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Modeling the Movements of Mobile Robots Designed for Locomotion over the Undeveloped Terrains

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Abstract

Objectives: The relevance of the study is determined by the demand for all-terrain transport vehicles for investigating various celestial bodies. In this regard, the article considers the issues of modeling all-terrain transportation robot locomotion, for example, lunar rovers and Mars rovers over complex topography and sandy soils. **Method:** Methodological approaches for solving this problem emerged in the last century in connection with the creation of self-propelled chassis of Soviet lunar rovers and Mars rover mockups in the USSR. Modern software allows getting more informative simulation results directly in the process of computer-aided design of new machines. **Findings:** The article presents the development of the model of interaction between the wheel and the supporting plane in the object-oriented modeling environment whose results coincide with the experimental and operational test data of planetary rovers. In particular, it is possible to visualize the motion of all-wheel drive transportation robot models with combined wheel-walking propulsor. Walking mechanisms of such a propulsor are also used to perform adaptive suspension functions when moving in the wheel locomotion mode. **Improvements:** Materials of the article are of practical value for experts designing mobile robots, planetary rovers and other wheeled vehicles who use the simulation results to develop design and control systems.

Keywords: Locomotion System, Mathematical Model, Mobile Robot, Object-Oriented Modeling, Planetary Rover, Wheel-Walking Drive

1. Introduction

Dynamic models in the classical theory the motor vehicle are based on the physical picture of the friction-tight pure rolling of traction wheels on a hard surface. During thrust-dynamic computations, this leads to single-mass design scheme, motion equation of which takes into account the rotating masses of wheels and transmission components.

Around the middle of the last century, due to the extensive development of all-terrain agricultural, military and special-purpose motor vehicles that are largely used off-road, on unprepared terrain, the pattern of interaction between pneumatic wheels and loose soils began to be studied. Traveling on such soils is inevitably connected with the longitudinal slippage of the traction wheels, the value of which depends on the angle of slope overcome and traction on the hook, and the direction and magnitude of the vehicle acceleration from steady speed.

Thus, depending on the terrain and the control mode, it is possible to move both with wheel spinning and skidding. In this period based on experimental studies of physical and mechanical properties (PMP) of deformable soils using various kinds of mechanical soil penetrometers and stamps Soviet[1-4] and foreign, primarily the US,[5] scientists proposed mathematical expressions to evaluate interrelated coefficients of full and free thrust, the difference of which is a locomotion resistance coefficient.

At the end of the 1960s, in connection with the beginning of works on creation of automatic (the USSR) and

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manned (the US) lunar rovers, the research front spread to study the issues of interaction between metal wheels and lunar soil. In both countries, completely independently of one another, ground channels are created for these purposes using mobile dynamometer equipment enabling to obtain functions of the above coefficients over the entire range of wheel spinning on loose soils.[6-12]

Some works[13-14] set out features of full-scale and mathematical modeling of planetary rover motion when traveling along an arbitrary profile to solve the problems of dynamic stability against overturning and to determine the dynamic loads on the chassis and container during vibration. The most consistent consideration of the issues of mathematical modeling of linear motion and rotation to solve the problems of the thrust dynamics of the wheeled and wheel-walking planetary rovers is given in [15-16]. Certain provisions of these works may serve as starting points for further development of simulation methods for design and configuration studies of new multi-functional research and adaptive locomotion systems.[17-18]

2. Concept Headings

The aim of the article is a brief analysis of methods for simulating the locomotion of the existing analogues of lunar and Mars rovers to assess the relevance of the accumulated backlog, as well as the presentation of contemporary approaches to modeling to improve the level of developing technical solutions at the early stages of the design of new, adaptive locomotion systems of planetary rovers. Materials of the article have been developed during the execution of the project No.14.576.21.0050 applied research.

The main features of the developed locomotion system for the Cosmonaut Assistant Robotic System (CARS) are determined by the rotation method, types and characteristics of propulsion, traction drive and suspension. Within the project a locomotion system (LS) with kinematic rotation was selected, consisting of four locomotion modules (LMs), each of which is connected with the frame. A dual-arm manipulator system described in[19] (Figure 1) is also installed on the frame.

Each LM includes a rigid wheel with the traction drive that is built into its hub connected with the suspension by means of two-lever equal-arm walking mechanism (WM) of special design providing the WM ability to operate either in wheeled walking mode or in active (adaptive) suspension mode.

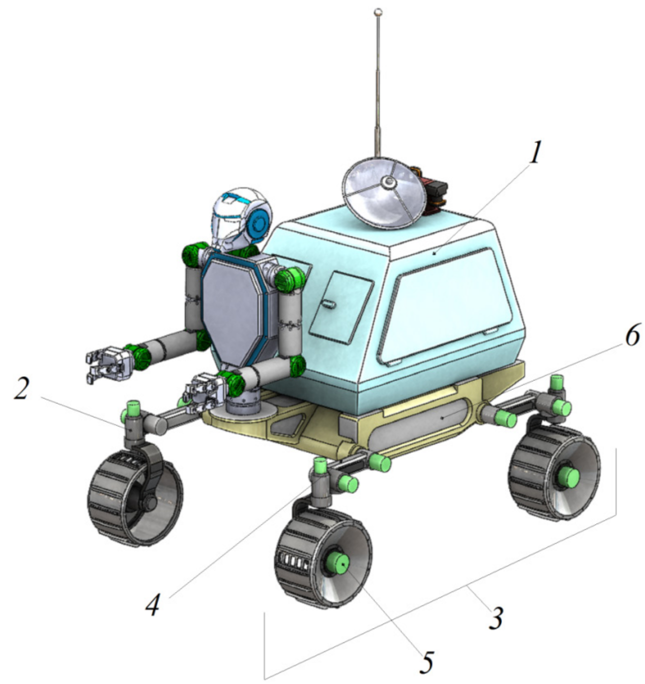


Figure 1. The components of Cosmonaut Assistant robotic system: 1 - container with detachable equipment; 2 - locomotion module; 3 - locomotion system; 4- two-lever walking mechanism; 5 - motorized wheel; 6 - locomotion system frame.

3. Methodology

3.1 The Features of Mathematical Modeling of Planetary Rover Locomotion

Mathematical model of a planetary rover includes three components: computational schemes, motion equations, algorithm and software for their computerized solution. Computational schemes of the Soviet lunar rovers (Figure 2), developed considering the results of their successful operation on the Moon take into account the axle configuration, airborne rotation, dissipative elastic container couplings with rigid wheels and independent electromechanical traction drives that are built into its hubs.[15]

Figure 2 shows: m-full weight of planetary rover, g- gravitational acceleration, R_{zi}, R_{yi} - normal and cornering force of the ground, P_{ki}, P_{fi}, M_{fi}- pulling force, locomotion resistance force and reactive torque, respectively, normalized to the rover housing assembly.

The mobile system of coordinates x, y, z (Figure 3) is connected with the center of mass of the planetary rover, x-axis coincides with a longitudinal symmetry axis, y-axis can generally be offset from the transverse symmetry axis by a value of Δx. The stationary XY coordinate system is connected with the supporting plane so that the X-axis coincides with the direction the maximum ascent angle, and the Y axis is directed to the left. The angular travel of the lunar rover on the supporting plane is described by the course angle Θ which is measured from the axis X.

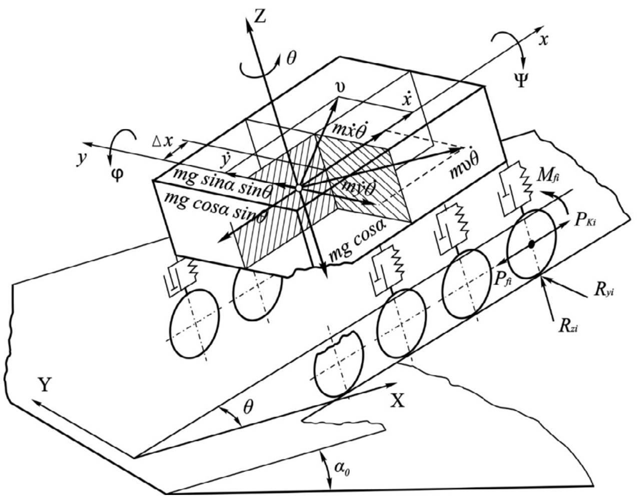


Figure 2. Calculated dynamic diagram of lunar rover with 8x8 wheel configuration and independent elastic wheel suspension.

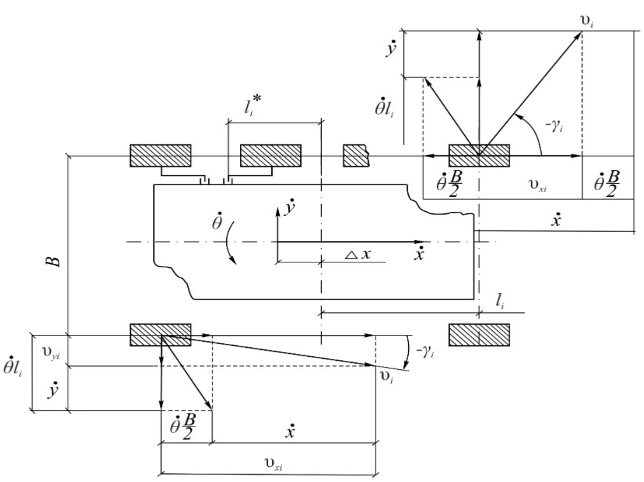


Figure 3. The i-th wheel velocity calculation scheme: O_1 - the chassis geometric center projection on the supporting plane, O - lunar rover center of gravity projection.

Design of suspension mechanisms with an elastic element in the form of the torsion rod allows realizing three degrees of freedom of the spring-suspended section - normal linear movement to the supporting plane (z) and angular displacements (ψ, φ) with respect of the longitudinal (x) and lateral (y) axes of the mobile coordinate system connected with the center of mass. Elastic torsional moments of suspensions (M_{yi}) depend only on the normal reactions.

The key issue of simulation is consideration of real characteristics of the interaction between the wheels with the lunar regolith characterized by low strength under the action of normal and tangential loads.

The application of torque to the wheel results in the appearance of elementary normal and tangential responses of soil on the surface of interaction. To formalize this interaction, when reducing responses to the wheel axis in the coordinates of the direction of motion, a conventional friction clutch was proposed as the new, at that time, structural element of the design scheme $\Psi(S)$.

Using the clutch in the model design leads to eight identical design schemes of motorized wheels (Figure 4), the axes of which are connected with the spring-suspended section through independent suspensions and their rims interact with the supporting plane. Here i is an ordinal number of motorized wheel: i =1, 2….n, where n – number of motorized wheels. Engine rotor with reduced to it masses of reduction gearbox J_D and wheel J_K have a connection characterized by torsional rigidity cg, dissipation coefficient b_g, angular freeplay $\varkappa$ and gear ratio ug. Engine torque M_{DI} braking torque T_1 are applied to the engine shaft.

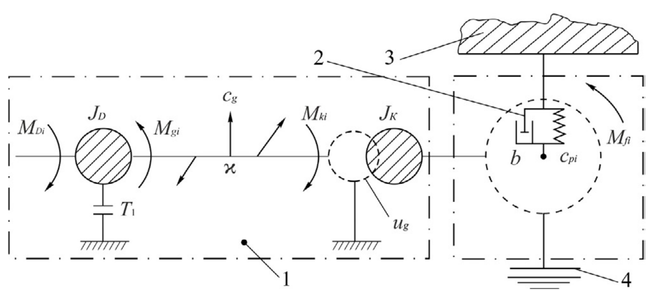


Figure 4. Calculated dynamic diagram of ani-th motorized wheel 1 - electro-mechanical drive; 2 - suspension; 3 - spring-suspended section, 4 - conventional friction clutch connecting the wheel rim with the ground.

The most reliable way to determine the properties of conditional friction clutch $\Psi(S)$, is, in our opinion, to test a single wheel in a ground channel using analogs of lunar soil. Despite the diversity of designs of dynamometric trucks, methods for simulating normal loads on the wheel and traction simulation on the hook, the test results allow accurately determining the dependencies of coefficients of full and free (Ψ и k_T, respectively)traction of the wheel on the value of the spinning coefficient (S_b). Dependencies of the form of $\Psi(S_b)$ and $k_T(S_b)$ can be called the generalized responses of the "wheel - soil" pair:

It is not possible to measure the locomotion resistance coefficient f by direct methods, but it can be determined as a difference:

$$f = \Psi - k_T. \tag{1}$$

When studying a curved path, the dependence of the lateral shift resistance coefficient μ on ɣ angle should be added to the enumerated characteristics:

$$\mu = R_Y / R_z. \tag{2}$$

Generalized responses completely define the external forces acting on the planetary rover propeller on the part of soil:

$$P_{\kappa i} = R_{Zi} \cdot \Psi_i(S_b),\ P_f = R_{Zi} \cdot f_i(S_b),\ R_Y = R_{Zi} \cdot \mu_i(\gamma_i). \tag{3}$$

In the All-Russian Research Institute of transport machine building VNIITransmash wheels of Lunokhod-1 and its experimental mockups were tested in the ground channels even in a flying laboratory with a short time (25 - 30 s) simulation of the gravitational field of the Moon, at the gravitational acceleration $g_л$=1,62 m/s^2 (Figure 5)[19].

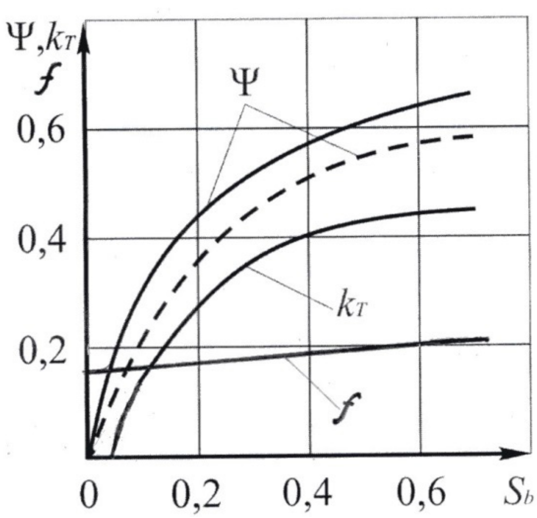


Figure 5 . View of generalized frequency responses $\Psi(S_b)$, f (S_b) during testing the Lunokhod-1 wheel on quartz sand (dashed line - during the Moon's gravity simulation).

It should be taken into account in the simulation that the most accurate results of the experiments in the ground channels are obtained with spinning ratios not exceeding approximately S_b = 0.8. With further increase of spinning, as well as with small spinning close to zero, edge effects manifest themselves. Therefore, to describe the functions $\Psi(S_b)$ and $k_T(S_b)$ in these areas power functions are often used. At a first approximation function $f_i(S_b)$ can be approximated by a linear function of the form:

$$f_i = f_0 + k' \cdot S_b \tag{4}$$

f_0 and k' are determined experimentally

The motion equations of dynamic multi-mass spatial system obtained with regard to the totality of relations of its components, based on the Lagrange equations of type II, as well as simulation results are discussed in detail in [15].

Design parameters of the lunar rover model which was aimed at assessing the marginal load-carrying capacity of the self-propelled chassis, available in[15], differ from the actual parameters of the Soviet lunar rovers in terms of inertial parameters. In particular, the total mass of the Lunokhod-1 was 756 kg and that of Lunokhod-2 was 840 kg. All other parameters of the model correspond to the design and characteristics of the self-propelled chassis of Lunokhod 1 and Lunokhod-2.

The calculations based on test results in ground channels assumed that the functions (3) do not depend on the number of wheel passages at a first approximation.

As an example of simulation results, Figure 6 shows the curves of torque variation when traveling in the start-stop mode on the front (i = 1) and aft (i = 4) wheels. The motion was simulated during the ascent α = 10°, on the ground with the locomotion resistance coefficient f = 0.12, where the full thrust ratio at the maximum ascent angles reaches Ψ = 0.67.

This roughly corresponds to one of the physical models of the lunar soil, representing pulverized pumice. In the period of time of 0-2 seconds acceleration from steady speed and motion at the first speed is simulated, during 2-5 s simulation refers to shifting to the second gear and to the first gear during 5-6 s.

The simulation results showed that the consideration of the wheel spinning significantly affects the nature of locomotion of the lunar rover model. In the absence of wheel rotation speed control, each motorized wheel operates in the individual power and speed modes. They are characterized by a significant redistribution of torques at the wheels when driving on slopes, reduced dynamic overload when starting up and shifting gear as a result of wheel slippage. The speed of lunar rover motion depends on the ascent gradient and is determined by aft wheels.

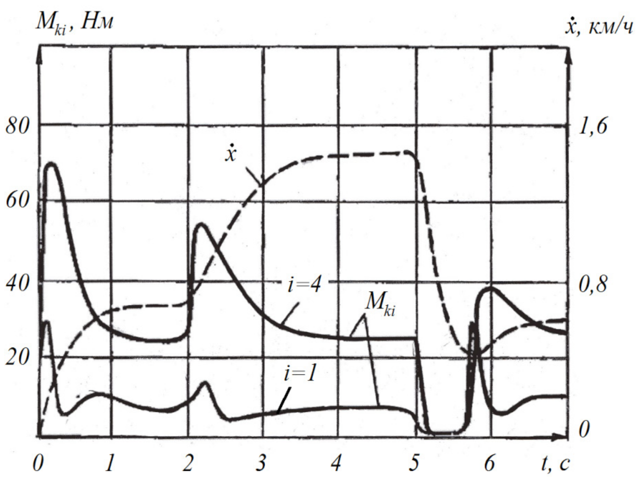


Figure 6. The results of modeling the dynamic loading of the motorized wheel drives –for the front and rear wheels during the ascent at α =10°.

Thus, developed in the last century mathematical modeling methods allow taking into account design features of planetary rovers and all the essential characteristics of their interaction with the environment in the "terrain-vehicle" system. The proposed approaches to the development of design schemes, including wheel non-holonomic constraint equations with deformable soil, remain relevant. However, algorithms, software and the entire methodology of computer modeling of planetary rover locomotion, design appearance of which is initially created by digital methods must undoubtedly conform to the modern level.

3.2 The Features of Computer Simulation Modeling

Modern practices of modeling the operations of the complex technical systems that include, as they do in our case, such different types of interrelations as mechanical, electrical, and informational ones, most commonly employ two widely accepted approaches to developing the model, namely, the block-oriented and the object-oriented approaches. Both of these approaches are founded on applying the unified modeling languages (UML).[20]

The use of block-oriented modeling is a powerful tool for simulation of mathematically "well" described systems, but often in the study of complex, multi-component objects and factors influencing them, this type of simulation modeling is not advisable.

Thus, for example, a block-oriented model of Cosmonaut Assistant Robotic System developed in the framework of the project,[17,21] in practice "grows" to a large number of blocks, which seriously complicates the applied design and configuration studies.

The basis of object-oriented models is formed by the blocks representing mathematical models of objects, which gave the name to the method. This allows using well-established software during model preparation that does not require another mathematical description. Since the quantity and quality of models is continuously increasing, their range of choice is very wide: from the solid state to the model of a vehicle, and the results obtained are in no way inferior the analytical solution.[21]

To test the adequacy of the method applied to one of the important practical problems of estimating the distribution of normal reactions and, consequently, the traction forces per planetary rover wheels, a self-propelled chassis model of Lunokhod-1 was developed as part of the project. In particular, we have used a model of elastic-damping interaction of wheels with a flat supporting plane, which changes its position relative to the horizon.

An indisputable advantage of the object-oriented modeling lies in the fact that 3D models of the objects developed with CAD systems and saved as one of the standardized formats can be used as the models of solid bodies. Thus, all mass and inertia characteristics of parts and assemblies can be imported automatically into the simulation modeling environment, which would considerably accelerate development and improve the precision of the identity of the design and its simulation model.

In addition, in all kinds of object-oriented modeling the simulation process is accompanied by a three-dimensional dynamic visualization of the object behavior, which further extends the capabilities of designers and researchers to analyze and understand the essence of the processes occurring during the locomotion.

In[22], where the general approaches to the formalization of design schemes and algorithms are considered, all bodies interacting on the plane are called polygons. The form of the interacting bodies is defined by entering the coordinates of points on the plane.

The block that simulates the contact of the wheels with the supporting surface, uses a model of elastic-damping interaction between the two bodies, with basic set parameters being:

k_A – stability factor for contact area, having unit of measurement N/m^2;

b_n – normal-directed damping factor, N·s/m;

μ_τ – tangent-directed friction factor.

The program computes the array of points that form the contact area of two bodies of arbitrary shape. Contact force has two components F_n and F_t, acting in the normal and tangential direction, respectively. This model of a contact in the "pure form" is not suitable for simulating wheel motion on the lunar soil, as they do not reflect the physical characteristics of interaction between such soils and rigid wheel of lunar and Mars rovers described in[16] and in the previous section of this article. In particular, it does not consider irreversible soil deformation and road resistance forces arising in this case.

However, in this simulation it is also possible to use dependencies of full thrust coefficient and locomotion resistance coefficient on the spinning ratio, an example of which is shown in Figure 6.

At a first approximation, these functions for interaction under consideration may be written as:

$$\psi\left(S_b\right) = 0,1 + 0,8(1 - e^{-\frac{S_b}{\tau}}) \tag{5}$$

where τ – a constant assumed to be equal to 0.3.

$$f\left(S_b\right) = 0,15 + 0,08 \cdot S_b \tag{6}$$

and the appropriate traction and locomotion resistance forces are defined by formulas (3).

To determine the actual speed of the "Lunokhod-1" model an odometer block is added in the diagram of object-oriented model.

4. Results

The adequacy of the designed model was assessed by the wheel weight load factor $i - \text{го}$ which is an actually implemented dynamic factor of this motorized wheel when driving on a real road or in the simulation of such motion[7,15].

The motion and modeling begins on the level ground, then the angle of slope of the supporting plane uniformly increases to 25°. The initial and final position during the simulation visualization are shown in Figure 7.

The results of object-oriented modeling are shown below (Figure 8), they largely coincide with the results of Lunokhod-1 on-board telemetry data processing.[8]

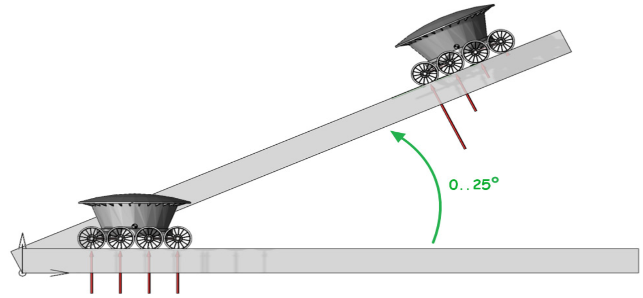
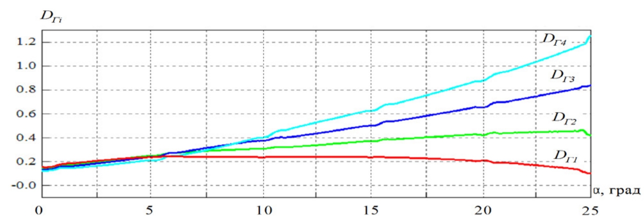
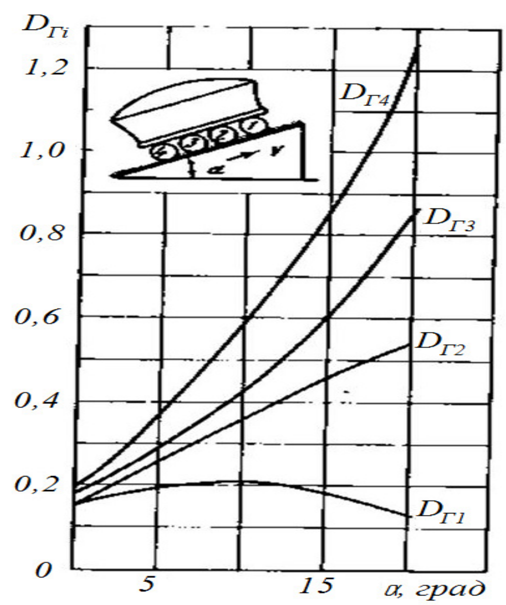


Figure 7. Initial and final position during visualization of Lunokhod-1 locomotion process modeling.



(a)



(b)

Figure 8. Comparison of dependency of the motorized wheel load factors on the angle of ascending: a - object-oriented modeling results; b - results of Lunokhod-1 experimental investigations.

As seen in Figure 8, the designed model of interaction between the rigid wheels and the soil is adequate to the real process of redistributing weight load factors of motorized wheels on one side when overcoming ascents of varying steepness.

Thus, the designed model can be used for further research of CARS locomotion system and obtaining reliable results with its help.

The design principles, the supporting plane of the CARS locomotion system model and assumed simplifications are identical to those discussed in the previous section. Figure 9 shows the visualization window with reference to the modeling time.

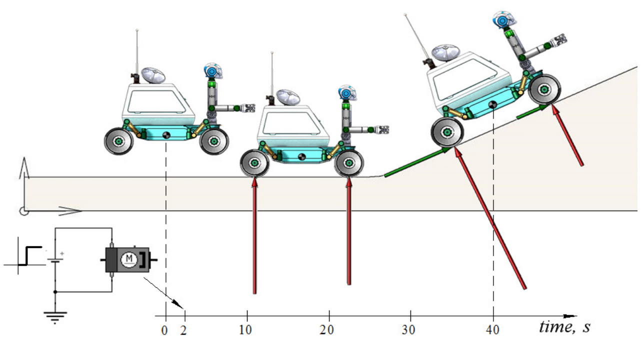


Figure 9. Modeling time-referenced visualization window

Figure 10 shows the results of LS modeling on the soil model proposed in the previous part which corresponds to Figure 5. Since at the time of the wheel contact with the soil it is of an impact nature, there are big jumps in the normal responses and a certain dynamic process, fading approximately by the second of the simulation.

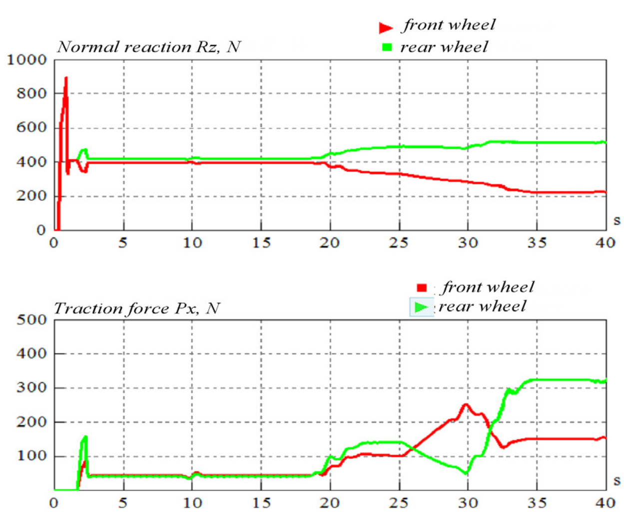


Figure 10. The results of simulating the locomotion system traveling on a flat and sloping surface with regard to the developed soil model.

Start of engines at the 2nd second causes a small multi-directional surge of normal reactions and thrust which do not exert a noticeable impact on the motorized wheel weight load redistribution on the level surface, at low load and hence reactive moments.

In 20 seconds after the simulation the LS starts entering the ascent overcoming mode. At the same times the loads and differences in the performance of the front and aft wheels increase.

5. Discussion

The result of this article is a designed model of the interaction between the wheel and supporting plane in the object-oriented modeling environment.

The designed model reflects the nature of the wheel interaction with the loose soil when wheel slippage creates extra traction. The obtained results differ from the already known ones as they bring together the enormous experience (both theoretical and experimental), accumulated since the beginning of the active study of the theory of the motor vehicle wheel motion, and advanced features of computer simulation.

The obtained results are largely consistent with the results of experimental studies, which suggests that the developed model is credible and adequate and can be used for future research of planetary rover being developed in the framework of the project.

6. Conclusion

As well as the methods of studying many complex technical systems, modeling of planetary rover locomotion switches from mathematical methods, when electronic digital computers helped the researchers to perform large amounts of calculations, to computer simulation, when the study of the properties of new objects takes place in the software environment of the same or a nearby computer, in which the object was created.

The advantages of the new methods, such as the object-oriented modeling method, include a high operational efficiency of the model creation, less time consumption, the possibility to visualize the occurring process, the possibility to import objects from CAD systems, which is essential at the early stages of design and development of technical solutions on an alternative basis.

At the same time the approaches to the development of design schemes proposed earlier and taking into account the peculiarities of planetary rover design and interaction with the environment in the "terrain-vehicle" system remain relevant.

The presented models will further allow analyzing the behavior of the CARS locomotion system when traveling not only in the wheel mode, but in the mode of adaptation to the uneven surface. Further development of the model involves adding different detachable equipment to the model and studying the behavior of the entire robotic system as a whole.

7. Acknowledgements

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