Design of an electro-pneumatic driving simulator

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Abstract. The paper discusses the construction of a car driving simulator prototype. The basic design assumptions for the mechanical structure of the simulator platform as well as the drives and control system are presented. A solid model of the device was presented and a solution to its kinematics was proposed to determine the stroke of the driving cylinders as a function of the angular displacement of its members. The issues related to virtual prototyping to determine the trajectory of movement and dynamic quantities characterizing the simulator were presented. The construction of the control system with the use of a dedicated computer control card is discussed. Such a solution enables testing the functions of the simulator control system before its connection with the real simulator. At the same time, the design process has been significantly improved and accelerated.

Keywords: pneumatic drive, driving simulator, mechatronic system design

1. Introduction

The task of the car driving simulator is to influence a person in such a way as to evoke the impression of movement. This effect is achieved by combining visual and audio effects with the movement of the simulation platform. The simulator is used as a research tool to study the driver's reactions in various simulated road conditions. A person driving the simulator is subjected to external stimuli, which in turn affect the human senses through receptors [3]. The simulator platform should generate motion in such a way that the driver is subjected to appropriate physical overloads. The most popular solutions of this type are flight simulators and driving simulators. The main challenge for simulator constructors is to induce comparable behavior of the simulator user and the real vehicle. To achieve this goal, simulator constructors place real cabins of various types of vehicles on special motion platforms with many degrees of freedom. Such a driving simulator is a tool that allows simulation participants to drive a vehicle on a virtual road, with the simulated conditions being carried out in safe conditions. Currently, driving simulators intended for research and training tasks usually use a platform with 6 degrees of freedom. The most advanced versions of simulators are used for training both military and civilian pilots [7], [9]. Their construction is usually based on the Stewart platform. These solutions are very expensive due to the use of complex propulsion mechanisms and control systems [4].

Hydraulic drives, pneumatic drives, linear actuators and electric motors are used to move the simulator platform [6]. Hydraulic actuators are mainly used in professional training simulators due to their ability to achieve high forces and accuracy. On the other hand, the main advantages of electric drives are their...
ease of control, high efficiency and low noise level. It is the most popular solution in simulators created for entertainment. The most advanced actuators of this type are displacing hydraulic drives in professional training simulators [5]. Due to the simplicity of design and ease of installation, the least popular pneumatic actuators are used in low-budget simulators. Their disadvantages are low load carrying capacity and lower precision compared to other actuators. Thanks to the development of mechatronic systems, the construction of such devices has become increasingly popular. In recent years, there have been many companies offering simulators, which while simplifying the design (reduction of degrees of freedom, use of electric and pneumatic actuators/motors) in comparison to professional, typically training solutions, offer equally high level of reproduction of forces acting on humans [10].

2. Simulator design

A model of a prototype electropneumatic car driving simulator is shown in Figure 1. In this simulator, pneumatic actuators (4) are used to drive the moving members [1]. Movements of the actuators cause movement of the forward tilt frame (2) and lateral tilt (3), which in turn allows for the corresponding inertial forces acting on the driver. The two frames form an articulated kinematic linkage with two degrees of freedom. The driver's seat (6) is mounted directly on the tilt frame (2). The simulator is equipped with a steering wheel, control sticks (7) and a monitor (9).

![Figure 1. General view of the simulator model: 1 - base, 2 - steering frame, 3 - acceleration and braking frame, 4 - pneumatic actuators, 5 - moving frame bearing, 6 - seat, 7 - steering wheel, 8 - control pedals, 9 - projection screen [8]. Such a construction of the device is to provide real-time imitation of all overloads occurring in a moving car, i.e.: acceleration, braking, turning, ascending and descending.](image)

![Figure 2. Simulator response during driving (a) acceleration, (b) braking, (c) turning.](image)
2.1. Kinematic structure of the simulator

Figure 3 shows the kinematic structure of the driving simulator. The diagram shows the mutual relationships of the kinematic pairs in the kinematic chain [11].

The kinematic structure of the simulator contains 3 rotational pairs $R_1$, $R_2$, $R_3$ providing movement during acceleration and braking, 3 rotational pairs $R_4$, $R_5$, $R_6$ responsible for tilting during turning. Propulsion in the designed simulator is provided by two pneumatic actuators ($P_1$ and $P_2$).

![Figure 3: Kinematic diagram of the simulator.](image)

![Figure 4: Flat kinematic diagram of the simulator axis s) $xz$ plane, b) $yz$ plane.](image)
The purpose of the kinematic analysis is to determine the value of displacements of piston rods of pneumatic cylinders acting in two perpendicular planes responsible for acceleration-braking $Z_1$ and torsion $Z_2$. This analysis is necessary for the proper work of the control system of the simulator drives. The whole system can be simplified and considered as two independent plane mechanisms (fig. 4).

Figure 4 shows the kinematic diagram of the forward-backward swing mechanism (Fig. 4a) and the lateral tilt mechanism (Fig. 4b).

The mobility in the $xz$ and $yz$ planes of the simulator is:

$$ W = 3 \cdot n - 2p_1 - p_2 = 3 \cdot 3 - 2 \cdot 4 = 1 $$

Where: $p_1$ and $p_2$ are kinematic pairs of class one and two, respectively. The $p$ pairs in the plane are pairs with rotational or sliding motion, $n$ the number of moving members of the kinematic chain.

In order to determine the displacement of the pneumatic actuators $Z_1$, $Z_2$ providing forward tilt ($Z_1$) and side tilt ($Z_2$) using the analytical method, the equations are obtained:

$$ h_1 \cdot \cos \alpha - l_2 = -z_1 \cdot \sin (\alpha_1) $$

(2)

$$ -h_1 \cdot \sin \alpha - l_1 = -z_1 \cdot \cos (\alpha_1) $$

(3)

$$ h_2 \cdot \cos \beta - l_4 = -z_2 \cdot \sin (\beta_1) $$

(4)

$$ -h_2 \cdot \sin \beta - l_3 = -z_2 \cdot \cos (\beta_1) $$

(5)

$$ z_1 = d_1 + s_1 $$

(6)

$$ z_2 = d_2 + s_2 $$

(7)

where: $d_1$, $d_2$ constant value.

The corresponding stroke of the $Z_1$ and $Z_2$ actuator is:

$$ s_1 = \sqrt{h_1^2 + l_2^2 + l_1^2 + 2 \cdot h_1 \cdot (l_1 \cdot \sin \alpha - l_2 \cdot \cos \alpha)} - d_1 $$

(8)

$$ s_2 = \sqrt{h_2^2 + l_4^2 + l_3^2 + 2 \cdot h_2 \cdot (l_3 \cdot \sin \beta - l_4 \cdot \cos \beta)} - d_2 $$

(9)

3. Mechatronic solution of kinematics tasks

To verify the kinematic model, a series of simulation studies were conducted using SolidWorks (physical model) and Matlab/Simulink (implementation and simulation studies) software. This software makes it possible to design a virtual model and check its behavior under fixed initial conditions. With this solution, the design process is significantly streamlined and accelerated. With the help of SimMechanics toolkit it is possible to import a ready solid model from SolidWorks to Matlab/Simulink. Figure 5 shows the virtual simulator model and selected parameters of the driver’s seat motion for the given duty cycle of the pneumatic actuators, determined during simulation in the SimMechanics program.
4. Control system

The manipulator control block system is shown in Figure 6. This system was developed assuming the use of electrically controlled pneumatic drives, where the control unit is a PC computer, working with a dedicated Velleman K8055 card. Additionally, X-Sim software was installed on the PC.

Figure 7 shows a schematic of the control system. The actuators (1, 2) that move the simulator are controlled by pneumatic distributor valves 5/3 [2]. The position of the simulator is read by two potentiometers (one for each drive axis). The whole is connected to the Velleman K8055 control card: valves digital outputs, potentiometers analog inputs. The card is connected to PC via USB interface. X-Sim software [8] was used to generate the simulator control signals.
Figure 7. Schematic of the control system: 1, 2 - pneumatic actuators, 3 – Velleman K8055 control card, 4 - resistive position measurement of actuators.

X-Sim software works with most of the virtual game simulators available on the market. This is its main advantage because each game manufacturer uses a different method to export real-time telemetry data [2]. The software consists of two main modules X-sim extractor and X-sim converter. The first one has "plugins" and tools needed to read data from the game, which are then used to control the simulator [8]. The read values such as longitudinal, transverse, vertical overloads, among others, are sent to the X-sim converter module. The X-sim converter module is used to convert game variables such as velocity or acceleration into actual simulator motion by converting game input data into actuator control data [1].

5. Conclusion
The car driving simulator solution presented in the article is a dedicated solution covering the area of application of the mechatronic system as a uniform, functionally integrated system in which an original solution of mechanics and control was used. The car driving simulator project presented in the work is a simple and relatively inexpensive solution compared to commercial solutions. The original design of the supporting and controlled frames allows the use of a minimum number of drives - actuators. The main problem of the designed mechatronic simulator system with a multi-drive system is to obtain full synchronization of the pneumatic drives. The manipulator uses pneumatic actuators as an effective solution, but in the absence of a pneumatic installation, electric linear actuators can be successfully used to build the simulator. Another improvement for the simulator will be the use of electro-pneumatic or electro-hydraulic positioning servos [1], which will result in improved dynamics and smooth movement of the driver's seat.
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