Residual life management of cyber-physical transport systems

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Abstract. The article deals with the problem of assessing the residual life of robotic agricultural vehicles. This problem is inextricably linked to the organization of effective vehicle maintenance. The robotic vehicle has a multifunctional remote diagnostics system, which makes it possible to assess the probability of component failure in real-time. In virtual commissioning, simulation is the most appropriate tool for researching and finding effective maintenance solutions. A simulation model based on timed colored Petri nets is proposed. The structure of the model is given, and its modules are described. Research is carried out by the method of statistical tests on a simulation model. An example of evaluating the delays in executing a production task, depending on the maintenance procedures and the probabilities of robotic vehicle unit failures, is given.

1. Introduction
Modern trends in the development of industrial transport are associated with the creation of cyber-physical systems that use the Internet of Things for constant control and monitoring of vehicles [1, 2, 3]. The features of cyber-physical robotic transport systems are as follows: the presence of an on-board measurement subsystem with a large number of sensors, constant remote monitoring of operating modes and the technical condition of units, control of groups of autonomous vehicles. The high cost of robotic vehicles (RV) leads to the need to ensure reliability and maintainability. In this regard, the task of organizing maintenance and repair and management of the residual resource of RV is urgent [4]. The promising direction in the concept of Industry 4.0 is the transition from preventive maintenance to predictive maintenance, which reduces the probability of failure of robotic vehicles and reduced maintenance costs [5].

One of the new directions of transport robotics development is creating robotic systems for agricultural purposes [6, 7]. This is due to the complexity of the external operating conditions, increased loads, and the high cost of organizing the service. The authors of this article participated in creating a robotic agricultural vehicle system based on the KAMAZ 65111 chassis. As part of the research, the information system for controlling RV modes was designed, and several digital twins of the central vehicle units were developed [8, 9]. One of the new tasks is to organize a maintenance system for RV complexes using digital twins to obtain information about the aging, deterioration, and failure of its units and components.

Several works on predictive maintenance of complex technical objects are known [10-12]. The methodological base is the extensive use of simulation models of various types. A review of sources
shows that in many cases, it is efficient to construct simulation models of the maintenance process based on temporary colored Petri nets [13-15]. The researchers also note the advantages and convenience of simulating cyber-physical systems using various extensions of Petri nets [16-17].

This article presents research results in residual life or remaining useful life (RUL) management for agricultural robotic vehicles.

2. Organization of maintenance in the robotic vehicle cyber-physical system

The KAMAZ PTC project is focused on solving the problems of agricultural enterprises, in which the logistics processes are crucial and essential. It is necessary to consider the trends in automation, robotization, and the use of advanced intelligent technologies in agriculture and cattle breeding. At the same time, a situation arises when most of the central and auxiliary processes in agricultural enterprises are automated, and the logistics processes are still provided only with classic vehicles. In the context of a large-scale digital transformation of agricultural production, it is necessary to ensure logistics processes using robotic vehicles.

The main goals of the project are:

- transition to advanced robotic technologies in transport using neural networks and machine vision;
- development of a dispatching system for remote control of a group of agrotechnical robotic vehicles;
- providing car manufacturers and robotic car operators with information about the current and forecasted state of equipment to improve the efficiency of maintenance and repair.

Achievement of these goals is realized by solving the following tasks:

- development of a top-level information system providing forecasting sustainable and efficient logistics and fleet management, solving the transport maintenance of technological processes of agricultural enterprises;
- providing monitoring, control, and corrective measures to improve the reliability of the robotic chassis by identifying and predicting the technical state of elements;
- development of a communication subsystem that provides a stable network connection of the elements of a robotic system to ensure reliable and efficient robotic vehicle operation.

The developed robotic system of agricultural vehicles involves three levels of control:

- traffic control of the car park;
- motion control of a single robotic vehicle;
- control of units and assemblies of the robotic vehicles, assessment of their technical condition, and maintenance organization.

This article focuses on solving the third problem to ensure the required level of robotic vehicle reliability and reduce operating costs.

3. Tasks of managing the technical condition of a robotic vehicle

To solve this problem, within the framework of the upper-level system, modules for monitoring and predicting the technical condition of vehicles are provided (figure 1).

Figure 1 shows the data and control signal flows: $X$ is the information coming from the RV monitoring system, $U$ is top-level control information, $Z$ are the control actions on units and assemblies RV, $D$ is the vector of RV parameters for assessing and managing the residual life, $Y$ are corrective actions on the maintenance system of robotic vehicles.
The system for technical condition and residual life managing of the vehicle contains ideal models (digital twins) of the behavior of the parameters of the car, given during its design. The system for managing the vehicle's technical condition and residual resource contains ideal models (digital twins) of the vehicle behavior, given during its design. For the correct operation of the system, a mechanism is provided for adapting the pre-failure matrix, initially formed based on expert knowledge, taking into account the operation, maintenance, and repairs of similar vehicles, including similar elements, assemblies, and assemblies aggregates.

![Diagram](image)

**Figure 1.** The structure of the monitoring system and the technical condition predicting of robotic vehicles.

The residual life is determined by performing the following functions:

- evaluation and analysis of RV performance data by comparison with passport operating time,
- analysis of information on the dynamic parameters of transient and stationary processes,
- statistical data processing of diagnostic information in the control units of robotic vehicle aggregates and subsystems.

We describe a robotic car with a parameter vector $D_{RV}$, as suggested in [18]:

$$D_{RV} = (i, M, t_r, t_l, t_{tm}, t_s, t_m, ml, C),$$

where $i$ is RV unique identification number, $M$ is the model and modification code, $t_r$ is current vehicle operating time, $t_l$ is the residual life, $t_{tm}$ is the time to maintenance, $t_s$ is initial operating time, $t_m$ is the accumulated operating time of RV, $ml$ is the vehicle mileage, $C$ is the operating cost.

4. **Maintenance system simulation based on Timed Colored Petri Net**

The main simulation object is a robotic vehicle RV. The model structure is shown in figure 2. Each car is described by a vector of $D_{RV}$ parameters, represented in the TSPN places as a marker with a color set corresponding to expression (1). The $D_{RV}$ components can be changed during the simulation following the specified expressions on the net's arcs and places. The time durations of operations are set by assigning transition firing delays in the TSPN.

The operation cost $C_{MT}$ of a robotic vehicle consists of the following components.

1. The cost $MT$ of performing the production task operations, including the cost of the driver's wages and fuel cost.
2. The maintenance cost of RV in the mobile online service OM.
3. The cost of transporting the RV to a stationary service.
4. The cost of repair or maintenance in a stationary service.
5. The transferring cost of the RV to the reserve.

Table 1 describes the positions and transitions of the Petri net.

Table 1. Places and transitions of the Petri net.

| Designation      | Condition (for places) or action (for transitions)                                                                 |
|------------------|--------------------------------------------------------------------------------------------------------------------|
| RVC              | The markers denoted RV, assigned to perform a given production task                                                    |
| Reserve          | The markers denote reserve RV                                                                                       |
| PQ               | RV queue for maintenance or repair                                                                                   |
| Start, Finish    | Starting and ending positions of the Petri net                                                                       |
| Service Station  | Performing repair or maintenance operations in a stationary service                                                  |
| Online Service   | Performing minor repair operations in a mobile service                                                                |
| MT               | Execution of the production task                                                                                    |
| PrMR             | Generation of "Minor repair or maintenance" events                                                                   |
| PrHM             | Generating of "Failure or Major Maintenance" events                                                                  |

The expression for the $C_{MT}$ is a linear form with Boolean variables $x_i$, $x_j$, $x_k$:

$$C = \sum_{i=1}^{l} C_{MT} x_i + \sum_{j=1}^{l_{OM}} C_{OM} x_j + \sum_{k=1}^{l_{HM}} C_{HM} x_k,$$

where $C_{MT}$ is the cost of the normal execution of the production task MT, $C_{OM}$ and $C_{HM}$ is the cost of maintenance and repair in the mobile or stationary service; $i$ is numbers of production cycles of the MT task, $j$ is numbers of production cycles in which maintenance is performed in the OM service, $k$ is a number of production cycles in which the stationary service performs repairs after failures or predictive maintenance.

Boolean variables are equal to 1 in case of corresponding event occurrence during MT execution.
5. Experimental results
The implementation of the simulation procedure consists of the sequential-parallel firing of transitions with given initial markings and time parameters assigned to places, transitions, and arcs of the network. As a result of statistical tests, the researcher obtains several values: the average time for completing a production task, the average duration of the robotic vehicle being in various states, the variances of the studied values. The study of the probabilistic nature of the dynamics of project execution is implemented in the stochastic Petri net model by assigning the corresponding transitions or places the probability distribution laws for a given set of events.

For example, we consider evaluating the completion of production tasks on time using a robotic vehicle. For this, a key indicator is calculated, namely, the task completion delay ratio $\gamma$.

Figure 4 shows the graphs of the dependence of $\gamma$ on time $t_M$ of performing maintenance, the time $t_{mt}$ before scheduled maintenance, and the failure rate $\lambda$ of robotic vehicle equipment, distributed according to the Poisson law.

Task completion delay ratio is $Y = \frac{(t_a - t_{sh})}{t_{sh}} \times 100\%$, where $t_{sh}$ is the task execution duration according to the schedule, $t_a$ is the real-time of the task execution when the RV moves for repair and maintenance.

![Figure 4](image.png)

**Figure 3.** Graphs of the dependence of the task completion delay ratio at the failure rate: (a) $\lambda = 0.04 \times 10^{-3}$, (b) $\lambda = 0.1 \times 10^{-3}$; time $t_{mt}$ between maintenance: 1 - 100 hours; 2 - 200 hours; 3 - 300 hours.

The dotted line in the charts determines the range of permissible values of RV parameters, providing the condition delay of the task is not more than 10%.

6. Summary
The proposed method for assessing the residual life of a robotic vehicle makes it possible to conduct virtual tests as part of the virtual commissioning of vehicles into production. This approach is currently widely used in the creation of complex cyber-physical systems [19]. In our case, virtual tests on simulation models based on Petri nets allow at the design stage of a robotic system to check various configurations of products and play various scenarios of their maintenance.

The versatility and functional flexibility of timed colored Petri nets allow them to study complex dynamic objects characterized by stochastic behavior.

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