HIL models formation principle in the design of automated vehicle braking system

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Abstract. The general principles of the HIL models formation in the design of an ABS-featuring vehicle braking system are considered. The proposed modular principle of compiling a mathematical model of subsystems allows improving the model by the iterative method, which makes it possible to add or remove blocks, change their mathematical content, while maintaining the composition of formal relationships for a complete description of the object. The iterative process continues until a model has been obtained to solve the problem, which can be considered the most fully reflecting the physical and temporal processes taking place in real objects. Virtual physical simulation data help to adjust model parameters, apply numerical optimization, explore alternative scenarios for controller bandwidth, test development sensitivity, and study other factors. The application of this method also makes it possible to compare different implementations of control systems on different boards, analyze the development and evaluate the trade-offs. Thus, developers will be able to verify that the embedded system works exactly as planned, before its final implementation. This technology makes it possible to combine field systems with a mathematical description of the dynamics of ongoing processes and phenomena. At the same time, the Virtual Physical Modeling Technology, unlike the commercial Hardware-in-the-loop systems, is not tied to the hardware of any particular manufacturer.

1. Introduction
When modeling it is necessary to closely reflect the real picture of the flow of working processes in the "Car - Driver - Road" (C-D-R) system, thus solving the problems of forming the main operational properties of the car in braking mode, i.e. stability, efficiency and controllability, at the design stage [1,2]. In this system, both mechanical movements of masses (sprung and unsprung) and physical processes accompanying the operation of various vehicle systems affect the vehicle motion characteristics (interaction of the wheel with the road, hydrodynamic processes in the brake system, rotation of the steered wheels when controlled movement, etc.).

2. Main part
In a systematic study of the general case of car behavior in braking mode, it is necessary to adopt a unified methodology for describing the interaction of various parts of the studied C-D-R system, which is reflected in Figure 1.
The most complex part of the C-D-R system is the subsystem "Car". Each module of this subsystem makes certain transformations of quantities and, therefore, is characterized by input and output parameters. In this regard, a structural diagram of the relationship between the models of modules in the "Car" subsystem is presented in Figure 2.

As illustrated by the above diagram, all modules can be arranged with some priority. The “Wheel” and “Body” modules have the highest priority, since without them it is generally impossible to simulate the movement of a car. The second priority is the module "Brake System", which, in accordance with the goal set above, is necessary to model vehicle braking.

The third priority are modules aimed at refining the model or solving any subproblems [3,4] (modules "Suspension", "Steering", "Transmission").
Such an arrangement of modules in the “Car” subsystem, when the modules with the highest priority are processed first, allows detecting the impossibility of solving a problem, insufficient communications with other modules, or a lack of initial data in the early stages of modeling. In addition, such a partition of the “Car” subsystem minimizes the number of interactions between the modules, which best affects one of the research tasks — the speed of solving a model on a computer.

The proposed modular principle of compiling a mathematical model of the subsystem "Car" makes it possible to improve the model by the iterative method, which allows adding or removing blocks, changing their mathematical content, while maintaining the composition of formal relationships for a complete description of the object. The iterative process continues until a model has been obtained to solve the problem, which can be considered the most fully reflecting the physical and temporal processes taking place in real objects. The effective operation of the mathematical model is possible only if reliable initial parameters are available. Otherwise, the complication of the model can lead to the opposite result, i.e. a decrease in its reliability. In our case, when modeling the braking dynamics of a car with ABS, such data include the parameters of the car itself (geometric, weight and inertia), wheels, brake system, steering, suspension, transmission, driver and road.

When designing an ABS from the initial design work to start it in series, developers primarily have to solve the following types of main tasks:

- form the algorithm of the braked wheel and the selection of the characteristics of the modulator;
- choose the control structure;
- optimise the control structure with account to the actions of the driver.

The studies of E.V. Hertz, G.V. Kreinin, N.F. Metlyuka, V.P. Autushko, A.A. Revina et al. established that describing the flow of fluid or gas in the brake line and the ABS modulator requires knowing a large number of parameters, which at the design stage are often impossible to obtain with the required accuracy. At the same time, the dynamics of the processes of interaction of the elastic
wheel with the road surface is well described mathematically. The most effective solution for this is the use of Virtual Physical Modeling (VPhM), when part of the object of study is presented in the form of a real unit (often a prototype), which allows the designer to carry out operational verification of the decisions made even at the stage of debugging and debugging the system, tied to the hardware of a particular manufacturer.

Therefore, when solving the problems of optimizing the working processes of automated brake systems and studying the vehicle’s dynamism in the braking mode, it is generally advisable to represent the brake circuit lines together with ABS modulators and working cylinders (including hose flexibility and stiffness of the block-drum system), subject to the preservation of the geometry of the highways and the location of the studied units. Then the car chassis, brake mechanism, steering, suspension, a pair of "tire - road", etc. is represented in the form of a mathematical model on a control computer complex. However, when using complex modeling technology, one of the most important requirements - to ensure real-time operation - must be met. At the first stage, when solving relatively simple problems, it is possible to select control computers based on the use of analog computers that have the property of working in real time. The studies conducted at Volgograd State Technical University [1] showed that the results of bench studies fully reflect the physical picture of the braking process and give good convergence in the final values of the parameters, which confirmed the possibility of their further use in studies of a complex modeling setup.

However, the complication of the mathematical description of various elements of the car necessitated the use of modern PCs, while it was necessary to ensure its most important property, i.e. real-time operation. Without the implementation of the latter, the use of complex modeling technology is impossible. When using a digital computer, this requirement is achieved when the following indispensable condition is fulfilled: the calculation time of the process should be less than the time of its actual course.

The practice of using the Virtual Physical Modeling Technology (VPhM) (or Hardware-in-the-loop) at Volgograd State Technical University showed that using system design and modeling, it is possible to build stands that combine new and existing mechanical, hydraulic and electrical actuators and sensors [5,6,7], while not tied to the hardware of any particular manufacturer.

Virtual Physical Modeling (or Hardware-in-the-loop) is especially effective at this stage of design, when a real object has not yet been built.

Figure 3 shows an example of an implemented stand for solving the problems of formation and optimization of the operation algorithm of the Electro-hydraulic brake system (EHB) [11,12,14].

The next task to be solved by the designers is the selection of a control structure.

The selection and optimization of the control structure can be implemented on the model of the class "chassis". At the same time, developers can use Virtual Physical Modeling (or Hardware-in-the-loop) to expand the capabilities of testing the chassis and electronic automotive systems that meet the stringent requirements of certification for health and safety. Physical simulation allows studying the entire system, which combines several different subsystems, and analyzing its performance in the conditions and environments too dangerous or expensive to conduct their field testing [15-18].

Virtual Physical Modeling is especially effective at this stage of design, since the requirements of security and speed demand to test the system before attracting people to its implementation, while it is necessary to minimize the downtime of a real object.

Depending on the objectives of the study, the mathematical models of the chassis can take a different configuration. Volgograd State Technical University created the mathematical models of the chassis of the following types of automatic telephone exchanges: biaxial, triaxial, truck and trailer trains. Practice has shown the need to solve the problem of choosing a control structure in addition to traditional ones, taking into account the following physical processes: the gyroscopic moments of the steered wheels during their self-rotation and the fading effect in the braking mechanism under the influence of the ABS, hysteresis and inertia of the braking mechanism when debugging the algorithm.
The stand shown in Figure 4, implemented in the laboratory of the Turin Polytechnic Institute as a result of scientific cooperation between research groups, clearly illustrates the possibility of solving problems of the chassis class.
During the tests, various technical solutions for connecting the blocks were used. So, to verify the operation of the stand, the electronic filling of the Bosch ABS and Bosch ESP blocks was used, and to develop our own algorithms, direct connection to the valve body valves was used [7, 14]. This made it possible to reduce the volume of road tests of active safety systems that combine several subsystems.

However, the optimization of the control structure is impossible without taking into account the driver’s actions to correct the direction of movement. Thus, the third task is the optimization of the control structure with account to the “man-machine” system interaction. Virtual Physical Modeling is especially effective at this design stage, as the safety requirements to the system testing are very strict. This technology (VPM) provides for testing the system performance in extreme modes, which are complex and dangerous to re-create, before its actual implementation by the staff. Figure 5 shows an example of the implementation of the stand for solving "chassis + driver" problems.

![Figure 5. A stand for solving task of the "chassis + driver" class.](image)

The problem can be solved by expanding the capabilities of bench equipment by:
- Providing visualization of the movement process perceived by the real driver;
- The implementation of channels of tactile information transmitted to the driver.

Rapid prototyping provides the developers of control and data processing systems with a quick and cost-efficient way to test a project in the early stages of development and analysis in order to choose the best solution. Depending on the tasks to be solved, a selection of implemented functional blocks is made (Figure 6).

3. Conclusions

Implementation of the Virtual Physical Modeling Technology makes it possible to automate many tasks, providing for:
- the performance of hardware testing of new active security systems and algorithms in real time;
- creation of alternative project options as soon as possible;
- spending more time optimizing the system.

VPM allows confirming the developed system functional capacity in-situ at the very early stages of its design. Verification is performed on equipment operating in real time. At the same time, the project can be quickly refined and modified until the required result is achieved. Virtual physical simulation data help to adjust model parameters, apply numerical optimization, explore alternative scenarios for controller bandwidth, test development sensitivity, and study other factors.

The application of this method also makes it possible to compare different implementations of control systems on different boards, analyze the development and evaluate the trade-offs. Thus,
developers will be able to verify that the embedded system works exactly as planned, before its final implementation.

Creating a system for Virtual Physical Modeling, a developer can choose the right equipment from hundreds of items by various manufacturers, in contrast to existing commercial solutions of Hardware-in-the-loop systems. The developer is absolutely free to choose I/O boards, processor power, type of execution, and other features of the iterative development environment.

These stands, combining several subsystems, make it possible to perform the following tasks:
- to develop and test the chassis and safety management systems without expensive road tests of vehicles;
- develop and test algorithms using models at earlier stages of development;
- implement rapid prototyping of controller algorithms;
- implement hardware and software modeling of electrical and mechanical components.

**Selection and implementation of functional blocks depending on the tasks**

Depending on the tasks, communications at the stands are implemented.

**Figure 6.** Selection and implementation of functional blocks depending on the tasks.

Verification and confirmation technologies used in the development process provide for the identification of errors in the early stages of the design process. Most errors occur at the stage of formation of the primary specification, though, they appear only during testing. Using models for virtual testing in the early stages of design, specialists can reduce development time by up to 50%.

Verification, confirmation and testing operations can be performed at all stages of the design process based on the model.

Virtual Physical Modeling Technology (VPhM) makes it possible to solve the above problems that the designers and testers of new systems [6, 7, 8, 9, 10, 13] face. With the modern design and test methods already in place, so-called V-cycles can be used in the design of active safety systems.
At the stage of designing and calculating the system, and subsequently a specific module, software packages of mathematical modeling (SIL) make it possible to facilitate the work as much as possible. At the stage of verification, control and testing, the widespread use of the Virtual Physical Modeling Technology (VPhM) is possible. This technology allows combining field systems with a mathematical description of the dynamics of ongoing processes and phenomena. In this case, the control of the physical object, as well as the calculation of the model, is conducted in real time. If, for example, an error was found at the stage of system verification, then it is possible to conduct rapid prototyping and apply the VPhM by adjusting the system specification, which does not cause significant delays in the design and the problem can be solved locally.

Using prototypes for early verification of system development gives users the opportunity to test, optimize, and test the developed algorithms on hardware before starting production. Early verification through Virtual Physical Modeling can dramatically reduce development time, while not being tied to the hardware of any particular manufacturer.

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