Simulation of the automated motion of a robotic agricultural 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
The development of the agrotechnical industry is closely related to new developments in mechanical engineering. In industrial production, robots are actively used not only when performing various production operations, but also as vehicles in the shops and on the enterprise territory. The need to find new ways to develop the agricultural industry has also led to the creation of robotic vehicles and automatic control systems that can provide the functioning of vehicle groups [1]. The development of complex robotic vehicles involves solving consumer problems associated with blocking car traffic (roads, slip). It will also provide remote monitoring of the condition of vehicles and timely decision-making on maintenance and repair.

The KAMAZ robotic agricultural vehicle system (RAVS) is an integrated hierarchical system, at the lower level of which there are single unmanned robotic chassis (RS) [2-4]. The automated control system for a single RS motion along routes in the space of agricultural enterprises is one of the main subsystems of the RAVS. Designing such systems is performed using cyber-physical approach [5-6], is to establish RS models and digital twins.

Studies on modeling the automatic motion of unmanned vehicles are known [7-11]. However, the models used do not describe difficult operating conditions, including off-road. Behavior under severe conditions is investigated in the development of tracked vehicles. Nevertheless, the specificity of caterpillar tractors does not allow the use of these models in the design of the RS based on a KAMAZ.
family wheeled vehicle. Various digital RS models were described in [12-14], but they mainly relate to the organization of the RAVS control system at the upper levels, or to the study the vehicle individual component operation.

This article focuses on the development of mathematical models and digital tests for automated motion of robotic chassis based on the modified model KAMAZ 65119.

2. The problem of controlling a robotic chassis in various operating conditions
Robotic chassis (RS) agricultural vehicle system is designed to perform logistic operations in conditions of motion outside asphalt roads and solid surface roads under different climatic and weather conditions. Model discussed below remote and autonomous control movement RS describes tracking systems that implement a dynamically changing value, characterized dynamics vector RS as it moves along the route (coordinate, time, speed). The main objective is the organization of RS motion on roads with difficult terrain, with a variable adhesion coefficient and in various climatic and weather conditions.

The most difficult driving modes were considered when designing the RC:
- mud, mud with stones, ascent, descent and cross slope through the mud;
- loose soil, wet loose soil, ascent and descent, and cross slope along loose soil;
- sand, ascent, descent and cross slope on the sand;
- loose snow, ascent and descent, and cross slope along loose snow;
- ice, ice under loose snow, under snowdrifts, ascent, descent and icy transverse slope;
- ascent, descent and transverse slopes in a pond with a hard and muddy bottom.

The simulation takes into account the parameters defining the modes of adaptive multiply connected control system for the RS motion along the difficult relief trajectories:
- multiplicative power value to an engine crankshaft;
- the reduced torque on the crankshaft during acceleration;
- pitch and roll angles;
- average reduced car body vibration frequency;
- average reduced amplitude car body vibrations;
- change in resistance motion;
- change in braking;
- normalized rolling resistance moment of the wheels;
- environmental parameters: temperature, pressure, humidity.

Management of low-level RS systems is organized based on a multiply-connected system with the supervisory controller. The supervisor regulator determines the formation of tasks for separate lower-level systems in various conditions (weather, loads, soil types) during the implementation of remote and autonomous motion modes.

3. Mathematical models of robotic chassis motion
One of the main problems in the design of the robotic vehicle is to develop a mathematical model of the entire complex (chassis and robotics system) in order to conduct its digital testing.

Digital tests using a model of a robotic vehicle’s motion control system achieve the following goals:
- checking the functioning of the RS lower-level control subsystem;
- checking the functioning algorithms of the machine vision system;
- verification of decision-making system algorithms.

The self-driving motion of a vehicle as a solid is modeled on a horizontal, non-deformable, flat supporting surface, taking into account translational motion and rotational motion relative to the chassis’ mass center.

The mathematical model is as follows:
\[
\begin{aligned}
\alpha_x = & \frac{dV_x}{dt} - \omega_y V_y = \frac{1}{m} \left( \sum_{i=1}^{4} R_{xi} - mg \sin(\alpha) - P_{w_i} \right); \\
\alpha_y = & \frac{dV_y}{dt} + \omega_x V_x = \frac{1}{m} \left( \sum_{i=1}^{4} R_{yi} - P_{w_i} \right); \\
J_z = & \frac{d\omega}{dt} = \sum_{i=1}^{4} M_{shi} + \sum_{i=1}^{4} \overline{M}(R_i); \\
V_x = & \frac{dx}{dt} = V_z \cos \theta - V_y \sin \theta; \\
V_y = & \frac{dy}{dt} = V_z \sin \theta + V_y \cos \theta; \\
\omega_z = & \frac{d\theta}{dt},
\end{aligned}
\]

where \( m \) is the mass of RS; \( J_z \) is the inertia moment of the RS relative to the axis \( z \); \( V \) - the velocity vector of the chassis’ mass center; \( a \) is the acceleration vector of the chassis’ mass center; \( dV/dt \) - the relative derivative of the velocity vector; \( \theta \) - the rotation angle of the chassis relative to the axis \( x \); \( R_i \) - the vector of the interaction force with the soil acting on the \( i \)th wheel; \( P_{w_i} \) - the air resistance force vector; \( M_{nai} \) - resistance moment to rotation of the \( i \)th wheel.

The air resistance is usually estimated by the concentrated force, which is the result of the vector sum of all air resistance components applied at a point called the center of application. The air resistance force vector \( P_{w} \) is directed against the velocity vector \( V_c \) of the chassis’ mass center. The value of the air resistance force depends on the aerodynamic properties of the chassis, the speed of the chassis’ mass center and the properties of the air environment, and is defined as:

\[
P_{w_i} = c_x p_n F_{front} V_z^2 / 2,
\]

where \( c_x \) – chassis’ aerodynamic drag coefficient in the longitudinal plane, \( F_{front} \) - frontal sectional area of the chassis; \( p_n \) is the air density.

The frontal sectional area is determined approximately by the expression: \( F_{front} = k_{front} BH \), where \( k_{front} \) – the frontal sectional shape factor.

Normal reaction wheels for the case of overcoming the rise are redistributed due to the force of the air resistance, the rolling resistance moment of wheels, mass center acceleration and the gravity force:

\[
\begin{aligned}
\sum_{i=1}^{4} R_i = & \ mg \cos \alpha, \\
\sum_{i=1}^{4} R_{xi} + \sum_{i=1}^{4} M_{fi} + P_{w_i} H_w = & -mH_z (g \sin \alpha + a_z); \\
\sum_{i=1}^{4} R_{yi} + P_{w_i} H_w = & -ma_y H_z,
\end{aligned}
\]

where \( x_o, y_o \) – coordinates of the \( i \)th wheel in a moving coordinate system; \( H_z \) – the height of the chassis mass center; \( H_{wx}, H_{wy} \) – heights of the application point of air resistance forces in the frontal and lateral chassis projections.

Suppose that each wheel suspension is equivalent to an ideal linear spring with a stiffness \( k \), which does not resist lateral forces. We will neglect the body vibrations and let the following relations be satisfied for joint elastic element deformations:

\[
\begin{aligned}
R_{i1} / k = & z + x_i t g \phi + y_i t g \psi; \\
\cdots
\end{aligned}
\]

The system of equations for joint deformations can be transformed as follows:

\[
\begin{aligned}
R_{i1} / k = & z + x_i t g \phi + y_i t g \psi.
\end{aligned}
\]
\[
\begin{align*}
Ax_1 + By_1 - R_{11} + D &= 0; \\
... \\
Ax_4 + By_4 - R_{44} + D &= 0. \\
R_{12} - R_{21} + R_{31} - R_{42} &= 0.
\end{align*}
\]

Thus, four equations for one plane are obtained. From this, it follows that the ends of the vectors of normal reactions lie in the same plane. The joint solution of the systems makes it possible to determine the normal reaction value of the support base for each wheel at each modeling step. In this case, the acceleration values are used in the previous simulation stage. If, when solving the system, several negative \( R_i \) values (two or more) were obtained, then this corresponds to the robotic chassis overturning.

4. Simulation results

The following software environments: Matlab - Simulink, Amesim, and VisSim were used to implement the simulation of the dynamics of a single RF. As an example of using the presented approach, the article presents the modeling of the steering system. Figure 1 shows a simplified model of the RS steering gear system. A first-order integrator describes the steering system transfer function:

\[ W(s) = 0.0349 / s. \]

**Figure 1.** The components of the complex model of a car.

We are implementing an optimal speed system, necessary to assign a high gain (proportional component) and the coefficient of the integrating part. In this case, the coefficient of the controller differential part is zero or negative. Table 1 shows the coefficients of the PID controller depending on the driving conditions of the RF.

| Settings | Normal motion | Full load | Off road | Normal motion | Full load | Off road |
|----------|---------------|-----------|----------|---------------|-----------|----------|
| Kp       | 95 - 100      | 67 - 80   | 105 - 120| 90 - 95       | 55 - 70   | 96 - 100 |
| Ki       | 60 - 70       | 45 - 60   | 93 - 102 | 55 - 65       | 40 - 50   | 80 - 97  |
| Kd       | 0             | 0         | -10      | -7            | -12       | -15      |

**Table 1.** Coefficients settings PID steering system.

**Figure 2.** Model of the influence of roll, pitch and yaw angles on the RS dynamics.
The model of the influence of roll, pitch and yaw angles on the RS dynamics is shown in figure 2. Figures 3 and Figure 4 illustrate the simulation results for various modes of RS motion. Figure 5 shows the screen form of the model with graphs of parameters when the robotic chassis stops before an obstacle.

**Figure 3.** Time diagram of RS pitch angle.

**Figure 4.** Freeze frame animation of the RS rollover when turning.

**Figure 5.** Time diagram of RS pitch angle.
5. Conclusion
The models developed for self-driving agriculture vehicle KAMAZ are the basis for constructing a “Digital Twin.” The issues discussed above affect only automated control motion in difficult conditions. Moreover, the proposed models are part of a comprehensive model of an unmanned robotic chassis. Further development of research is proposed to be carried out in the direction of conducting field experiments. It will clarify the structure and parameters of the models, conduct verification of their adequacy.

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