology described above, models of multi-object control for the three methods have been developed using probabilistic time graphs and generating functions. The probabilistic time graph of controlling each object for the first method is shown in Fig. 1.

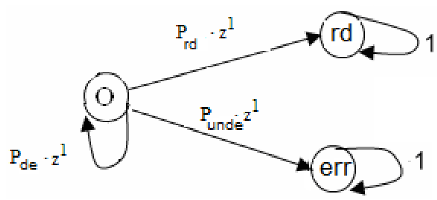

Fig. 1. Probabilistic time graph

In Fig. 1, the following are indicated: P_{rd}, P_{unde}, P_{de} are probabilities of correct control, undetected error, and detected error as a result of monitoring, respectively; P_{ck} and P'_{ck} are probabilities of correct monitoring when control is correct and when errors are not detected. The graph, according to Fig. 1, takes into account the relative time of performing the control stage about the time

$$T_{cntr} = T_{ic} + T_{ps} + T_d + T'_{ck}, \tag{2}$$

where T_{ic} is the time for information gathering, T_{ps} is the time for solving the control task, T_d is the time for delivering the control information, and T'_{ck} is the time for implementing the accepted decision and monitoring its execution. An error in control may occur if the control information is delivered incorrectly, the decision is incorrectly made and executed, and the monitoring fails to detect these errors (Fig. 1). It is considered that modern monitoring systems function satisfactorily if no more than 1% of errors occurring in the system are undetected. The components included in the time interval T_{cntr} for each controlled object vary. When analyzing the probabilistic-time characteristics of the network, it is necessary to focus on the maximum values of these components and, therefore, on $T_{cntrmax}$. This control interval depends on the size of the network, i.e., on M, the distances between objects, and their controlled properties. These features will be accounted for by the factor K_{cntr}. Consequently, the following equality holds true:

$$T_{cntrmax} = T_{cntr} \cdot M \cdot K_{cntr}. \tag{3}$$

By the division of controlled objects into three groups introduced earlier, it can be assumed that the following values of these coefficients might be adopted:

$$1)\ K_{cntr} = \frac{1}{M};\ \ 2)\ K_{cntr} = \frac{2}{M};\ \ 3)\ K_{cntr} = \frac{4}{M}. \tag{4}$$

The values of these coefficients can vary. However, this does not significantly impact the comparative characterization of multi-object control methods. The graph shown in Fig. 1, through equivalent transformations, is converted to the form presented in Fig. 2.

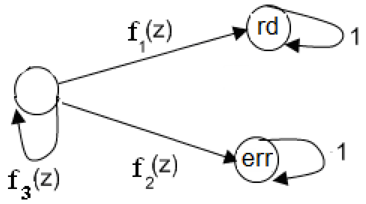

Fig. 2. Converted WBS

This graph depicts

$$f_1(z) = P_{rd} \cdot z^1; \tag{5}$$

$$f_2(z) = P_{unde} \cdot z^1; \tag{6}$$

$$f_3(z) = P_{de} \cdot z^1. \tag{7}$$

The relation defines the generating function:

$$F(z) = \left(f_1(z) + f_2(z)\right) / \left(1 - f_3(z)\right). \tag{8}$$

The relative average transmission time is:

$$T_{avg_1} = \frac{dF(z)}{dz}|_{z=1}. \tag{9}$$

The probabilities of correct decision-making and the probability of an undetected error are respectively:

$$P_{rd_1} = \frac{f_1(z)}{1 - f_3(z)}|_{z=1}; \tag{10}$$

$$P_{unde_1} = \frac{f_2(z)}{1 - f_3(z)}|_{z=1}; \tag{11}$$

Since objects are managed independently in an i-object system, the WBS in multi-object control transmission will have the form shown in Fig. 3.

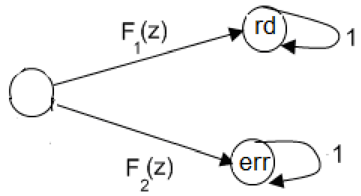

Fig. 3. Resulting WBS

For the graph presented, the following expressions are valid:

$$F_1(z) = \left(P_{rd_1}\right)^M \cdot z^{M \cdot T_{avg_1} \cdot K_{cntr}}; \tag{12}$$

$$F_2(z) = i = 1MC_M^i \cdot \left(P_{unde_1}\right)^i \times$$

$$\times \left(1 - P_{unde_1}\right)^{M-i} \cdot z^{T_{avg_1} \cdot K_{cntr}}. \tag{13}$$

The generating function takes the form:

$$F(z) = F_1(z) + F_2(z). \tag{14}$$

The formula determines the transmission time:

$$T_{avg} = \frac{dF(z)}{dz}|_{z=1}. \tag{15}$$

The probability of error equals:

$$P_{err} = F_2(z)|_{z=1}. \tag{16}$$

Fig. 4 and 5, respectively, illustrate the dependence of the relative average network control time and the error probability on the probability of correct execution of technology stages constructed by the obtained expressions (1-16). The graphs are constructed under parallel control of all network objects. From the presented graphs, it is apparent that in the considered case, the average time does not depend on the number of controlled objects (M) and is determined by the maximum control time of a single object. There is a significant dependency on the network size (coefficient K_{cntr}) and the probability of correct decision-making in control tasks (P_{rd}) when this probability varies within the range of 0.6 – 0.9. When $P_{rd} > 0.9$, changes in this probability have little effect on the average control time.

The number of controlled objects significantly affects the error probability in control (Fig. 5). This impact increases as the system's ability to detect emerging errors deteriorates (P_{unde}). When using independent control channels, there is a possibility for both object-specific control and sequential control of objects. With sequential control, the time to solve the task, compared to the results shown in Fig. 4, increases proportionally with the number of objects. Compared to the data in Fig. 4, the error probability remains virtually unchanged. The probabilistic time graph for the second control organization method is depicted in Fig. 6.

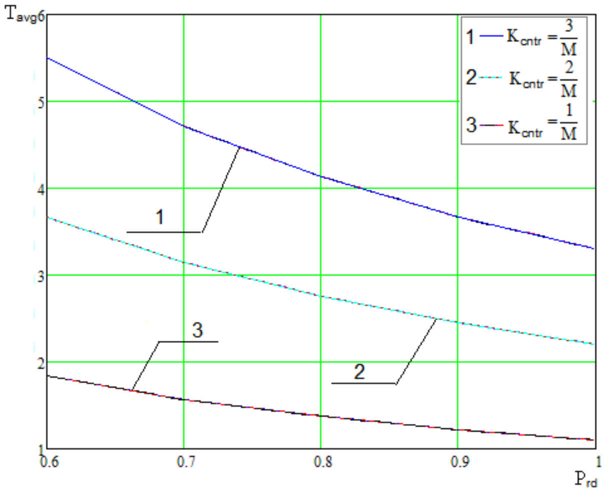

Fig. 4. Dependence of $T_{avg} = f(P_{rd})$
with different values

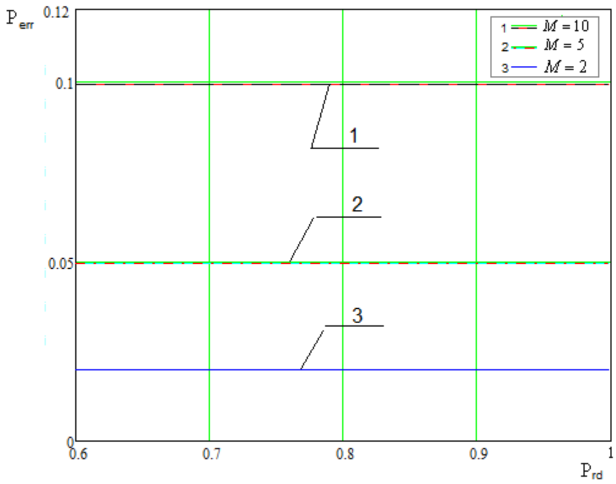

Fig. 5. Dependence of $P_{err} = f(P_{rd})$
with different values M

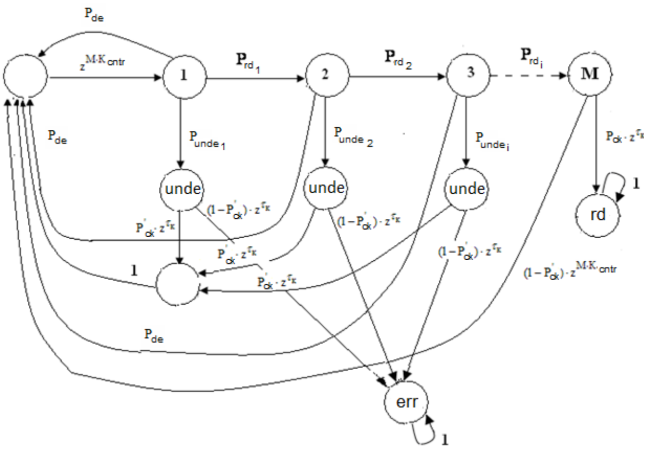

Fig. 6. The probabilistic time graph describing the functioning of an M-object system

In Fig. 6, the following notations are introduced: P_{rdi} is the probability of correct control for the i-th object; P_{dei} is the probability of error detection when controlling the i-th object; P_{undei} is the error non-detection probability when controlling the i-th object.

This probabilistic time graph is converted into its equivalent form through transformations, as shown in Fig. 7. On this graph, the following are denoted:

$$F_1(z) = z^{M\cdot K_{cntr}} \cdot (P_{ck} \cdot z^{\tau_\kappa}) \cdot \prod_{i=1}^{M} P_{rd_i},$$

$$F_2(z) = F_2'(z) \cdot (1 - P_{ck}) \cdot z^{\tau_\kappa};$$

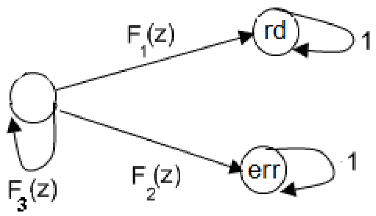

Fig. 7. The transformed probabilistic time graph

$$F_3(z) = z^{M\cdot K_{cntr}} \cdot \sum_{j=1}^{M} P_{de_j} \cdot \prod_{i=1}^{j} P_{rd_i} + F_2'(z) \times$$

$$\times P_{ck}' \cdot z^{\tau_\kappa + M\cdot K_{cntr}} + z^{M\cdot K_{cntr}} \cdot (P_{rd})^M \cdot (1 - P_{ck});$$

$$F_2'(z) = z^{M\cdot K_{cntr}} \cdot \sum_{j=1}^{M} P_{unde_j} \cdot \prod_{i=1}^{j} P_{rd_i}. \quad (17)$$

$$F_2(z) = F_2'(z) \cdot (1 - P_{ck}) \cdot z^{\tau_\kappa}.$$

For channels with identical characteristics, these expressions will have the form:

$$F_1(z) = z^{M\cdot K_{cntr}} \cdot (P_{rd})^M \cdot P_{ck} \cdot z^{\tau_\kappa};$$

$$F_2'(z) = z^{M\cdot K_{cntr}} \cdot P_{unde} \cdot (1 - (P_{rd})^M)/(1 - P_{rd});$$

$$F_3(z) = P_{de} \cdot z^{M\cdot K_{cntr}} \cdot \frac{1 - (P_{rd})^M}{1 - P_{rd}} + F_2'(z) \times$$

$$\times P_{ck} \cdot z^{\tau_\kappa + M\cdot K_{cntr}} + z^{M\cdot K_{cntr}} \cdot (P_{rd})^M \cdot (1 - P_{ck}); \quad (18)$$

The generating function is equal to:

$$F(z) = \left(F_1(z) + F_2(z)\right)/\left(1 - F_3(z)\right). \quad (19)$$

The error probability is determined by the expression:

$$P_{err} = F_2(z)/\left(1 - F_3(z)\right)|_{z=1}. \quad (20)$$

The average delivery time is determined by (1). Fig. 8 and 9, respectively, show the dependencies of control time and error probability on correct decision probability (P_{rd}) and the number of controlled objects in the channels (M), constructed using the above expressions with different initial data.

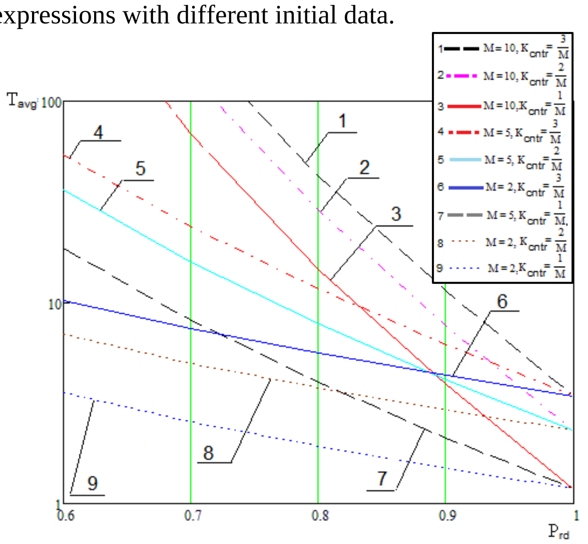

Fig. 8. The dependence of $T_{avg} = f(P_{rd})$
for different values of M and K_{cntr}

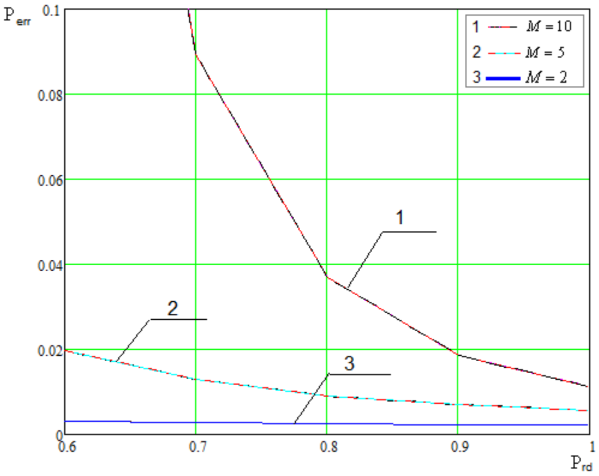

Fig. 9. The dependence of $P_{err} = f(P_{rd})$ for different values of M and K_{cnt}

From these Fig. 8, it is evident that the nature of the dependency of relative control time for the second method is similar to the dependencies for the first method.

However, in this case, the relative average transmission time increases significantly with the number of objects. There is a more noticeable dependence on the probability of a correct decision (P_{rd}) than with the first method. The error probability when using the second method is significantly lower than for the first method (almost an order of magnitude lower when P_{ck}=0.9) (Fig. 9).

Using the formulas and graphs obtained, one can set acceptable values of control time and error probability to determine the acceptable number of controlled objects and network size requirements.

The probabilistic time graph for the third control organization method is depicted in Fig. 10.

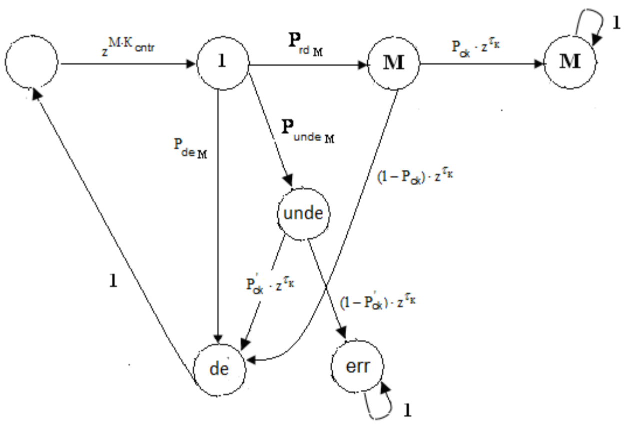

Fig. 10. Graph of the third control organization method

The generating function for the probabilistic-time graph shown in Fig. 10 is equal to:

$$\frac{\begin{pmatrix} P_{rd_M}\cdot P_{ck}\cdot z^{(M\cdot K_{cntr}+\tau_K)}+\\ +P_{unde_M}\cdot P'_{ck}\cdot z^{(M\cdot K_{cntr}+\tau_K)}\end{pmatrix}}{\begin{gathered}1-z^{M\cdot K_{cntr}}\times\\ \times\begin{pmatrix}P_{de_M}+P_{unde_M}\cdot(1-P_{ck})\cdot z^{\tau_K}+\\ +P_{rd_M}\cdot(1-P_{ck})\cdot z^{\tau_K}\end{pmatrix}\end{gathered}}. \quad (21)$$

On this probabilistic time graph, the following are denoted:

$$P_{rdM}(z)=z^{(M\cdot K_{cntr}+\tau_K)}\cdot\prod_{i=1}^{M}P_{rd_i};$$

$$P_{undeM}(z)=z^{(M\cdot K_{cntr}+\tau_K)}\times$$

$$\times\sum_{i=1}^{M}C_M^i\cdot P_{unde_i}^i\cdot\left(1-P_{unde_i}\right)^{M-i}; \quad (22)$$

$$P_{deM}(z)=z^{(M\cdot K_{cntr}+\tau_K)}\cdot\sum_{i=1}^{M}C_M^i\cdot\left(P_{de_i}\right)^i\times$$

$$\times\left(1-P_{de_i}-P_{unde_i}\right)^{M-i}+P_{rdM}(z)\cdot(1-P_{ck})\times$$

$$\times z^{(M\cdot K_{cntr}+\tau_K)}+P_{undeM}\cdot P'_{ck}\cdot z^{(M\cdot K_{cntr}+\tau_K)}.$$

The average delivery time is determined by formula (1). The error probability is given by:

$$P_{err}=\frac{P_{undeM}\cdot(1-P_{ck})\cdot z^{\tau_K}}{1-P_{deM}\cdot z^{M\cdot K_{cntr}}}\Big|_{z=1}. \quad (23)$$

Based on these formulas, graphs showing the dependence of relative time and error probability on various initial data were constructed (Fig. 11 and 12). The nature of these dependencies is similar to that of the second control method. However, the control time for the third method is shorter, and the error probability is almost the same as for the second method.

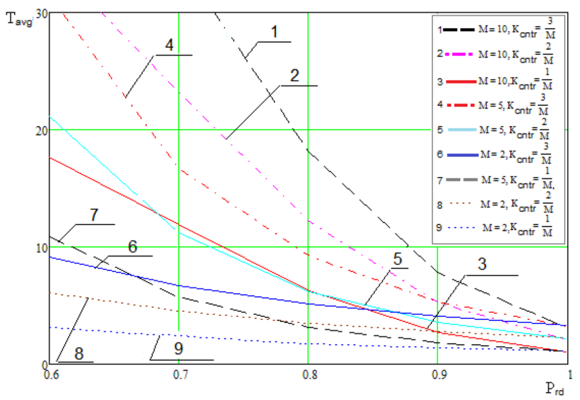

Fig. 11. The dependence of $T_{avg}=f(P_{rd})$ for different values of M and K_{cntr}

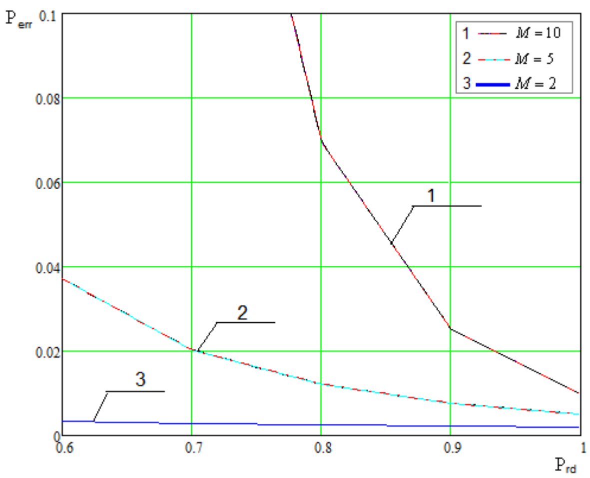

Fig. 12. The dependence of $P_{err}=f(P_{rd})$ for different values of M

The developed mathematical models for multi-object control organization enable the assessment of important characteristics such as average time and variance of control time, as well as error probability, considering the number of objects and their state.

As a result, it is possible to compare and reasonably choose the most efficient method for multi-object control. However, general recommendations can be made based on the available graphical dependencies. Since the error probability for the first method (independent control channels) is higher than for the second and third methods, it is preferable to use this method in small local networks or at the last level of the hierarchy in hierarchical control. This method's advantage is adapting the control process to the current situation, transitioning from object-by-object control to parallel control of all objects.

Additionally, implementing this method is significantly simpler than using the other methods.

Using the second and third control methods results in an error probability almost an order of magnitude lower. Therefore, these methods are recommended for use at the higher levels of hierarchical control, where tasks are distributed to lower levels and control errors are unacceptable.

If there are constraints on error probability and control time, the best method is the third one, which allows for parallel control of objects. This method allows for the possibility of selective control of individual objects. The final control decision is made considering the verification of control processes across all objects. However, the implementation of such a control method is significantly more complex.

Discussion

The study presents a comprehensive analysis of three distinct methods for multi-object control in network environments: independent control, sequential control with error correction, and simultaneous control with global error correction. The mathematical models developed and analyzed offer valuable insights into the efficiency and reliability of each method under various conditions.

The independent control method, where each object is controlled separately, offers simplicity and autonomy. This method allows for decentralized control, reducing the complexity of coordinating multiple objects. However, the lack of inter-object communication and coordination can lead to inefficiencies, particularly in larger networks.

The results indicate that the independent control method performs well in small-scale networks or scenarios with sufficient local control. However, as network size increases, the efficiency of this method diminishes due to the absence of synergies between control processes.

Sequential control with error correction involves a step-by-step approach, where each control stage is verified and corrected as necessary. This method optimizes control by leveraging the results achieved at each stage, ensuring high accuracy and reliability. The probabilistic time graphs and generating functions used in this study highlight the benefits of sequential control in error minimization. The primary drawback of this method is the potential increase in control time due to the sequential nature of operations. As network size grows, the cumulative delay from sequential processing can become significant, making this method less suitable for real-time or large-scale applications.

Simultaneous control with global error correction represents the most advanced method examined in this study. By controlling all objects concurrently and applying global error correction, this method aims to minimize overall control time. The models demonstrate that simultaneous control significantly reduces the time required to manage multiple objects compared to the other methods. However, this approach is highly sensitive to error frequency. In scenarios where errors are frequent, the need to repeat the entire control process can lead to substantial delays. Despite this, the method excels in environments with low error rates, providing rapid and efficient control across extensive networks.

The study's results underscore the importance of network size and control distance on the performance of multi-object control methods. For independent control, the efficiency decreases as the network size increases due to insufficient coordination between objects. Sequential control exhibits a linear increase in control time with network size, highlighting the cumulative nature of delays inherent in this method. In contrast, simultaneous control maintains a relatively stable control time across different network sizes, provided that error rates remain low.

Control distance, defined as the distance between the controlling and controlled objects, also plays a crucial role. Shorter control distances facilitate faster control processes, while longer distances introduce delays and reduce control efficiency. The study categorizes control distances into local, adjacent, and distant groups, demonstrating how each category affects control performance. The findings indicate that methods incorporating distance-based optimization, such as sequential and simultaneous control, outperform those that do not, particularly in large and geographically dispersed networks.

Error probability is a critical factor influencing the choice of control method. The models show that independent control has a higher error probability due to the lack of error correction mechanisms. Sequential control, with its built-in error correction at each stage, significantly reduces error rates, making it suitable for environments where accuracy is paramount. Due to its global error correction approach, simultaneous control achieves the lowest error probability, especially in scenarios with low initial error rates.

However, its performance degrades rapidly in high-error environments, underscoring the need for robust error detection and correction mechanisms.

The practical implications of these findings are significant for network control in various domains. Independent control offers a straightforward and effective solution for small, localized networks or scenarios where decentralization is beneficial. In contrast, sequential control is ideal for applications where accuracy and reliability are critical despite potential delays. Simultaneous control is best suited for large-scale networks where rapid control is essential, and error rates are low.

These insights can guide the design and implementation of multi-object control systems across diverse applications, from industrial automation to telecommunications.

Organizations can optimize the efficiency and reliability of their control systems by selecting the appropriate control method based on network size, control distance, and error probability.

Future research should explore hybrid approaches that combine elements of these methods to further enhance control efficiency and reliability. Additionally, investigating the impact of emerging technologies, such as machine learning and artificial intelligence, on multi-object control could provide new avenues for optimization and innovation in this field.

Conclusions

This study has comprehensively evaluated three multi-object control methods in network environments: independent control, sequential control with error correction, and simultaneous control with global error correction. By developing and analyzing mathematical models, we have identified key insights into the efficiency and reliability of each method.

Although simple and autonomous, independent control becomes inefficient in larger networks due to the lack of inter-object coordination. It is most effective in small-scale or local networks where the need for coordination is minimal. Sequential control with error correction, while optimizing accuracy and reliability through stage-wise verification, faces challenges with increased control time as network size grows. This method is best suited for applications where accuracy is crucial despite potential delays.

Simultaneous control with global error correction significantly reduces overall control time by managing all objects concurrently.

This method excels in large networks with low error rates, offering rapid and efficient control. However, it is highly sensitive to error frequency, which can cause substantial delays if errors are frequent.

The impact of network size and control distance on the performance of these methods is significant. Independent control loses efficiency with increasing network size, while sequential control's linear increase in control time reflects cumulative delays. Simultaneous control maintains stable control times across different network sizes, provided error rates are low. Control distance also affects efficiency; shorter distances facilitate faster processes, while longer distances introduce delays. Methods that optimize based on distance, such as sequential and simultaneous control, outperform others in large, dispersed networks.

Error probability plays a critical role in determining the most suitable control method. Independent control has a higher error probability due to the absence of error correction mechanisms. Sequential control effectively reduces error rates through built-in corrections, making it ideal for environments where accuracy is paramount. Simultaneous control achieves the lowest error probability in low-error scenarios but is less effective in high-error environments.

In practical terms, independent control is recommended for small or localized networks, sequential control for accuracy-critical applications, and simultaneous control for large-scale networks requiring rapid control and low error rates.

These findings guide the design and implementation of multi-object control systems, optimizing efficiency and reliability based on network characteristics and requirements.

Future research should investigate hybrid approaches combining elements of these methods to further enhance control efficiency and reliability. Additionally, exploring the impact of emerging technologies, such as machine learning and artificial intelligence, on multi-object control could offer new opportunities for optimization and innovation. This study lays the foundation for future advancements in multi-object control, aiming to develop more robust, efficient, and adaptive systems for increasingly complex network environments.

References

1. Ding, H., Tang, J. and Qiao, J. (2023), "Dynamic modeling of multi-input and multi-output controlled object for municipal solid waste incineration process", *Applied energy*, vol. 339, no. 120982, doi: https://doi.org/10.1016/j.apenergy.2023.120982
2. Guo, P., Xiao, K., Wang, X. and Li, D. (2024), "Multi-source heterogeneous data access management framework and key technologies for electric power Internet of Things", *Global energy interconnection*, vol. 7, no. 1, pp. 94–105, Feb. 2024, doi: https://doi.org/10.1016/j.gloei.2024.01.009
3. Dzheniuk, N., Yevseiev, S., Lazurenko, B., Serkov, O. and Kasilov, O. (2023), "A method of protecting information in cyber-physical space", *Advanced Information Systems*, vol. 7, no. 4, pp. 80–85, doi: https://doi.org/10.20998/2522-9052.2023.4.11
4. Kuchuk, N., Kashkevich, S., Radchenko, V., Andrusenko, Y., Kuchuk, H. (2024), Applying edge computing in the execution IoT operative transactions, *Advanced Information Systems*, vol. 8, no. 4, pp. 49–59, doi: https://doi.org/10.20998/2522-9052.2024.4.07
5. Liu, Q. and Jiang, X. (2024), "Dynamic multi-objective optimization control for wastewater treatment process based on modal decomposition and hybrid neural network," *J. of water process eng.*, vol. 61, doi: https://doi.org/10.1016/j.jwpe.2024.105274
6. Sundaresan, N., Yoder, T.J., Kim, Y., Li, M., Chen, E. H., Harper, G., Thorbeck, T., Cross, A. W., Córcoles A. D. and Takita, M. (2023), "Matching and maximum likelihood decoding of a multi-round subsystem quantum error correction experiment", *Nature Communications*, vol. 14, no. 1, 2852, doi: https://doi.org/10.1038/s41467-023-38247-5
7. Canaday, D., Pomerance, A. and Gauthier, D. J. (2021), "Model-free control of dynamical systems with deep reservoir computing", *Journal of Physics: Complexity*, vol. 2, no. 3, 035025, doi: https://doi.org/10.1088/2632-072x/ac24f3
8. Buyukkocak, A. T., Aksaray, D. and Yazıcıoğlu, Y. (2024), "Sequential control barrier functions for mobile robots with dynamic temporal logic specifications", *Robotics and autonomous systems*, vol. 176, doi: https://doi.org/10.1016/j.robot.2024.104681

9. Tamizi, M. G., Akbar, A., Azad, F. A., Kalhor, A. and Masouleh, M. T. (2022), “Experimental study on a novel simultaneous control and identification of a 3-DOF delta robot using model reference adaptive control”. *European journal of control*, vol. 67, doi: https://doi.org/10.1016/j.ejcon.2022.100715

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Ефективність та надійність методів мультиоб’єктного управління в складних мережах

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Анотація. **Актуальність.** Ефективне керування багатьма об’єктами в мережевих середовищах забезпечує оптимальну продуктивність та надійність. Через затримки та помилки традиційні методи керування часто стикаються з труднощами в управлінні складними великими мережами. **Мета дослідження**. Це дослідження має на меті оцінити та порівняти ефективність та надійність трьох різних методів керування багатьма об’єктами: незалежного керування, послідовного керування з корекцією помилок та одночасного керування з глобальною корекцією помилок. **Методи дослідження.** У дослідженні використовуються математичне моделювання, імовірнісні часові графіки та породжуючі функції для розробки та аналізу трьох методів керування. **Результати дослідження.** Для визначення продуктивності кожного методу дослідження враховує різні фактори, такі як розмір мережі, відстань керування та ймовірність помилок. Відстані керування класифікуються на локальні, суміжні та віддалені групи для оцінки їх впливу на ефективність керування. Незалежне керування, хоча й просте та автономне, стає неефективним у великих мережах через недостатню координацію між об’єктами. Послідовне керування підвищує точність та надійність завдяки поетапній перевірці, але стикається зі збільшенням часу керування у великих мережах. Одночасне керування значно скорочує час керування, керуючи всіма об’єктами одночасно, але є чутливим до частоти помилок, що може призводити до затримок у середовищах з високим рівнем помилок. Дослідження показує, що відстань керування та розмір мережі значно впливають на продуктивність цих методів, причому одночасне керування підтримує стабільний час керування в великих мережах за умови низької частоти помилок. **Висновки.** Незалежне керування є найбільш підходящим для малих локалізованих мереж, послідовне керування ідеально підходить для додатків, де важлива точність, а одночасне керування рекомендується для великих мереж, які потребують швидкого керування та низького рівня помилок. Майбутні дослідження мають дослідити гібридні підходи та вплив нових технологій, таких як машинне навчання та штучний інтелект, для подальшого підвищення ефективності та надійності керування багатьма об’єктами. Це дослідження забезпечує основу для оптимізації стратегій керування в умовах все більш складних мережевих середовищ.

Ключові слова: багатооб'єктне управління; ефективність контролю; мережа; стратегії контролю.