HARDWARE IN THE LOOP - THE TECHNOLOGIE FOR DEVELOPMENT AND TEST OF VEHICLE CONTROL SYSTEMS

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ABSTRACT

Developments in hardware in the loop (HIL) simulation technology are summarized. This technology enables a qualitatively new approach to develop and/or test vehicle dynamics control systems. The IPG-HIL test-rig is presented to identify important aspects that will make HIL simulation an integral part of vehicle systems development technology for the next century.

I. - INTRODUCTION

Whether one attends discussions among engineers or reads automotive industry periodicals, one will now hear or see the term "hardware in the loop simulation" frequently used and easily accepted. As many automotive engineers would attest, this was far from true even five years ago. In spite of nonrigorous and sometimes naïve use of the term HIL-simulation by many practicing engineers, there has been a very significant deepening of appreciation for HIL-methods in vehicle dynamics industry. There are several reasons for this.

- First, essentially *all* development activities prior to operation of a vehicle that is manufactured and delivered to a costumer are nowadays simulations. Here the word "simulation" includes all experiments (mathematical and/or physical) that emulate environments or conditions to be experienced by the product in its actual use. The most important tool in support of designing, testing and evaluating sophisticated electronic control units (ECUs) such as ESP-controllers is HIL, i.e. doing a highly realistic simulation of the equipment in an operational (real-time) virtual environment. Only this leads to designs that function effectively in situations that will be encountered by the ECU when it is fielded and in the hands of the costumer.
- Second, a highly critical problem in every field of engineering is making early decisions on specific design alternatives on a sound basis. During the design of the vehicle as well as of an ECU the state of information about the final product(s) is incomplete and in a constant flux. An additional important uncertainty is associated with an incomplete understanding of how the vehicle will be used in the hands of the customers. HIL helps to find a way out of this dilemma: it makes it possible to begin assessment of driver-vehicle-environment performance, well in advance of initial physical prototyping. This allows to carry-out timely design assessments, trade-off analyses and design optimizations.
- Third, still a couple of years ago, HIL was on the horizon, but time was not yet ready to allow its pervasive application. It is the ESP-boom that occurred since the mid 1990s that makes HIL simulations more important than ever before. The global competitive pressure on automotive industry will make it necessary to include new ECUs in order to optimize vehicle performance, and HIL will significantly impact this process.
  The same competitive pressure leads to the quest for ever decreasing product development cycles. The task of bringing an new ECU to the market is time consuming and expensive. HIL replaces field tests by computer simulations, thereby reducing development cost and time dramatically.
- Forth, the explosion in simulation software and computer hardware that occurred during the last decade suggests that robust high-fidelity real-time simulations are now in hand.

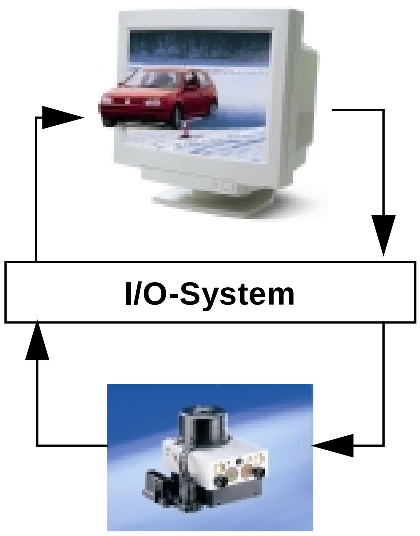


Figure 1 - A real Continental-Teves ESP-controller is interacting with a virtual VW Golf.

This paper highlights advances in HIL as a result of an IPG development initiative which started two years back. The vehicle dynamics simulation technology and know-how underlying the actual HIL applications has been developed by IPG since 1984. Since 1989 IPG is playing a leading role in extending the frontiers of HIL technology in automotive industry. The test-rig described in this paper illustrates the state-of-the-art in HIL. It allows test-engineers to fundamentally rethink the potential of HIL applications.

II. - HARDWARE PHILOSOPHY

Change is a given in computer technology. Computer systems can become obsolete overnight. Hardware platforms used for one application suddenly become attractive to another application. Users want a hardware that will grow as technology evolves. Users want to customize off-the-shelf products. And users want to use new tools for new situations and new applications.

One of the most important aspects of IPG's HIL solution is that it represents a fundamental shift in HIL technology - from the hardware-centric environment of some of our competitors to a software-based paradigm that promotes fast time-to-market and easy product upgrades. In keeping with this paradigm, the IPG solution is designed to give the users access to the actual generation's best hardware architectures.

The VMEbus standard is, and will continue to be the best way to configure individual HIL platforms: high performance specification, inherent multi-processor support, reliability, 16 year history and stability, international standardization and wide industry acceptance are some of the reasons. VMEbus systems achieve the optimum balance between the state-of-the-art of commercial technology available, flexibility, maintenance, price performance, modularity, scalability, portability and interoperability and combine them with all the other well known aspects of an open standard. One of the most important arguments to use VMEbus is that it makes the customer independent from expensive custom hardware. This allows to continually update the product range to accommodate the latest in technology and to support all customer needs with the most appropriate tools.

Today Motorola's PowerPC is IPG's actual choice. Motorola gives a 5 years warranty, continuity of supply and alternatives for obsolescent assemblies throughout the systems life cycle. Of course, IPG software can also handle hardware-platforms other than Motorola.

Resulting from the demand for a modular, flexible and therefore economical I/O system, it was decided to use mezzanine-type M-Modules with front-panel connections. M-Modules have been recognized as an official ANSI standard. A variety of 150 different M-Modules currently available on the market offer a way to use off-the-shelf components to achieve "customized" results and lead to about an optimum of flexibility to configure individual systems. M-modules are typically less expensive than other I/O designs of comparable quality. Currently IPG uses components by MEN Mikro Elektronik, Germany, the inventor of the M-Module specification.

The real-time computer is linked via Fast Ethernet to a

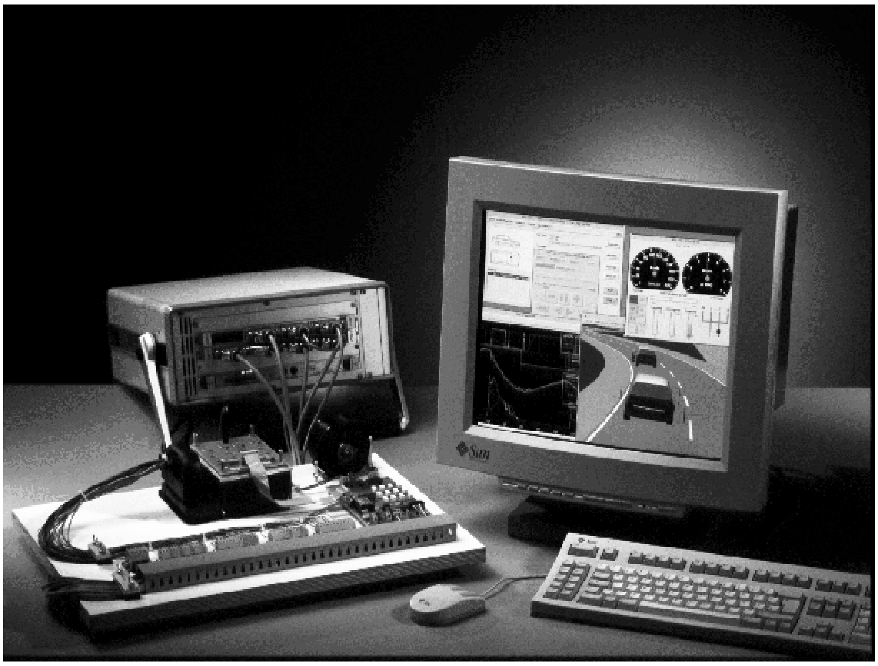


Figure 2 - A typical Hardware in the Loop test-rig consists of three components: (i the hardware specimen (here: a VW Golf ESP-controller), which communicates via I/O- modules with a (ii) real-time-computer, where the simulation models are calculated. (iii) A workstation builds the intelligent user-interface. Since the workstation is outside the simulation loop, the data-ransfer between real-time computer and workstation is not timecritical

SUN Ultra 10 Creator3D. This completely standard UNIX workstation is simultaneously responsible for user communication, defining the simulation-task and online displaying and storing the results of the real-time calculations. The system can be easily upgraded and extended.

III. - MECHATRONIC MODULES

IPG software modules provide a high degree of fidelity and realism with respect to at least three critical factors: (1) dynamic performance characteristics of the simulated vehicle, (2) control and cueing interfaces through which the ECU interacts in real-time with the simulated vehicle, and (3) the external environment (road, windload) in which the vehicle operates.

IPG products are designed to protect the investment of the costumer. According to this philosophy the IPG-approach has advantages over traditional "boxed" systems: the client can tailor the modules to his specific needs by creating new programs. The system is fully extensible, one can easily incorporate customer-specific code.

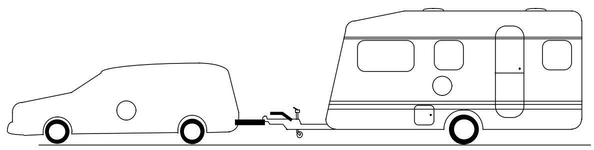
According to IPG's commitment to standards - written in C/C++, running under UNIX, Windows NT *etc*. - the costumer can exploit an extremely wide range of existing systems.

A IPG-CAR

The real-time multibody dynamics tool MESA VERDE is used to obtain the nonlinear differential equations of motion for the chassis model in source code. The mechanical system consists of 9 bodies. The nonlinear wheel-suspension kinematics and elastokinematics is modeled using look-up tables, leading to a total number of 14 kinematic and 20 elastokinematic degrees of freedom. These look-up tables are measured or generated off-line by (pre-existing) high-resolution MESA VERDE or ADAMS models and then imported into the real-time environment. The wheels are suspended independently or the two suspensions of the same axle are interconnected by mechanical devices. Force elements (springs, dampers, bump-stops, ...) are represented by nonlinear relations. The complexity of IPG-CAR might be compared to that of ARHMM - widely used in french automotive industry (PSA, Renault) -, parts of which were specified by IPG in a consultant project.

The mathematical model of the chassis is augmented with models of the vehicle subsystems that act upon or are acted upon by the dynamics model. Most of them include nonlinear characteristics and additional differential equations (dynamic elements). They will be described next.

B IPG-TRAILER



In order to test an ESP-controller, the use of an insulated vehicle only is insufficient. It is of additional importance to study the motions of a vehicle interacting with a trailer. This is particularly true, because the trailer-brakes are passive i.e. they are not controlled by the ECU of the vehicle. This might lead to an oscillatory behavior, which can become self-excited, finally leading to a possible instability of the entire vehicle. Accordingly, a detailed HIL-analysis of this coupled car-trailer-system is essential for the overall-assessment of ECU performance.

The equations of motion of the trailer are again formulated using MESA VERDE. The model contains one or two axles and most of the suspension types which are encountered in reality. Special attention is paid to the modeling of the trailer-tractor connection, because it is a critical element in stabilizing or destabilizing the whole dynamical system. The compliance of the suspensions is also accounted for.

C Powertrain

The power transmission system is a critical component of any vehicle. The IPG power transmission system contains a number of specialized components, which fulfill three purposes: creation, transformation or switching of power. The powertrain is in itself a dynamical subsystem.

- A nonlinear SIMULINK engine model developed by PORSCHE, which has been translated into C-Code using MathWorks' Real-Time Workshop is used. As with other SIMULINK models, IPG's SIMULINK interface provides a seamless integration of SIMULINK models into IPG's real-time software.
- Power transformation includes torque converters, gearing and axle-differentials. A torque converter is a fluid coupling creating a torque-speed relationship which is dependent on the speed differentials of the input and the output elements. Axle differentials compensate for the wheel speed differences due to vehicle maneuvering. The torque/speed relationship between the input shaft and the output shaft depends on the particular design.

- The clutch model employed represents the slipping clutch torque as a function of clutch pressure and slip velocity and the locked clutch torque as a function of relative shaft angle and clutch pressure. The clutch pressure as well as the transmitted torque level determine whether the clutch is slipping or locked.

D IPG-TIRE

As is well known, the dynamic performance of a vehicle is determined in large measure by the interaction of its tires with the road surface on which it is operating. Effective tyre force modeling is therefore crucial. IPG-TIRE takes into account transient nonlinear tyre responses and gives realistic results in the frequency range up to 30Hz and in the full range of tyre behavior. The TYDEX-format provides a standard interface to other tyre models. A library containing different tyre models e.g. some of the latest versions of Pacejka's Magic Formula have also been included in the simulation environment.

E IPG-ROAD

In addition to sufficiently realistic tire-models that compute tire forces and torques and transfer them to the wheel body in the multibody dynamics model, the road surface itself must be modeled to a high degree of detail, with respect to both, geometry and surface properties, such as friction. IPG-ROAD allows to asses the course details automatically (i.e. via an interface) from standard course-databases. The legendary Nürburgring Nordschleife as well as several famous cols in the Italian Alps (some of them being longer than 30km and with extremely steep grades and many hairpin curves) have been modeled using this method. A „road-pool" containing these and many other roads continues to grow. Another comfortable method consists in extracting course details from detailed topographical maps and/or engineering-drawings and to assemble them piece by piece using a graphical user-interface.

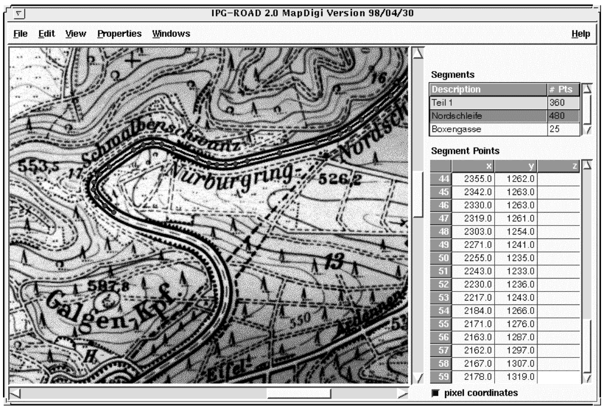


Figure 3 - A digitizing tool allows to model roads of arbitrary complexity and length.

F IPG-DRIVER

From a control-theory point of view the driver can be

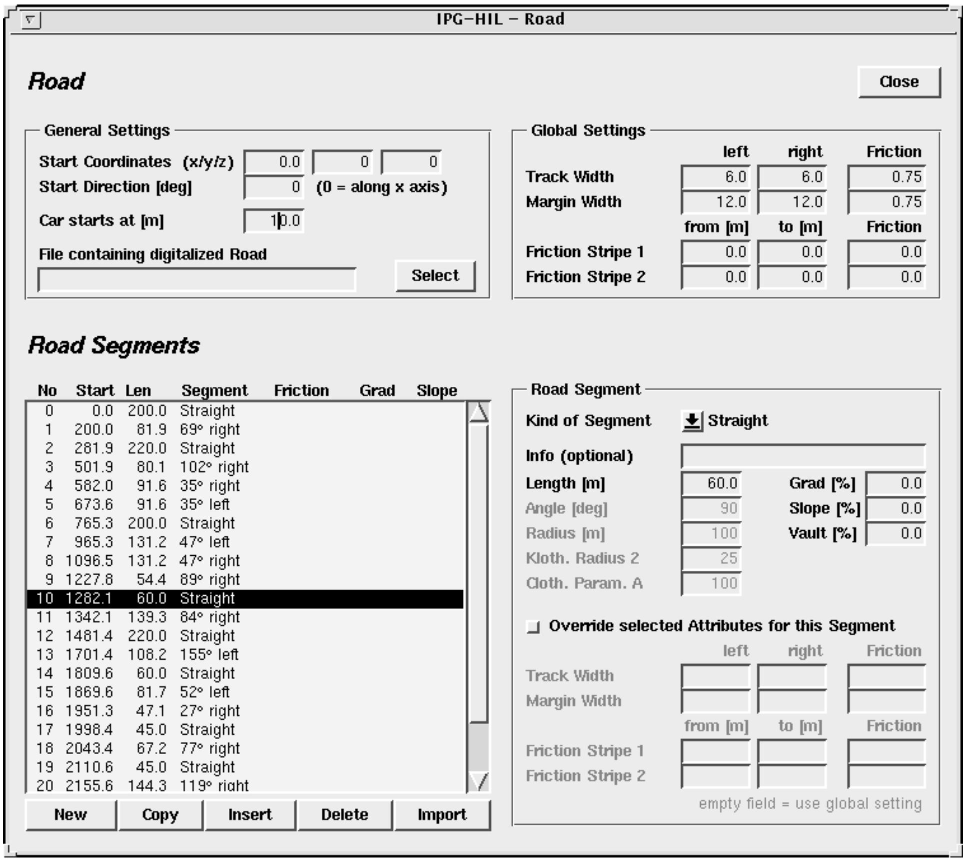


Figure 4 - The IPG-ROAD graphical user interface allows to define a realistic road topography just by "snapping" predefined segments together. Via a mouseclick IPG-ROAD produces IPG-MOVIE object-files, so you immediately see what you get.

thought as a controller which receives a number of inputs from the vehicle and the environment and outputs a few control signals. The predominant importance of a driver model in HIL is obvious: without a driver closed-loop simulations on complex tracks are impossible. IPG-DRIVER anticipates the driving situation ahead and adapts itself to the dynamics of the vehicle - much as a human driver does. Over the past decade IPG-DRIVER (also available as ADAMS/Driver) has firmly established itself as the *de-facto* standard for vehicle dynamics simulations.

IV. - MODEL VALIDATION

In order to validate the model, test drivers run a real car over a flat proving ground. Approximately 50 channels of vehicle and human performance data are collected during these runs. Via a special data import interface, the human performance data (steering wheel angle, accelerator, clutch and brake pedal position, gear-shift position) is then fed into the HIL model, with the same vehicle data being collected. Correlating the simulated and measured results allows to show the validity of the model.

Beyond model verification this import interface makes it possible to utilize the HIL environment to reproduce ECU errors which occurred during field tests.

V. - SIMULATION ANALYSIS

- IPG-CONTROL is a powerful tool for on-line (i.e. without interrupting the simulation) data display and analysis of virtually all the variables of the simulation. IPG-CONTROL structures the variables hierarchically and shows them simply by a mouse click. It is possible to overlay several signals in one frame. The zooming functionality allows to examine the signals in greater detail.

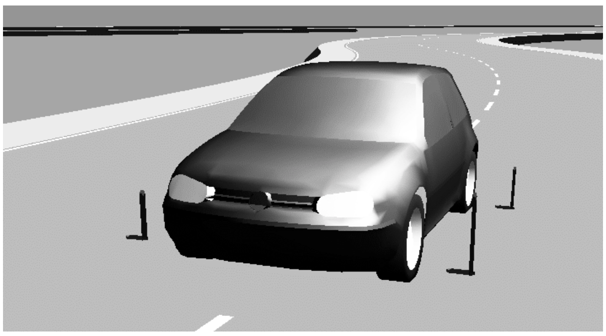


Figure 5 - IPG-MOVIE provides the engineer with a visually driven analysis environment.

- IPG-MOVIE: What you see is what you simulate! IPG-MOVIE is a powerful mouse-controled software-tool for online animation. It has been fully integrated into the HIL environment. Road-data, for example, is automatically transformed into movie-objects, with no further action by the user.

VI. - GRAPHICAL USER INTERFACE

The IPG-HIL graphical user-interface (GUI) is key to give engineers, who may not necessarily have extensive knowledge of computers, an easy-to-use simulation environment. It allows to work in a manner that parallels the way many test-engineers already test their vehicles in reality. It also improves the productivity of test-engineers by allowing them to focus on their core competencies.

VII. - TEST SERIES

People who test or develop new ECUs often work through many cycles of product development and/or testing. To be productive requires that these cycles are quick and are documented with careful records.

The IPG-HIL environment streamlines these cycles in ways that enhance the productivity of the user: The simulation environment is made available as a ready-to-run program. All inputs and parameters (vehicle definition, performance information) of a specific test-run are automatically logged. A professional database management system helps to keep the different HIL-applications transparent. It is easy to import existing datasets into new situations etc.

The IPG test-rig can be used to test and to control the *effects of variability* (of a parameter) on an ECU design. A variable (or imprecise) parameter is a parameter that may potentially assume any value within a possible range. The mass of the chassis or friction coefficients are typical examples. When variation is ignored, a nonrobust ECU can result that fails in service. Variations are defined in terms of tolerances which bracket the expected derivation of the model parameters. Test-runs are then repeated automatically again and again, for hours, days or weeks. And only in the case of failure, the failure situation is stored on the disc.

VIII. - SUMMARY

Car companies are commercial enterprises that are expected to make profit. They have to operate in a highly competitive market, in which design, styling and performance play a big part in influencing the decision to buy a particular vehicle.

It is therefore not surprising that *Active Vehicle Control* (AVC) systems, which help the driver to keep control of the vehicle in critical situations, is seen as an opportunity to steal a march on the competition. This is why car manufacturers are increasingly focussing on AVC technologies to attract prospective buyers. Notable well known examples include ABS and ASR. Recently several car manufacturers have improved performance by incorporating ESP systems, and others are planning to do so within the next few years. These systems actively intervene in the driving task by applying, where necessary, the brakes and the engine management system.

As we prepare to move towards the new millennium, there are new and emerging AVC systems in the pipeline.

Car manufacturers pride themselves on the ability to constantly improve the quality and reliability of the vehicles they produce. This needs very high standards being applied throughout the supply chain. This, of late, applies to the company's component suppliers delivering top-quality-products. Controlling quality is well understood when applied to conventional car components, but testing vehicle dynamics control systems is a completely different ballgame: the complex interaction between hydraulics, mechanics and electronics is difficult to understand at the best of times and - it seems to be so trivial as to be not worth mentioning - tests are only as good as the "data" used as input.

This has led IPG, a software and knowledge provider for car companies all over the world, to set up an extremely useful CAT-tool for AVC systems. This tool treats the control system, say ESP, as some kind of a black-box, whereas the "rest of the world" is present as a virtual component.

User-friendliness and real-time animation ensures a high level of acceptance and a short training period. With this conclusive simulation concept IPG is now a recognized market leader in the field.

By learning "lessons" on a computer-based environment, testers can conduct smarter, more focussed testing in the real-world. Moreover, laboratory testing enabled IPG costumers to detect structural hardware faults which had not previously been detected by real-vehicle testing. Summarizing the impression emerging from this fact: *At times virtual environments allow higher testing quality than the real world!* The result is a vehicle that is far more thoroughly shaken out than would have been possible with real-world testing alone.

In the future the pace of development is sure to be even faster than it is today. IPG-HIL helps to win the time-to-market battle, thereby incurring minimal engineering cost.

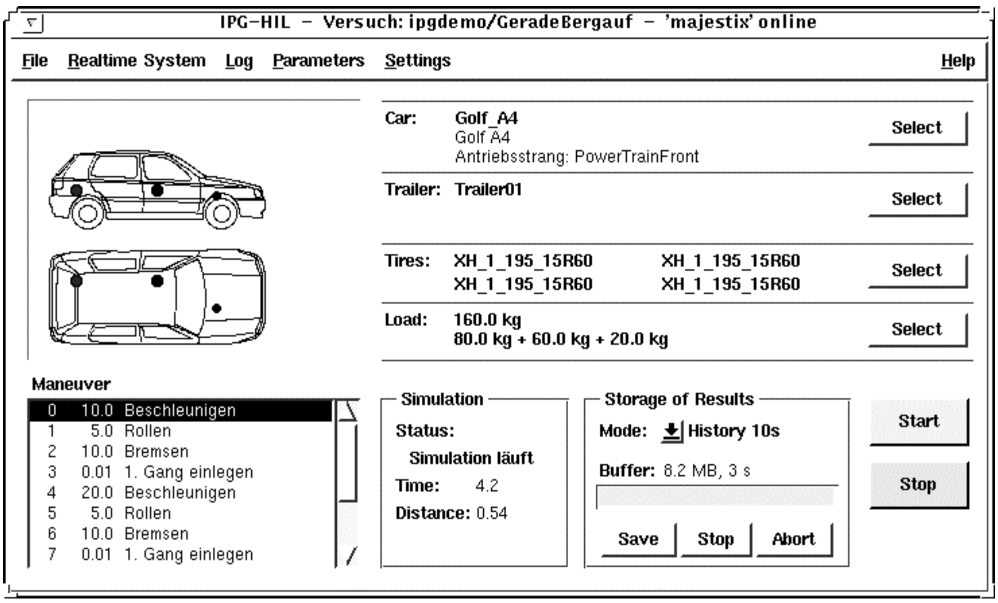


Figure 6 - IPG's unparalleled graphical-user-interface reflects the unique nature of the HIL-architecture itselfs. It enables the developer to be fully productive as quickly as possible