

Numerical Method of Designing an Automotive Driving Simulator for Training Drivers of Motor Vehicles

Larisa Rybak^{1,*}, Andrey Hurtasenko¹, Valeria Skitova¹ and Artem Voloshkin¹

¹Belgorod State Technological University V.G. Shukhov, Belgorod, Russia

Abstract. The paper presents the results of numerical simulation and design of an automotive driving simulator for training drivers of motor vehicles, which includes a six-stage dynamic mobility platform and an integrated system of virtual 3D models of real terrain using the software and hardware system "Route". On the basis of the developed mathematical model of the dynamic platform, optimization of geometric parameters was performed, various configurations of the platform were analysed. Optimization was performed using the PSO (Particle Swarm Optimization) heuristic algorithm. A digital twin of the platform has been developed in the MSC Adams (Automated Dynamic Analysis of Mechanical Systems) software package. The resulting digital twin has the properties of complete identity with the real prototype. A prototype of an automotive driving simulator is presented, which is equipped with a system of virtual 3D models of real terrain. The results of mathematical modelling, as well as experimental studies of the prototype are presented, which made it possible to evaluate its capabilities and characteristics.

1 Introduction

Currently, various simulators are increasingly being used to teach professional vehicle driving skills. A number of developments in the field of vehicle control simulators are aimed at obtaining high-quality, realistic images using virtual reality and neural network algorithms [1, 2, 3]. Another direction is the development of a physical environment of the driver, which repeats the cockpit of a real vehicle with all controls [4, 5], which is a whole automotive driving simulator for training a driver or pilot. The specifics of piloting aircraft are one of the areas in which dynamic simulators are actively being developed, including for remote control [6, 7, 8]. One of the means that can provide the required motion parameters is parallel mechanisms, thanks to such advantages as high rigidity, accuracy, load capacity and low manufacturing cost. The Gough-Stewart platform has a number of advantages, which justifies its use in various simulators and simulators. There are many configurations of the Gough-Stewart platform and mechanisms based on it. In each of the configurations, the platform includes 6 rods of variable length, however, the number of joints of the base and the moving platform may be different. The article [9] discusses the design of a 6-RUS configuration for

* Corresponding author: labbgtugos@gmail.com

a flight simulator and optimization of geometric parameters taking into account the physical limitations of the mechanism. Studies on simulators based on the Gough-Stewart platform are known and reviewed in a number of papers that investigate the effect of pitch and roll on the effectiveness of training using a sample of test subjects [10, 11]. Other studies are aimed at investigation of vibration effects that occur when driving vehicles in all environments [12]. As well as work aimed at improving lateral acceleration and lateral movements, rolls and yaw for a better perception of one's own movement, by eliminating errors of simulation models and improving the quality of control [13-15].

Analysis of existing solutions of automotive driving simulators allowed to show that most of them are used as flight simulators; for training drivers of ground vehicles, simulators based on either three-stage platforms or stationary ones for simulating a cab or a driver's seat are used mainly.

In this regard, there is a problem of developing effective automotive driving simulator that provide simulation of a vehicle at all six coordinates in space with the possibility of working out the required dynamics of the movement of a real vehicle, taking into account the terrain and geography of the real terrain in the city or beyond. The research presented in this paper is aimed at developing methodological foundations for the design of automotive driving simulator based on modern methods of numerical simulation and CAD/CAM design.

2 Mathematical model of the Gough-Stewart platform

Let's consider the structure of the Gough-Stewart platform (Fig. 1). The platform has 6 kinematic chains that connect the fixed base to the moving platform by means of linear actuators (L_i) and universal joints at the bases (A_i and B_i). Depending on the configuration, the number of joints of the base and the moving platform can vary, and their location can be either free or on circles of certain radii.

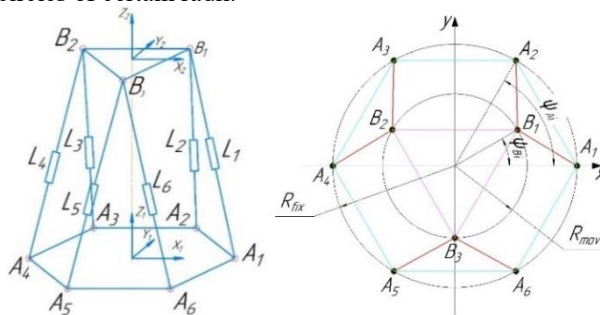


Fig. 1. 6-3 configuration of the Gough-Stewart platform.

The solution of the Gough-Stewart platform inverse kinematics for the input L_1 coordinate is written as

$$L_1 = \left((A_{1x} - B_{1x})^2 + (A_{1y} - B_{1y})^2 + (A_{1z} - B_{1z})^2 \right)^{1/2} \quad (1)$$

where B_{2x}, B_{2y}, B_{2z} – point coordinate B_2 in the coordinate system $X_1Y_1Z_1$ a fixed platform. The values of the other input coordinates are determined in the same way. Coordinates of points B_i defined as

$$\mathbf{B}_i = (B_{ix} \ B_{iy} \ B_{iz} \ 1)^T = \mathbf{M} \cdot (B_{ix}^{(2)} \ B_{iy}^{(2)} \ B_{iz}^{(2)} \ 1)^T \quad (2)$$

where $B_{i_x}^{(2)}, B_{i_y}^{(2)}, B_{i_z}^{(2)}$ – point coordinate B_i in the coordinate system $X_2Y_2Z_2$ mobile platform, \mathbf{M} – the transformation matrix for the transition from a movable to a fixed coordinate system. To compile the transformation matrix, we use Euler angles (α, β, γ) .

We introduce the following notation: $c_\alpha = \cos(\alpha)$, $s_\alpha = \sin(\alpha)$, $c_\beta = \cos(\beta)$, $s_\beta = \sin(\beta)$, $c_\gamma = \cos(\gamma)$, $s_\gamma = \sin(\gamma)$. In this case, the transformation matrix \mathbf{M} write it down as

$$\mathbf{M} = \begin{pmatrix} i_x & j_x & k_x & O_x \\ i_y & j_y & k_y & O_y \\ i_z & j_z & k_z & O_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_\alpha c_\gamma - c_\beta s_\alpha s_\gamma & -c_\gamma s_\alpha - c_\alpha c_\beta s_\gamma & s_\beta s_\gamma & O_x \\ c_\beta c_\gamma s_\alpha + c_\alpha s_\gamma & c_\alpha c_\beta c_\gamma - s_\alpha s_\gamma & -c_\gamma s_\beta & O_y \\ s_\alpha s_\beta & c_\alpha s_\beta & c_\beta & O_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

where O_x, O_y, O_z – coordinates of the center O mobile platform in the coordinate system $X_1Y_1Z_1$.

The parameters of the mobility platform were optimized based on the evolutionary algorithm of the particle swarm (Particle Swarm Optimization (PSO)). The range of orientation angles of the platform is accepted $\alpha \in [15^\circ; 15^\circ], \beta \in [15^\circ; 15^\circ], \gamma \in [15^\circ; 15^\circ]$. Optimization parameter ranges: $\psi \in [30^\circ; 100^\circ], \omega \in [30^\circ; 100^\circ], R_1 \in [200; 500], R_2 \in [200; 500], L_{min} \in [100; 500], L_{max} \in [200; 1000]$, where R_1 is radius of a fixed platform, R_2 is radius of a fixed platform, l_{min} and l_{max} are limit values for changing rod lengths, ψ and ω the angles of the relative position of the joints. The limitation of optimization is the condition of providing the required workspace, and the criterion function is obtained based on the condition of ensuring the compactness of the structure. As a result of repeated optimization, 10 possible platform configurations were obtained. In all tests, the radius value R_2 the mobile platform tends to the lower boundary. Also, in four out of ten tests, the minimum or maximum limit for the angle parameters was reached ψ or ω . The best value of the criterion function is obtained with the following parameters: $R_1 = 285.853, R_2 = 200, \psi = 30, \omega = 32.516, L_{min} = 433.094, L_{max} = 714.504$.

3 MSC Adams simulation

The obtained parameters of the lengths of the drive rods, the radii of the base and the movable platform and the angles determining the location of the joints were used to develop a digital twin using the MSC Adams software environment (Fig. 2). For convenience, the model is made in a cylindrical coordinate system, thus the points of attachment of the joints to the base and the working platform are set when using the radius of the circle (BD_R, TU_R) and the angle ($\phi_{01} - \phi_{60}$). External influences acting as force loads on the platform are the gravity G and payload PL specified in the model.

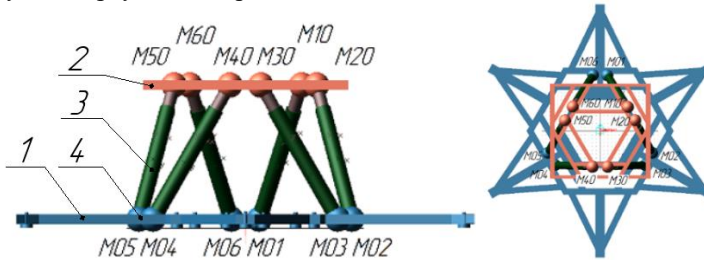


Fig. 2. a) - Parameterized 3D model of the Gough-Stewart platform (1 - base; 2 - moving platform; 3 - actuator, 4 – joint); b) - Variable parameters of the 3D model.

To simulate the operation of the model in 6 translational pairs simulating actuators, translational movements were developed using the Translation Joint Motion software operator, which implements the laws of linear displacement in the MSC Adams application.

To test the model, sets of trajectories with parameters reflecting the operational capabilities of the platform were used. The selected trajectories reflect the kinematic capabilities of the platform to realize various options for moving the object being installed. At the same time, the cases of the most loaded state of the studied structural elements are taken into account.

4 Simulation results

To test the model, 5 primitive types of trajectories were worked out. The initial (initial) position for all types of trajectories is the position in which the movable part of the platform is in a horizontal position, the geometric centers of the base and the movable part are on the same vertical line, the zero initial position in height is the minimum possible position of the upper platform, based on the technical requirements for the platform, this is 900 mm above the floor level with a weight of 600 kg. As a result, a velocity graph was obtained (Fig. 3), and the actions of the resulting forces on the joints (Fig. 4).

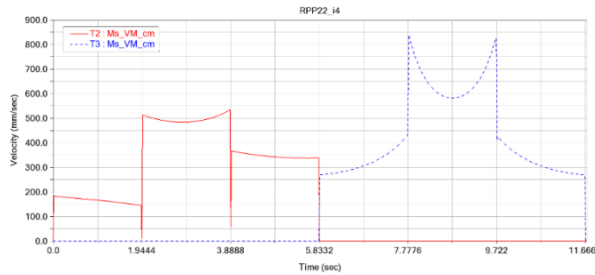


Fig. 3. Change in the resulting velocity of the center of mass when performing trajectories.

Sudden jumps and drops in speeds are due to the fact that when working out the completion of the movement on the site, all the actuators stop. Peak values of the resulting velocity occur when working out the trajectory No.3. Peaks of the resulting acceleration appear during acceleration and deceleration of the platform. The peak of acceleration of the center of mass occurs when working out the trajectory No. 3. At this site, all six actuators work, three of which (A22, A33, A55) work for elongation, and the other three (A11, A44, A66) work in the opposite direction.

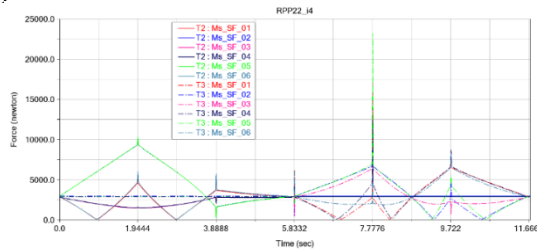


Fig. 4. Changing the resulting force values in the joints of the base M01-M06 when working out trajectories.

The greatest peak of the resulting sum of forces applied to the joint occurs when working out the trajectory No. 3 (similar to the maximum peak of acceleration). The maximum value

of the resulting sum of forces falls on the joint of the support M05. The greatest peak of the resulting sum of forces applied to the joint occurs when working out the trajectory 3 at time $t = 7.78$ s. In accordance with the digital twin of the platform, a prototype of an automotive driving simulator with an integrated system of virtual 3D models of real terrain (Fig. 5a), which includes a simulator and an operator console, has been developed. The operator's console allows to launch a dynamic platform, set a terrain map, install the driver's virtual car at a given point on the map, as well as track violations during the passage of the site. The characteristics of the prototype are shown in Fig. 5b



Fig. 5. a) a prototype of an automotive driving simulator with an integrated system of virtual 3D models of real terrain; b) technical characteristics of the automotive driving simulator.

Several tracks with different surface slopes were selected for testing the simulator. In accordance with the tilt of the virtual model, the roll and pitch changes of the dynamic platform were compared. In the simulation there are surfaces, the movement on which assumes a greater slope than the technical characteristics of the platform allow. In such conditions, the platform reaches the extreme position of the calculated workspace and stops. Other tests of the platform are aimed at achieving the maximum speed of the platform. As a result, the platform's actuators reached maximum speed. It is impossible to achieve a high speed with the power of simulation due to the established limitation.

Test runs were carried out in the simulation of the polygon, where there are obstacles of varying complexity, such as a slide and a railway crossing (Fig. 6a). Figure 6b shows test runs on the road in a simulation of urban conditions. In the city, a simulation of the flow of traffic is reproduced, in which the movement of cars occurs at different speeds. Installed traffic lights regulate the order of passage of the intersection.



Fig. 6. Test runs: a) - at the training ground; b) - in urban conditions.

5 Conclusion

Based on the obtained mathematical model, the geometric parameters of the Gough-Stewart platform were optimized, taking into account the minimization of dimensions and restrictions on the required workspace and singularities of the platform. In accordance with the obtained geometric parameters of the location and the lengths of the links, a dynamic model in the MSC Adams software package and its digital counterpart have been developed. The greatest peak of the resulting sum of forces applied to the joint occurs when working out the trajectory 3 at time $t = 7.78$ and is 23.17 kN . Based on the results of simulation and

unification conditions, a selection of drives and cardan joints was made. A prototype of the automotive driving simulator was made and tests were carried out. The automotive driving simulator is equipped with a system of virtual 3D models of real terrain using the software and hardware system "Route". Experimental studies of the prototype allowed to evaluate its capabilities and characteristics, adjust control algorithms.

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