Using HIL Simulation to Test Mechatronic Components in Automotive Engineering

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1 Introduction
As the number of mechatronic components increases, and with it the complexity of
electronic vehicle systems, tools and technologies for developing and specifically
testing electronic control units (ECUs) are required. For this reason an increasing
number of hardware-in-the-loop systems (HIL systems) is being used throughout the
development process, by suppliers as well as automobile manufacturers themselves.
HIL involves connecting the actual control units to the real-time simulation models of
the vehicle. This makes it possible to perform systematic, automated testing of all
ECUs both as individual components and within the overall system.

Currently there is a clear trend in automotive development towards the use of
intelligent sensors and actuators and towards the functional and spatial integration of
sensors and actuators (in the form of add-on ECUs). These new mechatronic
components are a particular challenge to HIL simulation, since with intelligent
sensors and actuators, ECUs no longer simply have analog and digital interfaces, but
also communicate with the sensors and actuators via proprietary or standard
protocols (e.g. CAN). Integrated sensors and actuators, on the other hand, require
the operation of physical and usually non-electrical interfaces.

This paper discusses the influence of this trend on HIL simulation and shows how
these new requirements can be implemented and logically integrated into existing
HIL concepts.

2 Development Methodology in Vehicle Electronics
Not only vehicle electronics have a high level of complexity; the processes and
structures inherent in developing automotive electronic systems do too. There are
various organizational and technical aspects that need to be taken into consideration.
In Germany and Europe at least, and increasingly in USA and Japan, the
development and production of automobiles is characterized by systematic
organization of the manufacturer–supplier relationship. Moreover, the development of
functions, hardware and software is usually decentralized within each company. This
requires smooth coordination between the manufacturer and all suppliers regarding
such matters as defined milestones. At the same time, the level of technical
complexity, and the fact that control functions are distributed across several ECUs
from different suppliers, make it necessary to use specific procedures defining how
functions and ECUs themselves are to be defined, specified, implemented and
tested.
In automotive development, and in particular in the development of electrics/electronics (E/E), an approach based on the V-cycle (cf. Figure 1) is now widespread\(^1\). This is described below according to the methods used in the various phases of the V-cycle.

![V-cycle diagram](image)

**Figure 1: The various development phases for ECU development (V-cycle)**

- **Function design**: Developing control functions and algorithms, and function testing on a simulated vehicle (software-in-the-loop simulation)
- **Rapid Control Prototyping**: Testing the developed functions in an actual vehicle or on a test bench
- **Target code generation**: Implementing the functions via automatic code generation for microcontrollers in the ECU
- **Hardware-in-the-Loop (HIL) Simulation**: Testing the ECU and its functions in a virtual/simulated environment
- **Application/calibration**: Fine-tuning of functions and algorithms by adjusting ECU parameters during test drives on the test bench or in the vehicle.

This paper will throw some light on HIL simulation and show the effects on HIL simulation of new developments, in particular the increasing use of mechatronic systems in vehicles.

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\(^1\) However, it must be emphasized that the V-cycle is applied repeatedly throughout the development phase and is not straightforward. As a rule, the entire V-cycle is run through at least once from one ECU development procedure to the next.
2.1 Hardware-in-the-Loop Simulation

Hardware-in-the-loop simulation is in widespread use, but because it is a key concept it will be briefly explained and used as a basis for further discussion below.

In hardware-in-the-loop simulation (HIL simulation), the behavior of the vehicle is simulated by software and hardware models. Real vehicle components (real parts) are then connected, via their electrical interfaces, to a simulator, which reproduces the behavior of the real-time environment.

![Diagram of Hardware-in-the-Loop Simulation](image)

Figure 2: Fundamental design of HIL systems

Figure 2 shows the fundamental design of HIL systems. Instead of being connected to an actual vehicle, the ECU to be tested is connected to a simulation system. This runs a model of the vehicle process and associated sensors and actuators that will usually have been developed and implemented with suitable modeling tools such as MATLAB/Simulink. C code is generated automatically from the representation within the modeling tools and then downloaded to special real-time hardware for execution. The real-time hardware is in turn connected to the ECU’s electrical interface via special I/O boards and suitable signal conditioning for level adjustment, using either simulated or real loads.

Using hardware-in-the-loop simulation has several advantages. The main ones are as follows:

- Control and regulation functions can be tested in the early stages of development, even before a test carrier (prototype vehicle) has been produced. The electronics system therefore reaches a high degree of maturity very early on, providing an improved starting-point for later development phases.
• The objective of using simultaneous engineering, or simultaneous development of ECU and vehicle, to cut the time needed for development, can only be achieved by methods such as HIL simulation.

• Expensive field trials or experiments in borderline zones and hazardous situations can partly be replaced by laboratory or desktop experiments.

• Extreme or unusual ambient conditions can be adjusted at will by varying the parameters in the model. Thus typical winter test drives under low-μ conditions (snow and ice) can be carried out in summer, and cold-start tests can be performed repeatedly.

• Failures and errors that could have devastating effects in a real vehicle (sensor failures, line breaks, ground errors, error frames on the CAN bus etc.) can be simulated and tested systematically.

• The experiments performed on the HIL system can be reproduced precisely, and automatically repeated as often as required.

2.2 Requirements for the HIL simulation

The development of HIL systems usually involves a large amount of adaptation work to meet the technical requirements of a given application. This conflicts with the need for application-specific systems that are tailor-made for specific test activities but require minimum technical overhead. The conflict between these two objectives can be solved by a system architecture that permits HIL systems to be constructed from reusable modules on a standardized technical basis. A further result is uniformity of HIL simulation throughout all the test and integration phases. dSPACE Simulator is used to implement this approach.

The requirements imposed on HIL simulation are many and various. They can be divided into technical and conceptual requirements.

Technical Requirements:

• Real-time-capable model: “As simple as possible, as detailed as necessary”, parameterizable and extendable

• Large computing power (for simulation, sampling rates of ≤ 1ms) and special I/O (e.g. for simulation of crank and cam shafts, generation of knock signals, PWM signals, CAN interface,...) by special hardware and support by software

• Signal conditioning with compensation of potential gradients (isolation by transformer and differential analog inputs and outputs)

• Real and/or substitute loads

• Automatability of the entire HIL system, e.g. in a script language

• Automatability of electrical error simulation

• Test automation that goes beyond mere sequencing: signal generation and capturing in real time, complex test sequence structures, access to external devices (e.g. diagnostics) and tools (for evaluation and documentation).
**Conceptual Requirements:**

- Low overhead for (customer-)specific adaptation
- Reusability of individual modules or whole HIL systems
- Use of standardized components
- Modularity and expandability at microscopic and macroscopic levels
- Scalability of the simulator and of costs by means of complementary version and overhead planning
- Tight deadlines, and even more importantly, deadlines that can be planned and met. Against the background of the development times and milestone scheduling that are currently prevalent, delays lasting months and resulting in non-availability of the HIL simulator are not acceptable to users.
- Openness, i.e. the use of widespread modeling tools such as MATLAB/Simulink, the support of standards such as ASAM MCD, and standardized connection options for external devices, e.g. via a CARB diagnostics connector (CARB: “California Air Resources Board”)
- Supplier competence: Knowledge of vehicle, simulation and software technology, and in particular experience in the fields of HIL simulation and test automation.

Whilst the technical requirements absolutely have to be fulfilled nowadays, the conceptual requirements have yet to be identified and implemented on the basis of experience with HIL simulation for different applications and customers. In dSPACE Simulator, the dSPACE company has devised an approach with associated products that systematically meet these requirements and moreover set new standards in many respects [1].

3 The Impact of “Mechatronization” on HIL Simulation

For years now, the development of motor vehicles has been shaped by development trends. One of these is an increasing degree of networking between electronic components by means of bus systems. To begin with, bus systems were used simply to save on cabling, reduce the weight of the vehicle and eliminate potential sources of error in mechanical and electrical connections. There was then a growing realization that additional functionality – mainly in the areas of comfort and safety - could be implemented by using bus systems and distributing functions over several control units, at a relatively low overhead.

A further development trend can be described as the “mechatronization” of vehicles. Mechatronization means the growing proportion of mechatronic components, in contrast to the classic separation of mechanical, electrical, hydraulic and electronic components.

3.1 Mechatronic Systems in the Vehicle

The reasons for mechatronization are similar to those for more intensive networking: the need to cut weight by avoiding unnecessary cabling and to reduce the number of plug-in connections with their potential for error. Moreover, the increasing use of mechatronic components also means more compact and space-saving design, which in the final analysis also enhances safety. Mechatronics also means that components that hitherto were purely mechanical, electrical or hydraulic can be given additional
functionality. Sensors and actuators that implement local diagnostics functions and that can tell the ECU of the current operating status or of possible error conditions are examples of this.

Expressed in abstract terms, mechatronic vehicle components take shape in two dimensions:

- By functional integration in the form of intelligent sensors and actuators
- By spatial integration as sensors and actuators integrated into the control unit (add-on control unit).

Examples of this are CAN-based sensors, ABS (Bosch) and gear control units (ZF), along with motor controls (integrated into the intake system, e.g. Siemens, Delphi). These new mechatronic components are a particular challenge to HIL. The issues involved are discussed in greater detail below, along with a description of what technical solutions would be appropriate from the point of view of HIL simulation.

### 3.2 Intelligent Sensor and Actuator Systems

Intelligent sensors and actuators usually have their own microprocessors (“local intelligence”). An intelligent sensor processes the electrical values provided by the measuring device and makes the technical information available to the control unit via a more sophisticated interface. Intelligent actuators work in the opposite direction, receiving information from the control unit and themselves turning it into electrical values to control the mechanical, hydraulic or electrical actuating elements.

These are some examples of intelligent sensors and actuators:

- NO\textsubscript{X} sensor with CAN bus connection (Siemens),
- Steering angle sensor with CAN connection (Bosch ESP, cf. section 4.1),
- Valve flap actuator in automatic air conditioning (serial bus),
- Electromagnetic valve drive with control of actuators via high-speed CAN (Siemens).

Using intelligent sensors and actuators shifts the interface between control units and technical vehicle process: intelligent sensors and actuators do not send information to or receive information from the control unit via purely electrical, binary or analog interfaces. Rather, more complex signals that implement the transmission of more or less complex communication protocols are used. The great diversity of options ranges from pulse width-modulated signals to serial interfaces, right through to the use of CAN buses. The consequences for HIL simulation are shown in Figure 3. The interface that is relevant to HIL simulation is no longer purely electrical in nature, but requires the generation and capture of more complex signals at the electronic interface by the HIL system. The appropriate signals have to be generated by special hardware (intelligent sensor, see Figure 3 a) or read in (intelligent actuator + simulation of actuator behavior, see Figure 3 b), and the associated protocols have to be implemented in the software. One feature that could be mentioned in this connection is rest bus simulation, meaning the simulation of non-available control units in the network, and also of non-available sensors and actuators on local bus systems, e.g. for audio/video systems or air conditioning control units.
3.3 Integrated Sensor and Actuator Systems

Another development, in a different direction, is the increasing use of control units installed directly on the aggregate to be controlled. Such units are generally known as “add-on ECUs” – in contrast to the classic “external ECUs”.

These are some examples of integrated sensors and actuators:

- Valve activation ESP (cf. Chapter 4.1),
- Speed sensors, pressure sensors and shift valve control in gear control units (e.g. ZF 6HP26 or Audi Multitronic, cf. section 4.2),
- Air mass sensors, temperature and pressure sensors in motor control units that are directly integrated into the motor’s intake system.

With control units like these, the electrical interface has moved towards the inside of the control unit, and is no longer directly accessible from outside\(^2\). In sensor simulation, such control units have to be stimulated on a diversity of physical principles, and the use of specially developed “stimulus actuator systems” (cf. Figure 4a) is necessary. On the actuator side, this development means that the principles of measurement that are applied must be specifically tailored to the non-electrical control unit outputs (cf. Figure 4b).

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\(^2\) The exception would be if the ECU manufacture exposes the connection. However, it is not generally possible to assume this will be done.
As a rule, interfaces require considerably more overhead to operate with integrated sensors and actuators than is the case with intelligent sensors and actuators. For instance, the physical stimulation of integrated sensors can be performed along the following lines:

- Pressure sensors: compressed air or hydraulics system,
- Temperature sensors: heating or similar,
- Air mass sensors: fan or ventilator regulated by real-time hardware,
- Speed sensors (inductive pickups): coils or similar.

An additional challenge is that the stimulus actuator system not only needs to be started, but often also regulated. This is the only way to ensure that the physical effects working on the integrated sensor match the ones computed in the simulation model.

This presents new technical challenges, particularly where a fast measurement control loop has to be suitably served. This is the case with the broadband lambda probe, for example. The control unit includes a very fast processor that captures the current lambda value via a current control and the voltages that occur. This involves not only measuring the actual current at any given time, but also simultaneously "artificially" generating the feedback signal via lambda probe simulation. Because of the fast dynamics of the control (in the kHz range), a suitable solution partly has to be implemented in the hardware.

With an integrated actuator system, the physical behavior of the actuator has to be captured by additional, real measurement sensors in order to simulate the effect of the actuator on the vehicle or vehicle model. Thus the signals from an ESP control unit with integrated valve activation are captured by means of Hall-effect sensors that are spatially arranged in the same way as the valves of the real hydraulic aggregate (cf. fig. 7). The signals from the Hall-effect sensors are then fed to the simulation model via A/D converter cards.
4 Use of HIL Simulation to Test Mechatronic Components – Examples

There follow a few examples of how intelligent and integrated sensor and actuator systems are used in an HIL control unit test scenario.

4.1 ESP Control Unit

The electronic stability program (ESP) is now in widespread use in virtually all vehicle classes. The current ESP systems (e.g. from Bosch or Continental Teves) are add-on control units (figure 5) directly installed on the brake hydraulics block. The valve control and return pump are directly connected to the control unit. In addition to this integrated actuator system, ESP also involves the use of intelligent sensors. Thus communication between the steering (wheel) angle sensor and the control unit is via CAN. As this system is critical to safety, the various sensors transmit special signal sequences each time they are switched on, so that the ESP control unit is informed of the error-free functioning of all subsystems [2].

Figure 5: Bosch ESP with control unit, hydraulics unit and return pump (left) with the layout of the ESP components in the vehicle (right)

The system configuration of the ESP with connected actuators and sensors is shown in figure 6.
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The features of interest to mechatronics are the integrated actuators (valve activation) and intelligent sensors (particularly the steering angle sensor):

a) Valve activation (integrated actuator system): The ESP control unit is implemented as a hybrid technology, and has integrated power drivers for coil activation in the valves. It is not possible to measure these control signals because of the integrated and closed design. The non-existence of a cable tree means that only the “effect” on the valves of coil activation can be captured, in other words the electrical field coming from the coils. HIL simulation therefore uses valve capture hardware that measures the 12 valve signals (figure 7).

Figure 6: System configuration in the ESP with sensor, actuator and brake hydraulic systems and the vehicle dynamics as a controlled system, also showing the connection to the engine and gears (control unit)

Figure 7: ESP control unit and valve capture hardware with signal conditioning
These signals are the inputs for the real-time simulation in the brake hydraulics, which is directly connected with the vehicle dynamics model. dSPACE ESP Simulator uses real-time-capable brake hydraulic and drive dynamics models from the TESIS company, Munich [3], based on MATLAB/Simulink.

b) Steering angle sensor (intelligent sensor system): The steering angle sensor has a CAN connection and its own diagnostics functions. It can therefore detect events such as implausibly fast rotation of the steering-wheel or other sensor implausibilities. In addition, the steering angle sensor has to be taught the actual control unit. This is done by the control unit issuing (random) code bits that are exchanged cyclically between the control unit and the steering angle sensor during operation.

Figure 8 shows how the configuration from figure 6 is implemented in a dSPACE hardware-in-the-loop system to test the ESP control unit [1]. The outputs from the ESP control unit are fed to the models of the brake hydraulics, the drive dynamics and the drive train by means of the valve capture described above (figure 7) via analog and digital inputs. The kinetic behavior of the vehicle resulting from the simulation (represented by wheel speed, yaw speed, lateral acceleration etc.) is fed to the ESP control unit via sensor simulation and various output channels (analog, digital, CAN etc.). In addition, motor and transmission control units that communicate with the ESP control unit via CAN are also simulated (rest bus simulation).

![Figure 8: Configuration of the ESP system for HIL simulation](image)

With dSPACE Simulator, the entire real-time simulation (including I/O) is performed on a PowerPC board (DS1005, 480 MHz) in approx. 600 µs. The I/O hardware used is the dSPACE HIL interface board DS2210, which provides a wide range of analog and digital input and output channels, PWM I/O, CAN and resistance simulation. Special hardware and software for ESP (highly dynamic wheel speed generation) and motor applications (generation of crank shaft, cam shaft and knocking signals,
plus capture of ignition and injection signals) round off the range of functions. Moreover, on the DS2210, signal conditioning for the automotive voltage level is implemented on the board itself. Thus the DS2210 board can be directly connected to a control unit, without any further signal conditioning. Specification of the CAN bus messages, and configuration of the other I/O signals, are performed directly and graphically in MATLAB/Simulink, which is also the basis for automatic generation of the entire real-time code.

![Figure 9: Overall constellation of dSPACE Vehicle Dynamics Simulator](image)

4.2 Further Examples
Below are a few more examples of how mechatronics components are used in hardware-in-the-loop test systems.

Engine ECUs:
With engine control units, there is an increasing trend towards installing ECUs in the intake channel of the combustion engine. The ECU can be cooled by the suction air, and location this close to the engine also cuts down on the quantity of cabling required. Sensors such as integrated air mass, temperature or even pressure sensors are the consequence. During the HIL simulation, either the ECU’s electrical interface has to be exposed (= expensive special control unit) or the appropriate interface has to be stimulated physically. For example, with the air mass sensor, the ECU can be installed in a pipe through which the appropriate air mass flow is generated by a ventilator controlled by the real-time hardware. Temperature sensors can be suitably stimulated by installing the ECU in a temperature chamber or by external heating elements.

Transmission ECUs:
With gear control units too, there is a clear trend towards add-on ECUs. These usually have integrated speed sensors (for gear input and output speed), pressure sensors, integrated microswitches and power drivers for the various hydraulic valves. Inductive speed sensors or Hall-effect sensors can be suitably stimulated by means of coils activated via the real-time hardware (simulation of speed). The stimulation of
integrated pressure sensors generally involves considerable effort, as it requires a real, controlled pressure supply (controlled hydraulic cycle).

Figure 10 shows the mechatronics module of the 6-gear automatic gear system 6HP26 from ZF [4]. This consists of an electronics module and a hydraulics system, and is fixed to the gears from underneath. Testing this control unit module within the framework of HIL simulation requires a control unit mount in which the electronics module can be installed, contacted and stimulated by the real-time hardware.

A further mechatronics application from the field of gears is the Audi multitronic, a stepless CVT gear [5]. The control unit is completely housed in the gear casing and has a variety of integrated sensors and actuators (figure 11). This device also requires a suitable control unit mount for stimulation of the physical interface.

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5 Conclusion

This paper presents the various options available for accommodating mechatronics components in HIL simulation for testing ECUs. There is a basic distinction between intelligent and integrated sensors and actuators.

Intelligent sensors are relatively easy to integrate into the HIL simulation by means of rest bus simulation and appropriate powerful CAN hardware and software (e.g. Real-Time Interface from dSPACE), though depending on the application, it may be necessary to implement complex software protocols.

In contrast, integrated sensors and actuators usually involve more overhead, but basically do not impose any restrictions on the application of HIL simulation. They require physical, frequently non-electrical stimulation or measurement at the ECU interface. Several different examples and corresponding approaches were presented in this paper.

6 Literature


