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Test Automation based on Computer Chess Principles

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Abstract

Automotive transmission systems are difficult to test and validate, due to the complex interaction of mechanics, hydraulics, electronics, and transmission control software. The tight interaction among an ever increasing amount of software functions and hardware subsystems leads to a new kind of complexity that is difficult to manage during mechatronic design. System tests have to consider huge amounts of relevant test cases. Validation with limited resources (time and costs) is a challenge for the development teams. We present a new instrument that should help engineers in dealing with the complexity of test and validation of transmission systems. TestWeaver is based on a novel approach that aims at maximizing test coverage with minimal work load for the test engineer for specifying test cases. The method integrates simulation (MiL/SiL) with automatic generation and evaluation of test cases, and has found successful applications in the automotive industry. We illustrate the approach using a 6-speed automatic transmission for passenger cars.

1 Introduction

When developing complex mechatronic systems, like a hybrid drive train or an automatic transmission for a vehicle, contributions from different engineering disciplines, design teams, departments, and organizations have to be integrated, resulting in a complex design process. Consequently, during development, design flaws and coding errors are unavoidable. For an OEM, it is then crucial that all those bugs and weak points are found and eliminated in time, i.e. before the system is produced and delivered to customers. Failing to do so may result in expensive recalls, high warranty costs, and customer dissatisfaction. OEMs have long realized this and spend up to 40% of their development budgets for test related activities. Software offers great flexibility to implement new functions, but also many hidden opportunities to introduce bugs that are hard to discover. Moreover, the complex behaviour that results from the interaction of software and physical systems cannot be formally and completely analysed and validated. Most often, it can only be evaluated in a limited amount of points with physical or virtual experiments. The development teams are often faced with a dilemma: on the one side, the system test should cover a huge space of relevant test cases, on the other, there is only a very limited amount of available resources (time and costs) for this purpose.

This paper presents a novel test method that has the potential to dramatically increase the coverage of testing without increasing the work load for test engineers. We achieve this by generating and executing thousands of tests automatically, including an initial, automated assessment of test results. The test generation can be focused on certain state spaces using constraints and coverage goals.

This paper is structured as follows: In section 2, we take a bird's-eye view on testing mechatronic systems. In section 3, we survey the main test methods used in the automotive industry today. Section 4 presents the proposed test method. Section 5 illustrates the proposed method using a 6-speed automatic transmission for passenger cars. Section 6 discusses implementation options for the required simulation model. We conclude the paper with a summary of the benefits of our test method, and discuss its applicability to other engineering domains.

2 The challenge of testing

When testing a mechatronic system, it is usually not sufficient to test the system under laboratory conditions for a couple of idealized use cases. Instead, to increase the chance to discover all hidden bugs and design flaws, the system should be tested in as many different relevant conditions as possible. Consider as an example an assembly such as an automatic transmission used in a passenger car.

In this case, the space of working conditions extends at least along the following dimensions:

- *weather*: for example, temperatures range from -40°C to 40°C , with significant impact on oil properties of hydraulic subsystems
- *street*: different road profiles, uphill, down hill, curves, different friction laws for road-wheel contact
- *driver*: variations of attitude and behavior of the human driver, including unforeseen (strange) ways of driving the car
- *spontaneous component faults*: during operation, components of the assembly may spontaneously fail at any time; the control software of the assembly must detect and react appropriately to these situations, in order to guarantee passenger safety and to avoid more serious damage
- *production tolerances*: mechanical, electrical and other physical properties of the involved components vary within certain ranges depending on the manufacturing process
- *aging*: parameter values drift for certain components during the life time of the assembly
- *interaction with other assemblies*: a transmission communicates with other assemblies (engine, brake system) through a network that implements distributed functions; for example, during gear shifts, the transmission might ask the engine to reduce the torque in order to protect the switching components.

These dimensions span a huge space of possible operational conditions for an assembly. The possibilities along each dimension multiply to form a huge cross-product. The ultimate goal of testing is to verify that the system performs adequately at every single point of that space. It would be great to have techniques to mathematically prove certain properties of the system (such as the absence of unwanted behavior), which would enable a test engineer to cover infinitely many cases within a single work step. However, such proof techniques (e.g. model checking, cf. [1]) are by far too limited to deal with the complexity of the system level test considered here.

In practice, the goal of covering the entire state space is approximated by considering a finite number of test cases of that space.

3 A critical view on some test methods in use

Testing at different functional integration levels (e. g. component, module, system, vehicle) and in different setups (e.g. MiL, SiL, HiL, physical prototypes) is nowadays an important, integral part of the development process. The earlier problems are discovered and eliminated, the better.

Very often, however:

- relevant tests can only be formulated, or have to be repeated, at system level - consider, for instance, the system reaction in case of component faults
- system-level tests are only performed in a HiL or physical prototype setup.

There are several reasons why the latter is very often the case. An important one stems from the complexity of the mechatronic development processes: several disciplines, teams, tools, suppliers – together with lacking standards and practices for exchanging and integrating executable functional models.

Let us briefly review some of the limitations of the HiL- and physical prototype based testing:

- *time, costs, safety*: physical prototypes and HiL setups are quite expensive and busy resources; testing takes place late in the development cycle; not too many tests can be conducted; the reaction to certain component faults cannot be tested with physical prototypes due to safety hazards
- *lack of agility*: it usually takes a long time between the change of a software function and the test of its effects
- *limited precision or visibility*: due to real-time requirements the physical system models used in HiL setups are often extremely simplified and therefore extremely imprecise; debugging and inspection of hidden system properties is difficult if not impossible for these setups.

Note, the above limitations are not present in MiL / SiL setups. While the importance of the HiL tests and of the tests based on physical prototypes should not be underestimated, our argument here is that they must be complemented by a more significant role of MiL and SiL tests at system level. See also [2], [3].

Irrespective of the setup used, the main limitation of common system-level test practices is the limited test coverage that can be achieved with reasonable effort. For example, test automation in a MiL / HiL setup is typically based on hand-coded test scripts for stimulating the partially simulated assembly with a sequence of test inputs, including code for validating the measured response. Coding and debugging such test scripts is a labor intensive task. Given typical time frames and man power available for testing, only few (say a few dozen) cases from the huge space of possible use cases can be effectively addressed by such a script-based approach. For testing using a test rig or by driving a car on the road, this figure is even worse. For example, it is practically impossible to systematically explore the assembly's response in the case of single component faults in a setup that involves dozens of physical (not simulated) components.

When testing for the presence or absence of a certain system property (such as 'the clutches should not get too hot during gear shifts'), script-based tests verify such a condition only during a few, specifically designed scenarios and not throughout all tests.

In practice, this means that many scenarios are never explored during system test and that for those scenarios explored, usually only a few of the relevant system properties are tested. Consequently, bugs and design flaws may survive all tests. These are risks the method presented here can help to reduce, adding additional robustness to the design process.

4 Exploring system behavior with TestWeaver

TestWeaver is a tool supporting the systematic test of complex systems in an autonomous, exploratory manner. Although the method could, in principle, be applied to HiL setups as well, it is primarily geared towards supporting the MiL and SiL setups. The main benefit of using TestWeaver for system test is:

- dramatically increase of test coverage, with respect to system behavior
- with low workload for the test engineer .

To achieve this, TestWeaver generates test cases autonomously. Hand-coded test scripts can still be used, but the overall test process does not longer exclusively depend on hand-coded test scripts any more, overcoming thus the main hindrance on the way towards broad test coverage.

4.1 The “chess” principle

The key idea behind TestWeaver is: Testing a system under test (SUT) is like playing chess against the SUT and trying to drive it into a state where it violates its specification. If the tester has found a sequence of moves that drives the SUT in such an unwanted state, he has won a game, and the sequence of moves represents a failed test.

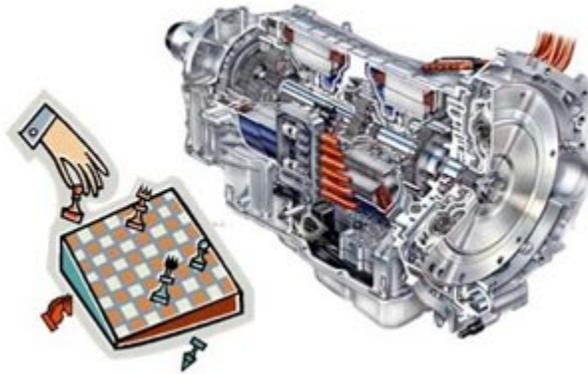


Figure 1: The chess principle

There are more analogies: To decide for a next best move, chess computers just explore recursively all legal moves possible in the current state and test whether these lead to a goal state. This search process generates a huge tree of alternative (branching) games. In TestWeaver, the automated search for bugs and design flaws is organized quite similarly (Fig. 4). TestWeaver requires that the SUT is available as an executable simulation (MiL) or as a co-simulation of several modules (SiL). As usually done, the SUT is augmented with a few components that communicate with the test driver. These communication components, called *instruments*, implicitly carry the “rules of the game” that TestWeaver is “playing” with the instrumented SUT. Namely, they carry information about: the control actions that are legal in a certain situation, the interesting qualitative states reached by the SUT, and, eventually, the violation of certain system requirements. Each instrument specifies a (relevant) dimension of the SUT state space. The value domain along each dimension has to be split into a finite set of partitions. Each SUT, or SUT-module, has to be configured individually by placing and parameterizing the instruments inside the SUT. The “game” is played in this multi-dimensional partitioned system space.

Given an instrument SUT, TestWeaver systematically generates thousands of differing simulation scenarios. For this purpose TestWeaver analyses the results of the past simulations in order to intelligently (a) search for violations of specifications and to (b) maximize the test coverage.

Test coverage is defined as follows: the domain of each variable controlled or monitored by a TestWeaver instrument is partitioned into a small set of intervals by that instrument. This way, the instruments of a model define an n-dimensional discrete (i.e. finite) state space. The coverage goal of TestWeaver is to reach every reachable discrete state in that space at least once.

4.2 Instruments

An instrument is basically a small piece of code added to the uninstrumented version of the SUT using the native language of the executable, e. g. Modelica, Matlab/Simulink, Python, or C. The instruments can be placed inside a model (e.g. Simulink, or Modelica), or - in case of co-simulation - into a separate module, implemented e.g. using Python. The instruments communicate with TestWeaver during test execution, which enables TestWeaver to drive the test, to keep track of reached states, and to decide during test execution whether an undesired state (failure) has been reached. TestWeaver supports basically two kinds of instruments, *action choosers* and *state reporters*, that can come in several flavors:

1. state reporter: this instrument monitors a discrete or a continuous variable (e.g. a double) of the SUT, and maps its value onto a small set of partitions or discrete values (e.g. low, medium, high). During test, this instrument reports the discrete value of the monitored variable to TestWeaver. This is used by TestWeaver to keep track of reached states and to maximize the coverage of the partitioned / discrete state space.

2. alarm reporter: this is actually a state reporter. In addition the partitions are associated with severity levels, such as nominal, warning, alarm, and error. The reachability of a “bad” state corresponds to a failure of the test currently executed. Note: these failure conditions are verified throughout all the tests run by TestWeaver.

3. action chooser: this instrument is associated with an input variable of the SUT. In an automotive application, an input variable may represent the acceleration pedal or the brake pedal of a car. Depending on the details of the instrumentation, this instrument asks TestWeaver either periodically or when a trigger condition becomes true to choose a discrete input value for its input variable from the partitioned value domain of the variable.

4. fault chooser: this is a special case of action chooser. The value domain is partitioned into nominal and fault partitions and can be used to represent alternative fault modes of a component of the SUT. For example, a shift valve model may have behavior modes such as: ok, stuck-Closed, and stuckOpen. Instruments like these are used by TestWeaver to inject (activate) a component fault occurring spontaneously during test execution.

Instrument heatA

Instrument role: ALARM

Instrument type: REAL

Instrument unit: J

Declared by: Car

partitions	occurrence	severity	color	values
damaged	10	10	#F03939	80000.0 : 1.0E10
ok	10	0	#AFDFDF	-0.1 : 40000.0
hot	10	0	#7FBFBF	40000.0 : 80000.0

Figure 2: Reporter shown in Fig. 6 as displayed by TestWeaver

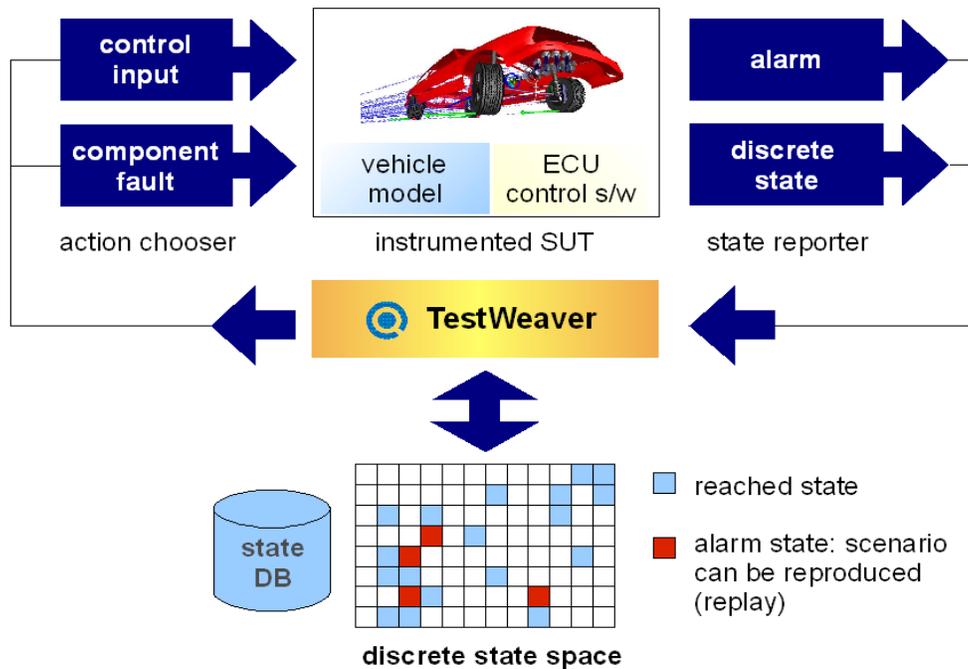


Figure 3: Instruments connect SUT to TestWeaver

Engineers like to work with their favorite modeling environment. Therefore the above instruments are available for many modeling environments and programming languages, including Matlab/Simulink, Modelica, Python, Silver, and C/C++. The idea is to allow the test engineers to instrument a SUT in their favorite modeling language, i.e. using the native implementation language of the SUT, or of the SUT-module that they are working on.

In addition to the explicit instruments, TestWeaver monitors the process of executing the SUT and records problems, such as divisions by zero, memory access violations, or timeouts in the communication.

4.3 Experiments, scenarios and reports

In TestWeaver, an *experiment* is the process of exploring and documenting the states reached by the SUT during a certain period of time, possibly taking into consideration additional search constraints and coverage goals. An experiment usually runs completely autonomously for a long time, typically several hours, and without requiring any user interaction.

When running an experiment, TestWeaver generates many differing scenarios, by generating differing sequences of answers for the action choosers. A *scenario* is the trace (or protocol) of a simulation run of the given SUT in the partitioned state space. TestWeaver combines several strategies in order to maximize the coverage of the reached system states and to increase the probability of finding failures. The results are stored in a *scenario data base* of the experiment, i.e. a tree of scenarios (actually a directed graph), as shown in Fig. 4.

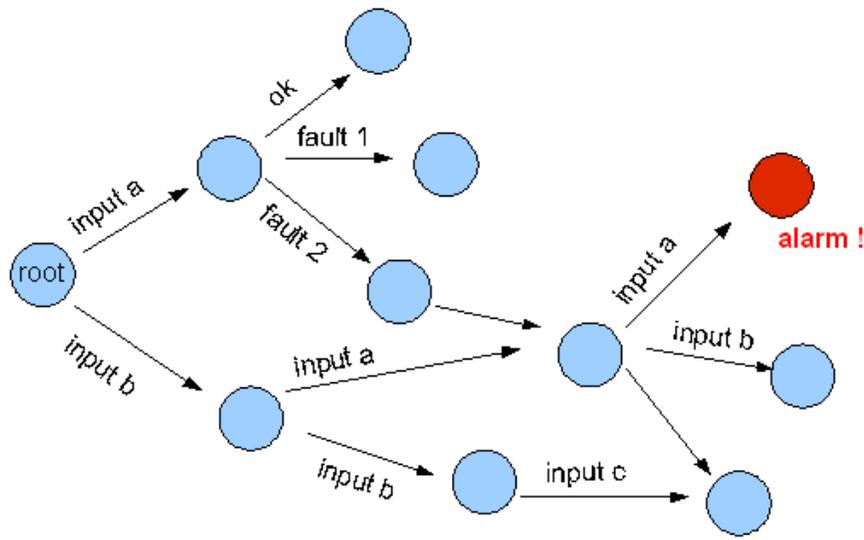


Figure 4: Scenarios generated by an experiment

The user can investigate the states reached in an experiment using a high level query language similar to the SQL select statement. Results are displayed in reports. A *report* is basically a table that displays selected properties of the scenarios stored in the scenario data base. The user specifies the structure and layout of a table by templates, while the content of a table depends on the content of the scenario data base. There are two kinds of reports: *overview reports*, that document state reachability, and *scenario reports*, that document details of individual scenarios.

For example, the overview report shown in Fig 8 is specified by the following select statement

```
select currentGear, targetGear, clutchA, clutchB, set(2, scenarios)
from States
group by currentGear, targetGear, clutchA, clutchB;
```

The colors of table cells are generated by TestWeaver automatically, where red marks alarms and green-blue marks nominal states. A report may also contain editable comment columns used by the test engineer to assign his assesment of the relevance of alarms and counter measures. This supports traceability of all identified problems.

A user may specify, start, and stop an experiment, reset the experiment's data base and investigate the reports generated by the experiment, the last even while the experiment is running. Individual scenarios can be *replayed*: i.e. the SUT is restarted and is fed with the same sequence of inputs as the one recorded in order to allow detailed debugging of a problem, e.g. by plotting signals and other means.

4.4 The experiment focus

The dimensions and the partitions of the state space are configured by the instruments of the SUT. Apart of these there are also other means that can constrain the exploration, either as part of the instrumented SUT, or as explicetly defined in the specification of the *experiment focus* in TestWeaver. The focus of an experiment specifies which region of the state space should be investigated when running the experiment. During an experiment, TestWeaver tries to drive the SUT into those states that are in the experiment's focus. The experiment focus is currently specified using two means:

- *constraints*: the constraints limit the size of the considered state space of an experiment. They can limit, for instance, the duration of a scenario, or the allowed combinations of inputs and states. A high level constraint language is provided for this purpose. In an automotive application, a user could, for example, exclude all scenarios where brake pedal and acceleration pedal are engaged simultaneously. For a fault analysis, a constraint could be used to exclude certain fault modes from investigation, or to limit the number of faults inserted in a scenario: typical values are 0, 1 and 2. Higher numbers are reasonable when investigating fault-tolerant systems, e.g. systems with complex fault detection and reconfiguration mechanisms
- *coverage*: the user can tell TestWeaver to use some of the reports of the experiment as defining the coverage goals of the experiment. A report used in this way is called coverage report.

Experiments with different SUT versions and with different focus specifications can be created, run and compared with each other.

4.5 Analyzing and debugging problems

The alarm and error states of the SUT are reported in the overview reports. For each problem one or more scenarios that reach that state can be recalled from the scenario database. The scenarios can be again *replayed* and additional investigation means can be connected. Depending on the SUT simulation environment these can be, for instance: plotting additional signals, connecting additional visualization means such as animation, setting breakpoints, and even connecting to step-by-step evaluation with source code debuggers – for instance for SUT modules developed in C.

5 Example: automatic transmission

As an application example for TestWeaver, consider the development of the control software for an automatic transmission. An instrumented Modelica model of an entire car, including the transmission is shown in Fig. 5. The connection object establishes a TCP/IP connection of the model to TestWeaver, enabling TestWeaver to remotely control the model and to monitor its behavior.

In the example, the control software is developed using Simulink. The executable SUT is created as Silver co-simulation of two modules: the compiled Simulink model of the control software, and the compiled Modelica model shown in Fig. 5.

Since the Modelica model has been instrumented, the SUT also contains functions to communicate with TestWeaver. When TestWeaver starts the SUT to perform a system test, all contained instruments register themselves at TestWeaver with all their declared static properties (intervals, labels, severities etc.). TestWeaver then displays a list of these instruments, see tree in Fig. 8. Selecting an instrument in the tree displays all its properties. Fig. 2. shows how TestWeaver displays the heat reporter of Fig. 6. The tree shown in Fig. 8 also contains an item for each report of the experiment. Selecting such a report displays the report as table. Fig. 8. shows a report that shows which gear shifts have already been reached during the experiment, and whether critical temperatures at the clutches A and B have been reported. For each state, up to two scenarios are referenced in the right most column. Clicking on such a reference displays that scenario as a sequence of discrete states. It is possible to reproduce the entire scenario with an identical simulation such that the test engineer can access all its details. For ex-

ample, runtime exceptions of the control software (such as division by zero) can be reproduced this way and inspected using the usual software debugging tools.

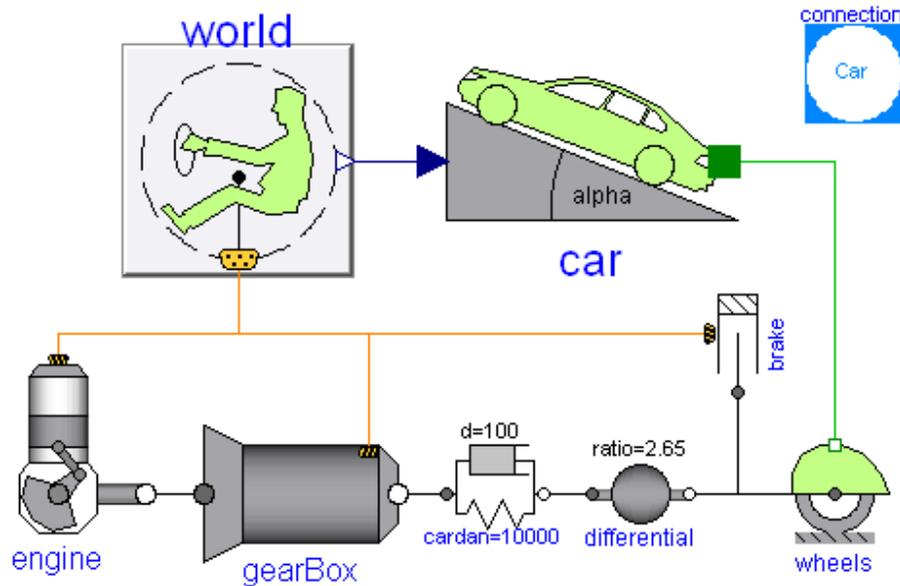


Figure 5: An instrumented car model

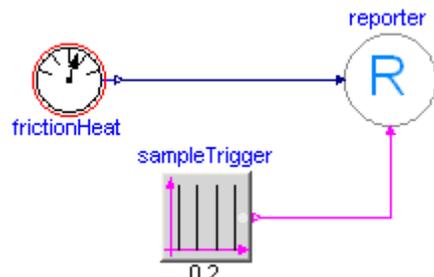


Figure 6: Reporting a temperature.

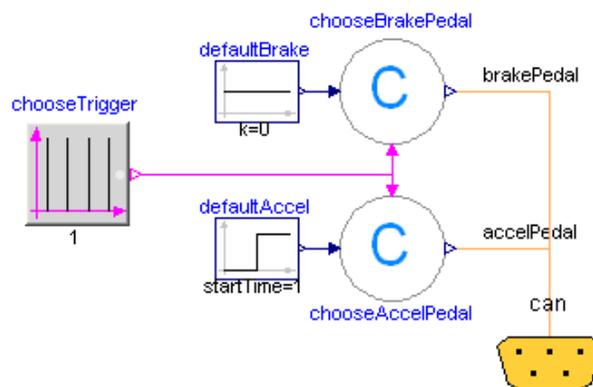


Figure 7: Controlling two pedals in a car

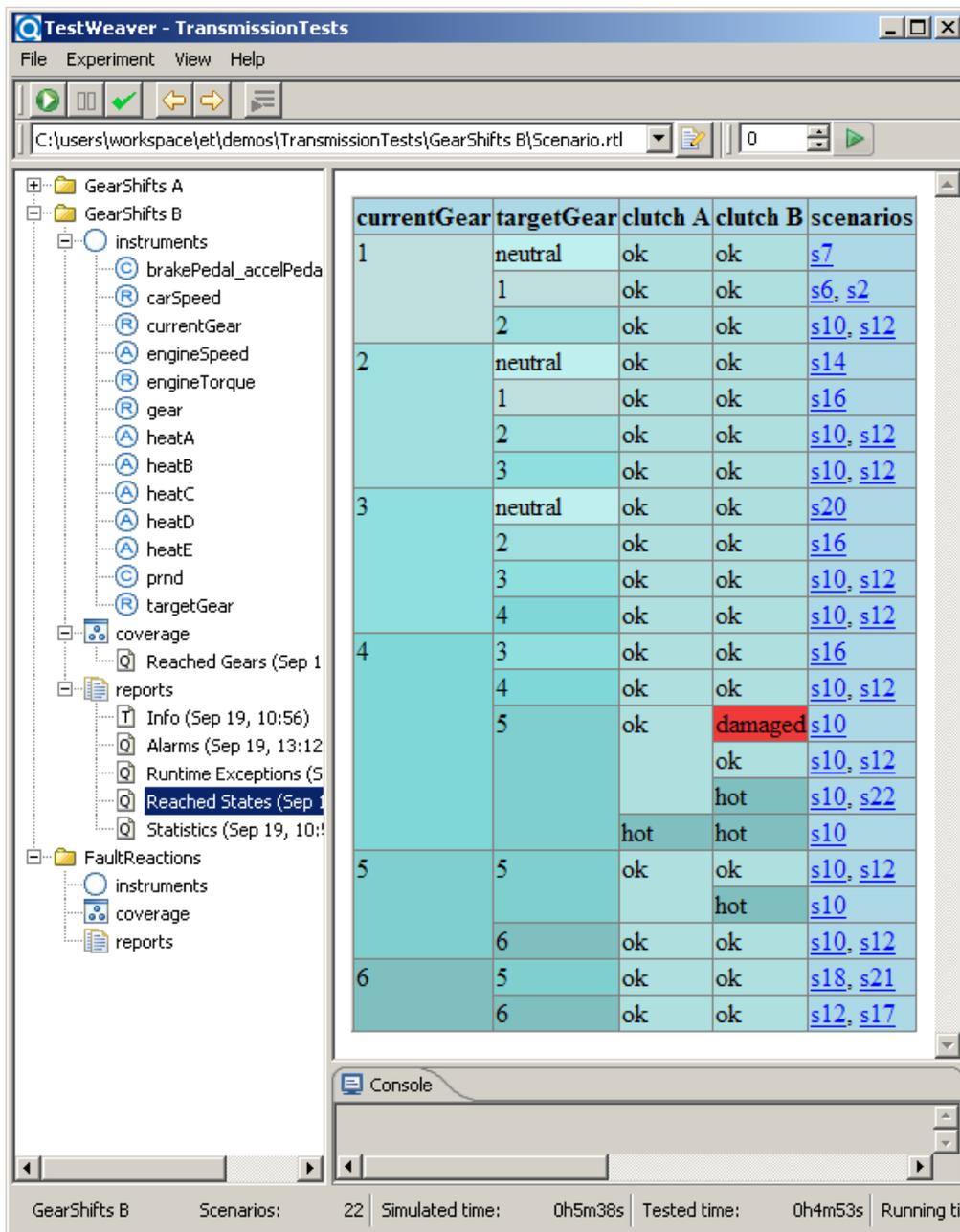


Figure 8: TestWeaver displaying an overview report

6 Implementation of the simulation model

TestWeaver requires a simulation model of the system under test (SUT). Such models are often available anyway, due to the model-based development process, the standard approach for automotive software development today. TestWeaver communicates with the SUT exclusively through the instruments described in Section 4. This simplifies the connection of TestWeaver to simulation tools and environments a lot. TestWeaver has been connected to the following simu-

lation tools and programming environments: Visual C/C++ (Microsoft), Python 2.5, Matlab/Simulink with RealTime Workshop R2006 (MathWorks) or TargetLink (dSpace), Modelica/Dymola 6.x (Dynasim), Modelica/SimulationX 3.1 (ITI). A connection to Simpack (Intec) is currently under development.

The SUT can also be implemented as co-simulation of several modules, where each module can be developed with another tool. For example, the vehicle model may be implemented using Modelica, the control software using Simulink, and the TestWeaver instruments using a Python script. A co-simulation tool such as Silver [3] can then be used to run the composed model. To use Silver, all modules have to be exported from their native development environments as compiled, self-integrating modules (dynamic link library DLL). The required export functions are delivered with Silver. The exported modules are then cyclically executed by Silver within a single process using fixed macro step width. The modules exchange signals at each macro step. Within a macro step, a module may use variable step size on a much finer scale to perform numerical integration. The macro step width corresponds to the sampling rate of the involved ECUs, e.g. 10 ms for a typical TCU. This way, Silver enables a virtual system integration and an assessment of the resulting system behaviour.

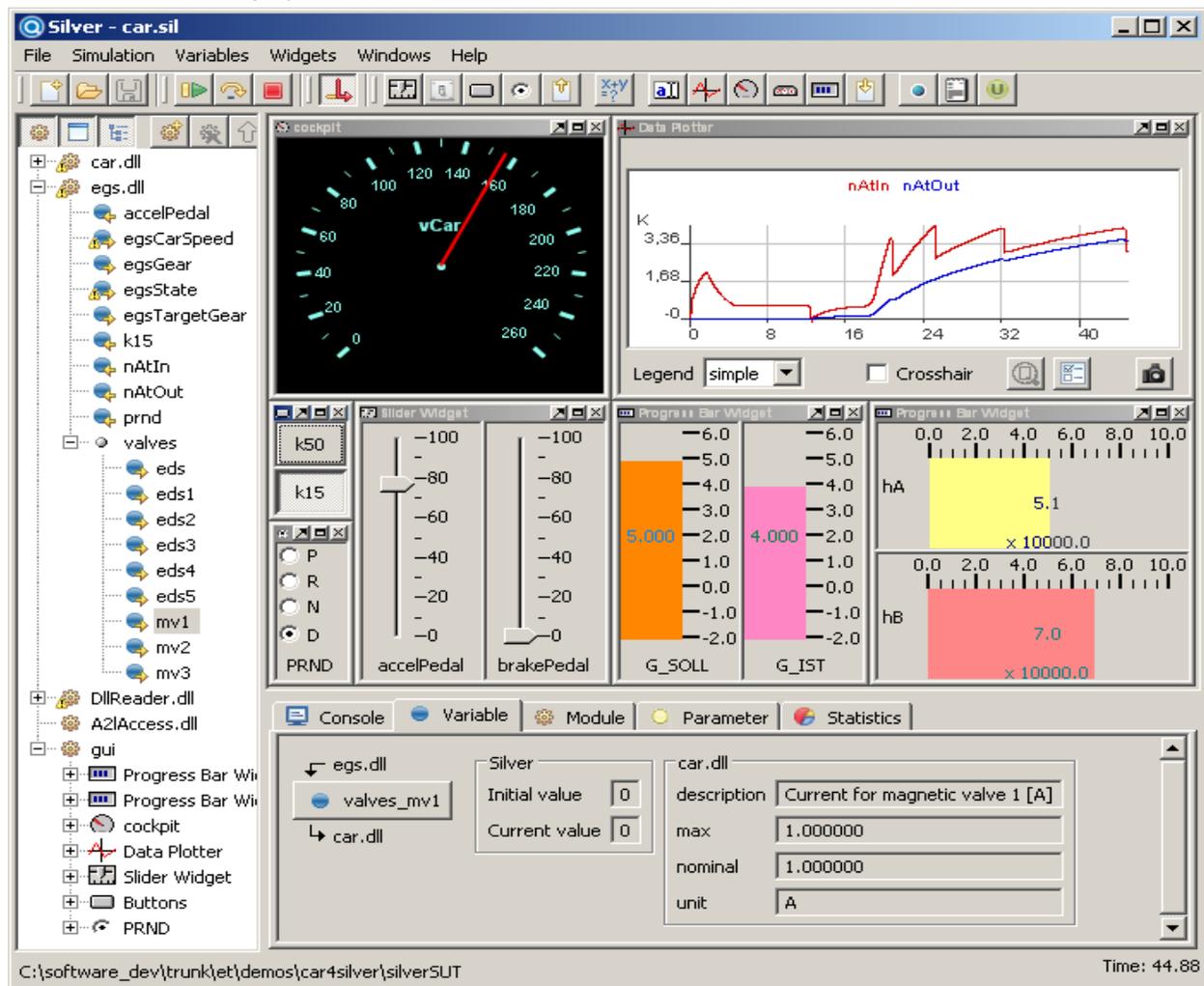


Figure 9: Co-Simulation with Silver

The advantages of the specific Silver approach to SiL/MiL is, besides the ones already discussed in section 3:

- Exchange of compiled modules does not expose module sources. This simplifies collaboration between OEMs and suppliers.
- Compiled modules run much faster than their interpreted counterparts, e.g. in Simulink. This is relevant here, because TestWeaver runs many simulations during an experiment.
- Modules can be developed with different tools. This way, the optimal tool can be used for each modelling task.
- Integration of vehicle calibration data through ASAP2/A2L (ASAM), DCM (ETAS) and of measurements through MDF. Support of measurement and calibration through XCP (ASAM). This way, TestWeaver can test the system together with the calibration data. Moreover, Silver can be connected to the same calibration tools (e.g. CANape) that are also used in the real vehicle.
- Powerful test and debugging options: tools for test automation (such as TestWeaver), JIT (just in time) debugging of Microsoft Visual C/C++ to catch exceptions in the ECU software and to step through the program code.
- Built-in TestWeaver instruments: Silver contains build-in instruments to catch program exceptions and to report these to TestWeaver, including additional information such as kind of exception and line of code in the program source.

Fig. 9 shows a vehicle simulation in Silver. Modules and their input and outputs variables are shown on the left to the configurable user interface, used here to start and drive the simulated car.

7 Summary and conclusions

The increasing pressure to shorten and cheapen development for more and more complex products requires new test strategies. Today we see early module tests and late system-level tests, like HiL and test-rigs, as state of the art. The importance of early system-level testing increases with the increasing complexity of module interaction because bugs on system-level are more likely, more costly to fix and harder to find. Testing before physical prototypes exist, for both controllers and hardware, is one necessary step towards early system-level testing.

As long as the behavior of a system can be described easily using stimuli-response sets, script-based testing is a feasible strategy. With increasing system complexity, this method fails to provide the necessary coverage at reasonable cost. On the other side, our test method allows to:

- systematically investigate large state spaces with low specification costs: only the rules of the “game” have to be specified, not the individual scenarios
- discover new problems that do not show up when using only the predefined test scenarios prescribed by traditional test methods; TestWeaver can generate thousands of new, qualitatively differing tests, depending on the time allocated to an experiment
- increase the confidence that no hidden design flaws exist.

In section 5, we have sketched the application of TestWeaver to a SiL-based system test of an automatic transmission. We have several years of experience with this kind of applications. However, the application of TestWeaver to other domains seems promising as well, especially for those cases where a complex interaction between the software and the physical world exists.

For instance:

- *driver assistance systems*: in car systems such as ABS, ESP, etc. we meet a complex interaction among the control software, the vehicle dynamics and the human driver; this leads to myriads of relevant scenarios that should be investigated during design (cf. [6])
- *plant control systems*: in plants for chemical processes, power plants etc. we meet the interaction of the control software, plant physics and the actions of the operators; again, the same kind of complexity that calls for a systematic investigation during design.

TestWeaver and Silver are in everyday use in automatic transmission development projects, for instance at Daimler AG (cf. [7]). With the help of these new technologies, OEM and suppliers can develop very complex systems significantly faster, with lower costs, and yet with an increased reliability and quality.

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