General Principles of Application of Temporal Petri Nets in Intelligent Real-Time Decision Support Systems of Railway Automation of Uzbekistan

Asadulla Azizov[1, 2] and Elnara Ametova[1, 2]
[1]Tashkent State Transport University, Temiryolchilar Str. 1, 100167 Tashkent, Uzbekistan
[2]University of Diyala, 32009 Baqubah, Diyala, Iraq
azizov_a@tstu.uz, elnara_84@tstu.uz, elnara.ametova.84@mail.ru

Keywords: Railway Automation, Graph Theory, Mathematical Modeling, Control Relays, Intelligent Systems, Petri Nets, Algorithms.

Abstract: The relevance of this study lies in the need for modern scientific and technological advancements to enhance railway transportation management, ensuring efficiency and safety amid increasing train traffic and freight turnover. The solution of these problems is primarily due to the need to use modern achievements of microelectronic technologies, telecommunication capabilities associated with a high risk of errors at the design stage of such, hybrid systems (containing simultaneously relay and microprocessor equipment) and extremely high price for these errors during operation. Petri Nets provide a mathematical framework for railway automation, yet their full potential in real-time intelligent decision support systems remains underexplored. The purpose of this paper is to synthesize and study a mathematical model with the possibility of organizing the work of simulated devices of railway automation and telemechanics with qualitative time dependencies, and the presence of priority for some operations and proposed extension of the apparatus of colored Petri nets (CPN) - PPN RT - with support for temporal interval logic Allen. The method of research is based on the fact that the set problems are solved using the methods of discrete mathematics, mathematical logic, graph theory, algebraic model theory and the method of analyzing the complexity of algorithms. The results obtained by the authors have practical and theoretical significance. The method of modeling of responsible circuits of railway automatics presented in the article will contribute to the effective implementation of microelectronic technologies in the existing relay systems of automation and telemechanics.

1 INTRODUCTION

The need to apply the latest scientific and technical developments, progressive labor methods, thorough reforming of transportation process management is dictated by the high intensity of train traffic and ever-increasing freight turnover, while unconditionally ensuring the safety of train traffic. Modern means of automation and control over the technical condition of railway automation devices help to solve these problems. The current pace of development of microelectronics makes it possible to freely apply them to the development of automation means, to link them by means of hardware and software complexes [1-18].

Petri nets (PN) are mathematical objects and as such are independent of physical interpretation. They can effectively describe parallelism. Their graphical representation is used as a tool for modeling and analyzing digital systems, especially logic control devices.

However, a significant disadvantage of classical Petri nets is the complexity of modeling the functioning of real-time systems, when it is necessary to take into account the time factor and temporal dependencies. As a result of research efforts [8,9], a new extension, colored Petri nets with support for Allen's temporal logic [8], has been proposed to model both quantitative and qualitative temporal dependencies. This logic is characterized by sufficient expressiveness and the presence of polynomial inference algorithms, which allows its application in systems such as intelligent real-time decision support systems. The paper [7] gives a description and an example of using the developed basic software tool for this class of Petri nets.

Colored Petri nets (CPN) are an interpretation and extension of ordinary, classical Petri nets by associating with each chip and transition of a colored Petri net a value of some type - gamut of colors. This value can be of arbitrarily complex type. The functioning of the CPN depends not only on the presence of tokens in the input locations of the crossings, but also on their coloring, and the priorities for triggering the crossings can also be determined by coloring them. For example, when the conditions for triggering two or more transitions are met at the same time, priority is given to a predetermined color scheme; in the models of systems responsible for train safety, the red color is given priority (see Figure 3).

Tools for modeling and analysis of complex parallel and distributed systems, including real-time systems, of which real-time (RT) intelligent decision support systems (IDS) are characteristic representatives, are of great interest [4, 5]. In the case under consideration, when modeling the relay control unit for changing the direction of train movement, there is a time delay of some relays, in real time, in order to ensure synchronous operation of the means used.

The relevance of these tools is primarily due to the high risk of errors at the design stage of such systems and the extremely high cost of these errors at the operational stage. Classical Petri nets have long established themselves as a convenient, illustrative and at the same time mathematically rigorous formalism for modeling and analysis of distributed systems, however, when modeling the functioning of real systems it is necessary to explicitly take into account the time factor and temporal (temporal) dependencies, which is quite difficult in the theory of classical PN. Known PN extensions allow to take into account quantitative time dependencies, while in IDS RT it is often necessary to have tools for representing and operating with qualitative dependencies. The optimal option is a tool environment that allows operating with both types of dependencies. Classical Petri nets have also been extended and supplemented by novel computational paradigms to improve railway system modeling and control, including approaches based on quantum computing [19].

This paper considers the possibility of organizing work with qualitative temporal dependencies and proposes an extension of the apparatus of colored Petri nets (CPN), the CPN RT, with support for Allen's temporal interval logic [8].

In recent years, the problem of creating computer (software) systems that automate various types of human activities in order to improve efficiency has become more and more urgent. A typical representative of such systems are intelligent decision support systems actively implemented in various subject/problem areas. Including real-time decision support systems (IDS RT), designed to assist a person or a device (hereinafter referred to as DMF - decision maker by face) in managing complex technical and organizational objects under conditions of rather strict time constraints and in the presence of various kinds of uncertainty (inaccuracy, vagueness, incompleteness, contradiction) in the incoming information.

In [9] it is shown that in practice CPN represent a more compact and convenient modeling language than classical PN.

2 RESEARCH METHODS

The tasks are solved using methods of discrete mathematics, mathematical logic, artificial intelligence, graph theory, algebraic model theory and the method of algorithm complexity analysis.

3 FINDINGS AND DISCUSSION

This paper considers the modeling of a single shooter relay control unit. Let us define the temporal modification CPN of the real-time (CPN RT) relay control unit as a tuple.

$$CTPN\ \text{RT} = \langle \Sigma, P, T, \dot{F}, \dot{\xi}, \dot{\gamma}\, \varepsilon_{\Sigma}, \varepsilon_{\tau}, m_0 \rangle,$$

where $\Sigma -$ a finite set of types (colors), $P \equiv \left[p_1, p_2, ... p_{|p|} \right] -$ finite ordered set of positions, $T -$ finite number of transitions, $P \cap T = \varnothing$; $\dot{F} \subseteq (P \times T) \cup (T \times P) -$ non-empty set of arcs; $\dot{\xi} : P \to \Sigma -$ function that matches each position $p \in P$ peculiarity of its chip (color scheme); $\dot{\gamma} : T \to Bool$, where $Bool = \{true,\ false\} -$ protective (guarding) function, which puts in correspondence a transition $t \in T$ with some logical expression.

At the same time, when developing the model of the single shooter control device, we assume that the initial state of the network is shown in Figure 1. where

$$I(1PC) = \text{Aktive1} \quad (1)$$

$$O(1PC) = [\text{Aktive2}], \left[\dot{\gamma}(t)[1PC\ d\ 1MC]^{/true} \right]; \quad (2)$$

$$I(1\overline{PC}) = [\text{Aktive2}], \left[\dot{\gamma}(t)[1PC\ d\ 1MC]^{/true} \right] \quad (3)$$

$$O(1\overline{PC}) = \text{Aktive1}; \quad (4)$$

$$I(\text{Aktive1}) = \left[(1\text{-}13)\ d\ (1\overline{MC})\ d\ (1-3) \right] \quad (5)$$

$$O(\text{Aktive1}) = 1PC \quad (6)$$

$$I(\text{Aktive2}) = \begin{bmatrix} 1MC \\ or(1\overline{-3}) \\ or(1\overline{-13}) \end{bmatrix}, \left[\dot{\gamma}(t)[1PC\ d\ 1MC]^{/true} \right] \quad (7)$$

$$O(\text{Aktive2}) = 1\overline{PC} \quad (8)$$

$$I\left\{ \left[\dot{\gamma}(t)[PC1\ d\ MC]^{/true} \right] \right\} = 1PC \quad (9)$$

$$O\left\{ \left[\dot{\gamma}(t)[1PC\ d\ 1MC]^{/true} \right] \right\} = 1\overline{PC} \quad (10)$$

there is a position $1PC-$ plus control relay the presence of a chip in this position, $1PC = 1$ corresponds to the excited state of this relay.

$1\overline{PC}-$ inverse state of the relay, that is $1\overline{PC} = 1$ presence of the chip in this position corresponds to the de-energized state of the relay. It should be borne in mind that the simultaneous fulfillment of the condition $1PC = 1, \overline{PC} = 0$ and $1PC = 0, \overline{PC} = 1$ is permissible, while the simultaneous fulfillment of the condition $1PC = 1, \overline{PC} = 1$ and $1PC = 0, \overline{PC} = 0$ is not permissible.

The model provides a protective logical transition function in accordance with Allen's temporal logic .

$\dot{\gamma}(t)[1PC\ d\ 1MC]^{/true}$,defining the impossible and dangerous condition of the control unit of a single arrow, when two arrows are simultaneously in the plus position. Failure to fulfill this condition (*false*), v (I) and weekend (O) functions are given in the system of (1)-(10).

For the graph of the second starting control, relay shown in Figure 2, the extended input (I) and output (O) functions are given in the system of (2). In the initial state, a colored temporal real-time Petri net is defined as a tuple with the relation.

$$\text{CTPN RT}\ m_0 \equiv \langle \Sigma = 2, P = 2, T = 3, F = 5, \dot{\xi} = 1, \dot{\gamma} = 1, \dot{\varepsilon}_{\Sigma} = 4, \varepsilon_{\tau} = 1 \rangle$$

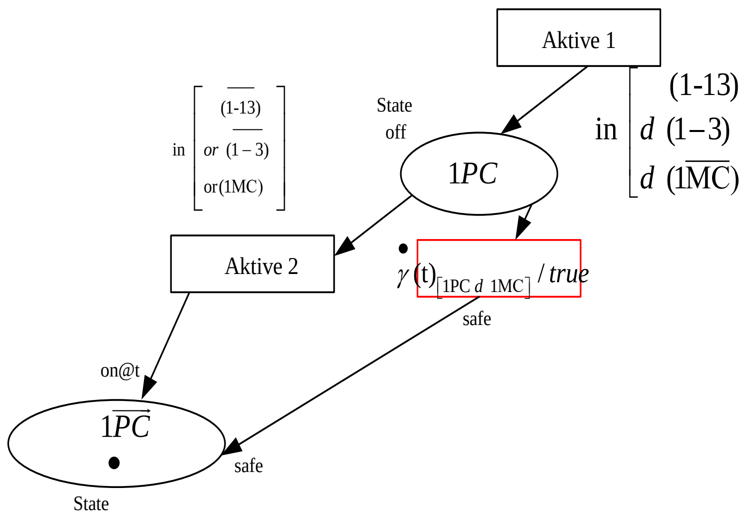


Figure 1: Operation model of the 1PC control unit relay (CPN RT with Allen logic support).

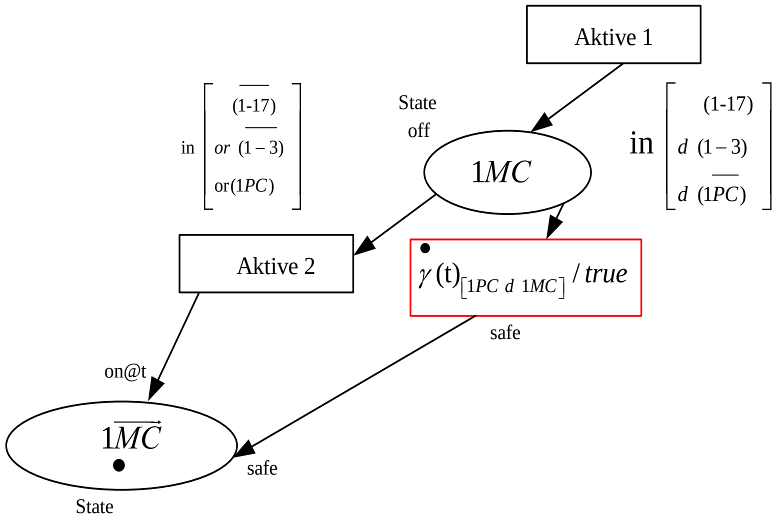


Figure 2: Operation model of the 1MC control unit relay (CPN RT with Allen logic support).

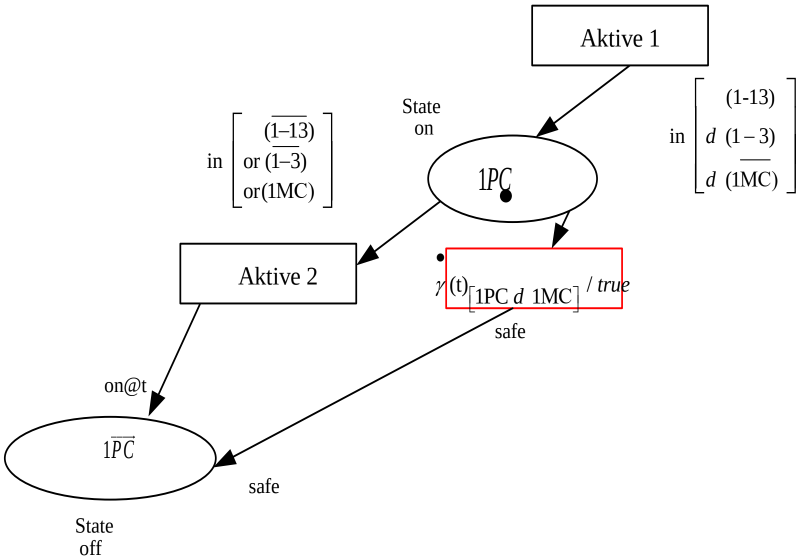


Figure 3: Model of de-energized relay 1PC control unit (CPN RT with support of Allen logic).

Let's consider the state of the model when the conditions for relay operation are met 1PC. In this case, there is power at the terminals (1-3) и (1-13) and the variables reflecting this state will take the value of that is $(1-13)=1, (1-3)=1$. Relay 1MC и 1PC are de-energized, therefore, the transition conditions are satisfied *Aktive* 1, which helps to move the chip from the position $1\overline{PC}$ in position $1PC$, and changing its status from State off to State on, which corresponds to the excited state of the relay 1PC. In this case, the model will take the form shown in Figure 3.

$$I(1MC) = \text{Aktive1}, \tag{11}$$

$$O(1MC) = [\text{Aktive2}], \left[\dot{\gamma}(t)[1PC\ d\ 1MC]/true\right], \tag{12}$$

$$I(1\overline{MC}) = [\text{Aktive2}], \left[\dot{\gamma}(t)[1PC\ d\ 1MC]/true\right], \tag{13}$$

$$O(1\overline{PC}) = \text{Aktive1}, \tag{14}$$

$$I(\text{Aktive1}) = \left[(1\text{-}17)\ d\ (1\overline{PC})\ d\ (1-3)\right], \tag{15}$$

$$O(\text{Aktive1}) = 1MC \quad (16)$$

$$I(\text{Aktive2}) = \begin{bmatrix} 1PC \\ or(\overline{1\text{–}3}) \\ \text{or}(\overline{1\text{–}17}) \end{bmatrix}, \left[\overset{\bullet}{\gamma}(\text{t})[1PC\ d\ 1MC]^{/true}\right], \quad (17)$$

$$O(\text{Aktive2}) = 1\overline{MC}, \quad (18)$$

$$I\{\left[\overset{\bullet}{\gamma}(\text{t})[1PC\ d\ 1MC]^{/true}\right]\} = 1MC \quad (19)$$

$$O\{\left[\overset{\bullet}{\gamma}(\text{t})[1PC\ d\ 1MC]^{/true}\right]\} = 1\overline{MC}, \quad (20)$$

The algorithm of the microelectronic control unit of a single arrow developed according to the results of the study, colored real-time Petri net on the basis of intelligent decision support system and using Allen's temporal algorithm is presented in Figure 4. In the mentioned algorithm, special attention is required to be paid to the transition 5, made in red lines, to emphasize the necessity of periodic control of the fulfillment of the condition of safety violation, in a programmatic way.

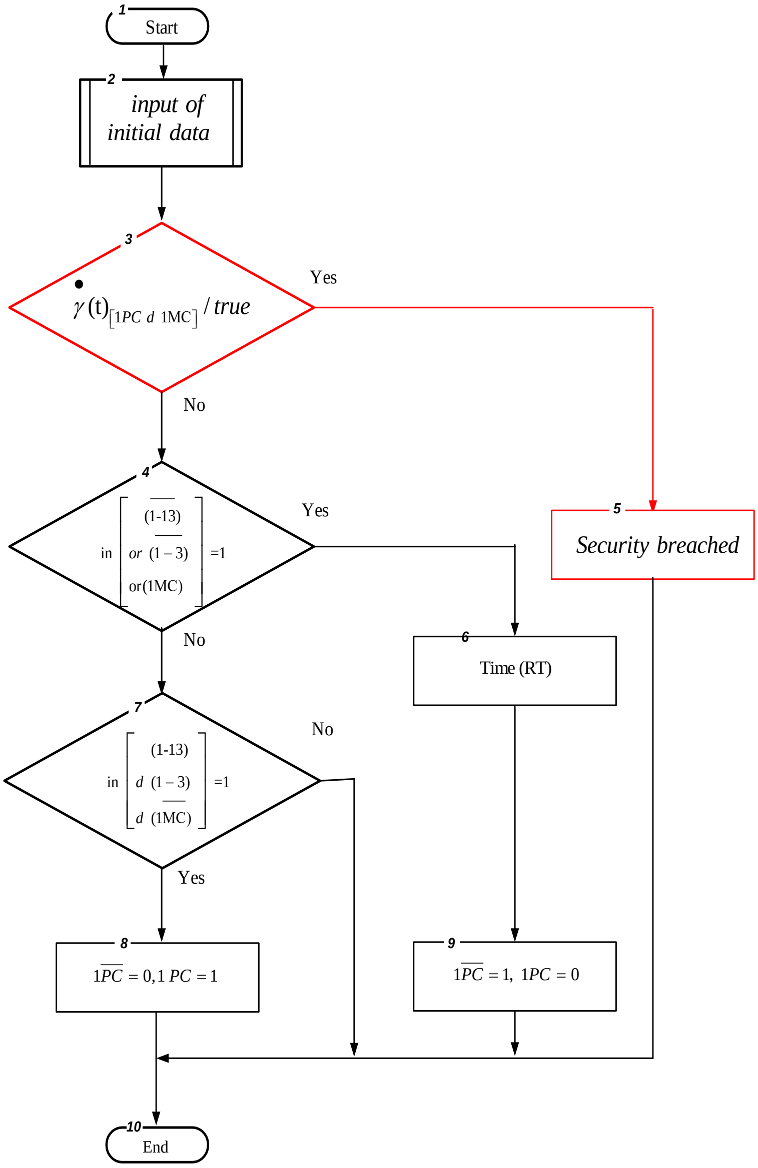


Figure 4: Algorithm of operation of the positive control relay of the microelectronic control unit of a single switch (CPN RT with support of Allen logic).

Fulfillment of the conditions of block 4 leads to the procedure of de-energizing the relay 1PC, hence, the software translates the variables into the state of $1PC = 0, \overline{PC} = 1$ with time delay, the numerical value of which is determined by the factory characteristics of the device.

Let us consider the operation of the model relative to the negative control relay 1MC. The graph of this model is presented in Figure 2. For this graph, the expanded input (I) and output (O) functions are given in the system of equations (11-20). In the initial state, relay 1MC is in a de-energized state, which is reflected in the graph by the presence of a chip in position $1\overline{MC}$, therefore, the software variables reflecting the state of this relay have the following values $1MC = 0, 1\overline{MC} = 1$. To transfer a chip $1\overline{MC}$ from $1MC$ one position to another according to the graph in Figure 2, it is necessary to fulfill the conditions of "Active1" and the system of equations, where the input function is $I(1MC) = \text{Aktive1}$ (11). This transition can be started when the logical condition is met $(1\text{-}17) d (1-3) d (1\overline{PC}) = 1$, that is there must be power on terminals 1-17 and 1-13, and the condition that the variable must be met must also be met $1\overline{PC} = 1$. The launch Active1 of the transition facilitates the transfer of the chip to the position $1MC$, which corresponds to the operation of relay 1MC.

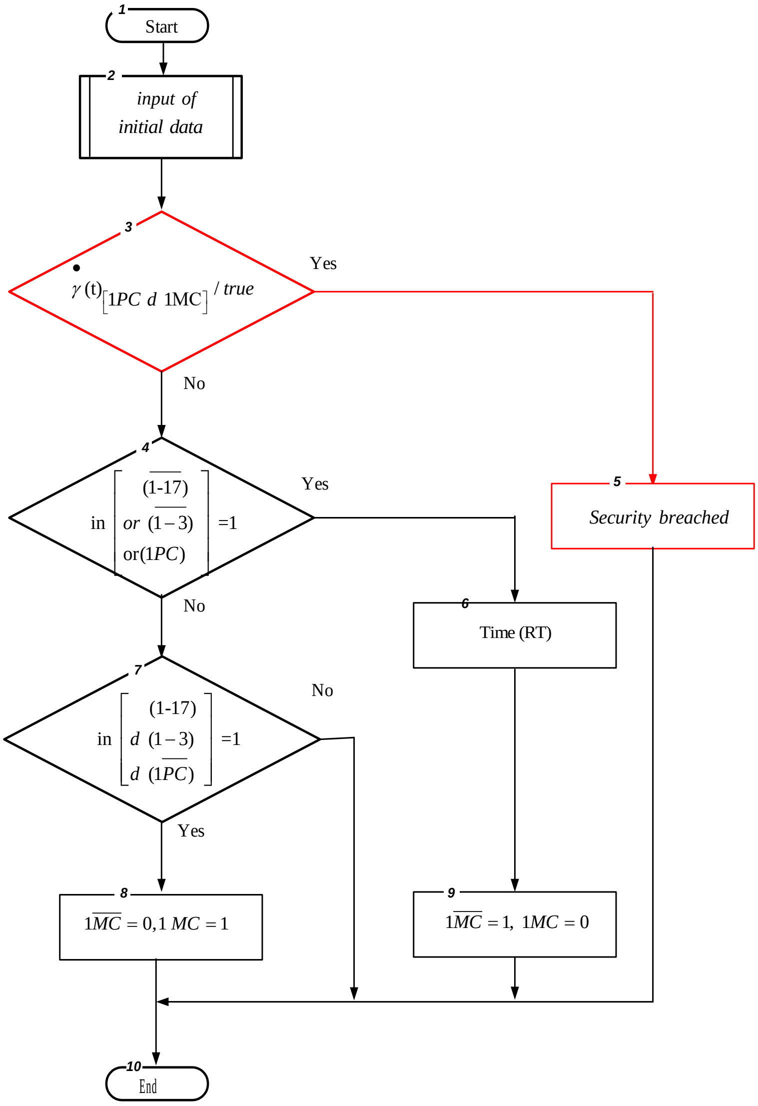
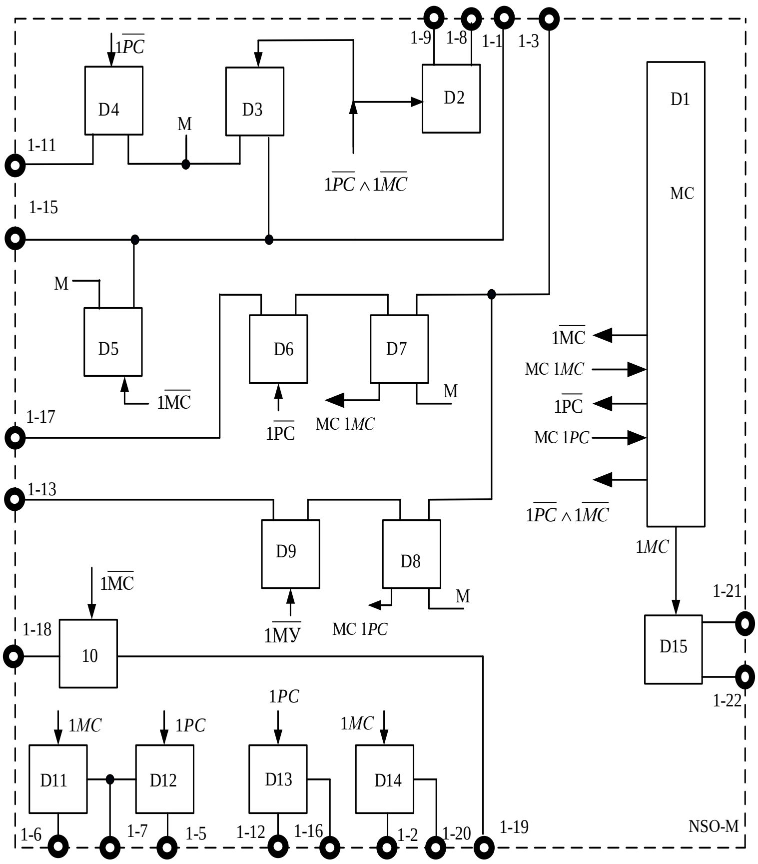


Figure 5: Algorithm of operation of the minus control relay of the microelectronic control unit of a single switch (CPN RT with support of Allen logic).



D1 ⇒ *microcontroller*; D2 - D6, D9, D10-D15 ⇒ PVG-612, D7,D8 ⇒ PC-817

Figure 6: Functional diagram of the microelectronic control unit for a single switch.

The safety conditions are checked by the microcontroller software by continuously monitoring the state of the variables $1MC$ and $1\overline{MC}$, the relationship must be completely excluded $1MC = 0, 1\overline{MC} = 0$ or $1MC = 1, 1\overline{MC} = 1$ for this purpose in the column of Figure 2 this position is colored red. De-energization of relay 1MC occurs when the transition trigger condition is met according Aktive2 to equation $I(\text{Aktive2}) = 1PC or \overline{(1–3)} \text{or} \overline{(1–17)} = 1$ (11), that is

$1PC = 1$, $\overline{(1–3)} = 1$, or $\overline{(1–17)} = 1$. According to the operating conditions of the relay system, relay 1MC has a delay time for dropouts, which is implemented in the graph of Figure 2 by the presence of the variable $on@t$. Similar reasoning is also valid for the position of 1PC in the system of equations (1-10).

The functional diagram of the microelectronic unit is shown in Figure 6, where as a microcontroller (MC), a simplified version can be used ARDUINO. Similar reasoning is also valid for the algorithm of the minus control relay, shown in Figure 5.

4 CONCLUSIONS

The application of colored Petri nets in the study of intelligent real-time decision support systems based on Allen's temporal algorithms with real time scaling is considered $on@t$ system operation TCPN IDS RT. A model of a microelectronic control unit for a device for changing the direction of train movement (single switch), a block route relay interlocking system has been developed and studied. As a result of using the advanced capabilities of classical Petri nets, it was possible to obtain a universal graph that implements the modeling of all the listed control relays. in particular, time components in the form of time delays, by changing some variables, which in real relay systems is called the anchor release real time. The universal graph also shows the positions that lead to dangerous failures, marked in red.

The algorithms of its operation is obtained, and the blocks of the algorithm are emphasized $Bool = \{true, false\} -$ realization of which leads to a violation of train traffic safety, which are marked by colored lines on the graph and algorithm in Figure 4 and Figure 5.

REFERENCES

[1] K. Hameed, "A state space approach via Discrete Hartley transform of type and For the solution of the State model of Linear time-invariant systems (L.T.I.S's.)," IJApSc, vol. 2, no. 1, pp. 53-60, Mar. 2025, [Online]. Available: https://doi.org/10.69923/k1qp1d65.

[2] A. Azizov, "Microelectronic device for control of rail line integrity in Uzbekistan," E3S Web of Conferences, vol. 583, p. 07007, 2024, [Online]. Available: https://doi.org/10.1051/e3sconf/202459207017.

[3] H. H. Saleh, W. Nsaif and L. Rashed, "Design and Implementation a Web-Based Collaborative E-Learning Model: A Case Study - Computer Science Department Curriculum," 2018 1st Annual International Conference on Information and Sciences (AiCIS), Fallujah, Iraq, 2018, pp. 193-200, [Online]. Available: https://doi.org/10.1109/AiCIS.2018.00045.

[4] N. Aripov, A. Sadikov and S. Ubaydullayev, "Intelligent signal detectors with random moment of appearance in rail lines monitoring systems," E3S Web of Conferences, vol. 264, p. 05039, 2021, [Online]. Available: https://doi.org/10.1051/e3sconf/202126405039.

[5] P. F. Bestemyanov, "Methods of Providing Hardware Safety for Microprocessor Train Control Systems," Russ. Electr. Eng., vol. 91, pp. 531-536, 2020, [Online]. Available: https://doi.org/10.3103/S1068371220090036.

[6] A. B. Nikitin, "Increasing the efficiency of electrical centralisation systems," Automation, communication, informatics, no. 4, pp. 4-7, 2010.

[7] K. Jensen, Coloured Petri Nets. Basic concepts, analysis methods and practical use, vol. 1-3, 1992-1997.

[8] J. F. Allen, "Maintaining knowledge about temporal intervals," Communications of the ACM, vol. 26, no. 11, pp. 832-843, 1983.

[9] J. Peterson, Petri net theory and the Modeling of Systems, Moscow: Mir, 1984.

[10] V. A. Khodakovsky, "Modeling of technical problems by Petri nets in the HPSim environment," in Actual issues of development of railway automation and telemechanics systems, V. V. Sapozhnikov, Ed., St. Petersburg: St. Petersburg State University of Railways, 2013, pp. 41-51.

[11] A. Sadikov, N. Aripov, Z. Yusupov and O. Vaisov, "Intelligent Processing Time Characteristics of the Flow of the Impulse Component of the Train Shunt Resistance," Lecture Notes in Networks and Systems, vol. 912 LNNS, 2024, [Online]. Available: https://doi.org/10.1007/978-3-031-53488-1_15.

[12] M. Loqman and N. Khalaf, "Preview the predictive performance of the STR, ENN, and STR-ENN hybrid models," IJApSc, vol. 1, no. 1, pp. 9-23, Jun. 2024, [Online]. Available: https://doi.org/10.69923/IJAS.2024.010102.

[13] O. Muhiddinov and S. Boltayev, "Route management modeling of high-speed trains on the train dispatcher section," E3S Web of Conferences, vol. 376, 2023, [Online]. Available: https://doi.org/10.1051/e3sconf/202337604033.

[14] N. M. Aripov, D. Kh. Baratov and D. Kh. Ruziev, "Formalized Methods of Analysis and Synthesis of Electronic Document Management of Technical Documentation," in Proceedings of 17th IEEE East-West Design & Test Symposium (EWDTS'2019), Batumi, Georgia, 2019, pp. 531-539, [Online]. Available: https://doi.org/10.1109/EWDTS.2019.8884415.

[15] S. T. Boltayev, R. B. Abdullaev, B. G. Ergashov and B. Q. Hasanov, "Simulation of a Safe Train Traffic Management System at the Stations," in 2022 Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), Saint Petersburg, Russian Federation, 2022, pp. 566-571, [Online]. Available: https://doi.org/10.1109/ElConRus54750.2022.9755616.

[16] A. Manakov and A. Rakhmonberdiev, "Protection of track circuit equipment in case of failures in the AC traction network," Automation, Communication, Informatics, no. 10, p. 23, 2023, [Online]. Available: https://doi.org/10.34649/AT.2023.10.10.002.

[17] Q. A. Kosimova, S. I. Valiyev and S. T. Boltayev, "Method and Algorithm of the Automatic Warning System of Train Approaches to Railways," in 2022 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 2022, pp. 532-538, [Online]. Available: https://doi.org/10.1109/ICIEAM54945.2022.9787181.

[18] A. R. Azizov and F. F. Shakirova, "Method for assessing the diagnosis of the technical condition of an integrated microprocessor pulse generator of railway automation and telemechanic," IOP Conference Series: Materials Science and Engineering, vol. 862, p. 052073, 2020, [Online]. Available: https://doi.org/10.1088/1757-899X/862/5/052073.

[19] A. D. Khomonenko and M. M. Khalil, "Quantum computing in controlling railroads," E3S Web of Conferences, vol. 383, p. 01010, 2023, [Online]. Available: https://doi.org/10.1051/e3sconf/202338301010.