Digital tests of the robotic chassis’ cyber-physical system for agricultural unmanned vehicle

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Abstract. The report explored the problem of digital testing of a robotic agricultural vehicle. The approach to representing the robotic chassis as a cyber-physical system is to build a complex of digital models of units and built-in measuring tools for monitoring physical processes. Based on a model-oriented approach, a digital twin of a robotic chassis for diagnostics and forecasting was built. Information from the vehicle’s on-board measurement system is used to continuously correct model parameters. Models of a car driver, chassis, individual units, and subsystems have been developed. A car model with fifteen degrees of freedom is described. The simulation results for various scenarios of the movement of a robotic vehicle are presented. The simulation results were used in the design of the KAMAZ unmanned vehicle for agricultural purposes.

1. Introduction

A key trend in the automotive industry of recent years is the creation of automatic or robotic systems that can autonomously carry out movement without the participation of a driver.

The car is controlled either by the operator remotely or based on the specified route, adaptable to the environment. The robotic transport system (RTS) is now finding increasing applications in various fields [1]. From the first transport robots oriented to enclosed and well-organized spaces, there is a transition to autonomous robotic cars operating in natural conditions. One of these areas is the creation of RV for agricultural purposes [2, 3].

A robotic car is a cyber-physical system since its functioning is based on a combination of complex physical and information processes: physics of fuel combustion, mechanical motion, material fatigue processes, information processes, intelligent data processing systems, and motion control using technical vision [4, 5]. The construction of full-scale models in the design of such systems is costly and does not allow considering various scenarios and predicting the performance of the RTS.

In this regard, an effective way is the integrated use of digital models of aggregates and subsystems RTS and carrying a large amount of digital tests. Promising is a model-based approach that allows the diagnosing and predicting of the RTS performance using a study of the models of the main units and subsystems, representing as a single complex [6 - 10].
This paper solves the problem of creating a “digital twin” for unmanned robotic chassis and conduct comprehensive tests on models.

2. Robotic chassis digital twin based on mathematical models
Existing techniques, software systems, and modeling technologies allow you to create models of any technical systems. For this purpose, we use the phenomenology of the processes, engineering, operational parameters and wear both based on the empirical and technical data and in the process of conducting hybrid digital system tests.

Vehicle “Digital Twin” - is a single model with the maximum degree that adequately describes all the features of the object and the processes associated with its production [11]. It allows creating a highly adequate copy of the physical world, in which all data on materials, components, structural properties, operations performed, and operation characteristics of a robotic vehicle are recorded.

The robotic transport system implemented a model-based approach. The parameters characterizing the actual state of the RTS systems and units come from the on-board system. They are periodically compared with the parameters of the RTS models, taking into account the wear of components and environmental influences. By the deviation magnitudes of parameters from model values, the state of the RTS is assessed. The alert states of the systems and units are determined, and the residual life of the equipment and systems is forecasted.

Figure 1 shows the components of a complex model of car. Based on the analysis, the system generates recommendations for the RTS service personnel as a whole, regarding the timing of replacement of components, and the schedule of maintenance.

![Figure 1. The components of complex model of a car.](image)

3. Unit models of a robotic chassis
The report discusses several examples of developed models for the main RTS units. Under the vehicle chassis generally understood as a set of units of the running gear, transmission and control mechanisms. When constructing a digital twin, issues of modeling the axles of the chassis, car suspension, transmission, steering and braking systems were considered.

Figure 2 shows the chassis axles model of a KAMAZ car.
Differential equations of the model are presented in the form:

\[
\dot{\psi} = \frac{1}{l_y} (l_y (F_{y11} \cos \delta + F_{y12} \cos \delta + F_{x11} \sin \delta + F_{x12} \sin \delta) - l_y (F_{y21} + F_{y22}) + \frac{E}{2} (F_{y11} \sin \delta - \\
F_{y12} \sin \delta + F_{x12} \cos \delta - F_{x11} \cos \delta + F_{x22} - F_{x21}));
\]

(1)

\[
\dot{\beta} = -\dot{\psi} + \frac{1}{m V_y} ((-F_{x11} + F_{x12}) \sin(\beta - \delta) + F_{y11} \cos(\beta - \delta) + F_{y12} \cos(\beta - \delta) + F_{x11} \cos(\beta - \delta) + \\
(F_{x21} + F_{x22}) \cos \beta - (F_{x21} + F_{x22}) \sin \beta);
\]

(2)

\[
a_y = \frac{1}{m} (F_{x11} \cos \delta + F_{x12} \cos \delta + (F_{x12} + F_{y22}) + F_{x11} \sin \delta + F_{x12} \sin \delta); 
\]

(3)

\[
a_x = \frac{1}{m} (-F_{y11} \sin \delta - F_{y12} \sin \delta + F_{x11} \cos \delta + F_{x12} \cos \delta + F_{y21} + F_{x22});
\]

(4)

\[
\dot{V}_y = V_y \dot{\psi} + a_y;
\]

(5)

\[
\dot{V}_x = V_y \dot{\psi} + a_x;
\]

(6)

\[
\dot{V}_g = \frac{1}{m} ((F_{y11} + F_{x12}) \cos(\beta - \delta) + F_{y11} \sin(\beta - \delta) + F_{y12} \sin(\beta - \delta) + (F_{x21} + F_{x22}) \cos \beta + \\
(F_{y21} + F_{y22}) \sin \beta);
\]

(7)

where \(\psi\) – the angle of rotation around the transverse axle, \(\beta\) – the angle of deviation of the mass center velocity vector from the longitudinal axe, \(V_g\) – the speed of the car mass center, \(F_{x1}, F_{y1}\) – the longitudinal and transverse forces acting on the front and rear wheels, \(\delta\) – the steering angle, \(\alpha_x, \alpha_y\) – the lateral withdrawal angles of the front and rear wheels, \(l_y, l_x\) – the distance from the car mass center to the front and rear axle, respectively.

Expressions (1) - (7) are used in a complex cyber-physical model of an unmanned vehicle.
For modeling trucks with three or more axles, a separate simulation scheme is used. Each axle is modeled separately with the required number of wheels, drive and steering, and then assembled into a complex model. In this case, the axle is modeled as a solid of a given width, the mass of which can be neglected. The axle is considered to be rigidly connected with the car body and does not have its degrees of freedom. It is joined by models of wheels and suspension, as well as the brake system.

For a complex model, a set of individual models has also been developed:

- suspension model,
- steering model,
- model of the brake system,
- transmission model,
- wheel model.

Based on this set, structural elements were integrated into a single dynamic vehicle model. The operator then executed digital testing, further validation and use as a digital twin to check the calibration tables of algorithms for controlling the robotic chassis.

4. Digital tests

Digital tests designed RTS used software package LMS ImagineLab AMESim [12]. To solve the problems of developing car control algorithms, we chose a car model with 15 degrees of freedom. Figure 3 shows one of the components of a complex cyber-physical model, namely a transmission sub-model of a robotic chassis.

![Robotic chassis transmission model](image)

**Figure 3.** Robotic chassis transmission model.

Digital tests were carried out for different scenarios:

- Situation 1 - the dynamics of the truck movement during acceleration and braking on a flat road;
- Situation 2 - the truck movement when climbing a mountain with a constant slope of 25 degrees;
- Situation 3 - simulation of a lane change by a truck when driving on a horizontal surface and with a relatively steady speed mode;
- Situation 4 - braking mode when driving uphill under a set of conditions under which it becomes impossible to race, with the ASR connected.

Examples of simulation results are shown in figure 4 and figure 5.
Figure 4. Diagrams of the rotation frequency, engine shaft torque and gear shift signal (situation 1).

Figure 5. Diagrams of the rotation frequency, engine shaft torque and gear shift signal (situation 2).

5. Conclusion
The developed digital twin of the KAMAZ unmanned vehicle is used in the project of creating agrotechnical robotic cars. The main difference from the previously used models is a description of the mutual influence of the connections for all units and subsystems of the car, the use of a common database for storing models and the results of previous tests. This approach makes it possible to diagnose and predict the performance of the RTS in real-time, using measurement information from the on-board measurement system. Further development of work in this direction is associated with the identification of failure conditions, the management of maintenance of the RTS system, and the provision of repair and maintenance work.

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