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Model-based development and test of device drivers

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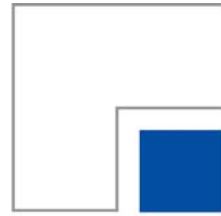
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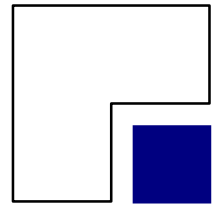
Working Papers

Kompetenz schafft Zukunft

Creating competence for the future

Model-based development and test of device drivers

Stefan Ferstl



Fachhochschule
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Abstract

The development of device drivers in the automotive industry is often confronted with the problem of not yet available hardware, which can be used for testing. This paper describes how to build up a test environment in Simulink, which contains a model of the physical and logical behavior of an intelligent smart power switch that is used to control multiple bulbs in a car. To get a closed-loop simulation, a bulb model was developed, which calculates the current depending on voltage and temperature for diagnostic purposes. By using this configurable environment, it was possible to develop and test a driver with TargetLink, although the device, which it has to control, was not yet available. In order to get experience in HIL tests using the interface between CANoe and Simulink, this approach was analyzed in detail.

1 Introduction

The software development for electronic control units in automotive applications was affected by a rapidly rising deadline pressure in the last years. More and more functions should be implemented in less time. This causes a decreasing testing time, since it is hard to shorten the time that is needed to program new features. Today, the effectiveness of the development- and quality assurance processes becomes a decisive factor for the capability of the product [1].

A new method, which is able to shorten both, implementation and testing time, is the model-based software development. It affects all parts of the software development process, i.e. the requirement management, software design, implementation and testing. This method should help to reduce the complexity of the software by using a more abstract view. It is even possible to reduce size and runtime by using code optimization modules for certain microcontrollers.

One of the aims of model-based development is to get an executable model of the functionality at an early stage. It is possible, for example, that the logical behavior of a component is completely described in a model, so that a specification sheet with all its ambiguities is not needed any longer. This model can be used as basis for the stepwise refinement of the interface description in the software design process. If the model meets all the requirements, it is possible to generate C-code for a specific target microcontroller automatically.

Another advantage is that the model can be tested with simulations of the real hardware. This reduces the test equipment needed, e.g. if an electric motor can be replaced with a correct model of its physical behavior. At the same time there is a rising variety of the test cases, because parameters, which are not constant over the life-span of the product, can easily be changed in the simulation. For this reason, it is possible to test whether the software can handle these variable parameters.

Even if the software has to control semiconductors, like the Smart Corner Light Switch (SCLS), a lot of possible faults can be avoided if all the material tolerances (dependencies on temperature, silicon, etc.) can be set to their maximal and minimal values.

2 Development of a model of the SCLS

2.1 Description of the SCLS

Modern cars contain about 50 to 80 electronic control units (ECUs). One of them is the body computer module. This device is used for applications with high current consumption, like wiper, seat heater and lighting. Previously, these loads were switched with relays.

The next step of development was the invention of Smart Power Switches, which consisted of MOSFETs that were able to carry high current. Nowadays, these semiconductors are able to protect themselves against various faults and to inform the microcontroller about their state.

The disadvantage of these devices is that the analysis of this information takes a lot of the microcontroller resources. Furthermore, a malfunction of the CPU would cause a failure of the complete lighting.

Because of this, Continental Temic and a manufacturer of semiconductors develop a new generation of high side power switches, the Smart Corner Light Switch. This ASIC contains five internal MOSFETs and a gate driver for one external MOSFET. Therefore, one SCLS can control all bulbs in one corner of the car:

Output	SCLS front	SCLS rear
Out1	Parking light	Tail light
Out2	Low beam	License light
Out3	High beam	Rear drive light
Out4	Fog light	Stop light
Out5	Indicator	Rear indicator
FETout	Spare	Rear fog light

Table 1: Typical loads

A mirror of the current through the bulbs is routed to the microcontroller. The desired output can be selected via the SPI interface. Control and diagnostic features are done via SPI, too. In normal case, the SCLS can produce pulse width modulation (PWM) for all outputs. If a fault was detected (e.g. a microcontroller crash), it is possible to control the most important functions (emergency and hazard light) by external inputs.

There are three different faults, which can be detected separately for the first five outputs: Open load, overcurrent and overtemperature. Overcurrent surveillance is very important in order to prevent short circuits, which would damage the cables or destroy the SCLS. The inconvenience of this measurement is the nonlinear characteristic of the connected bulb. In the simplest case, a standard halogen bulb is switched on at room temperature. In the first few milliseconds after switching it on, the current can be ten times the nominal one. The SCLS has three different current thresholds to satisfy this behavior. Figure 1 shows a typical bulb characteristic, which is enveloped by the overcurrent window:

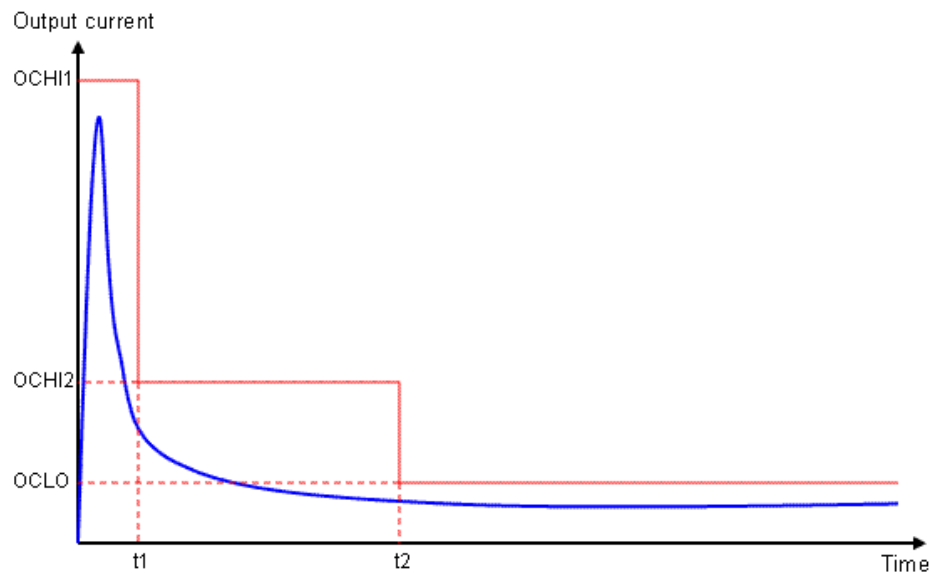


Figure 1: Bulb characteristic (blue) and overcurrent thresholds (red)

It is possible to configure each output for connected halogen bulbs, xenon bulbs or LEDs. The frequency and duty cycle for the PWM are generated by a clock signal that has to be applied at an input of the SCLS. For diagnostic purposes, it is possible to route one of the scaled output currents to a sense output. This is done by an internal multiplexer, which can be controlled via SPI. When receiving a command, the SCLS simultaneously sends one of three possible answer messages, containing the fault bits for the outputs and the device status.

2.2 Approach of modeling

The model of the SCLS was developed according to a simplified version of the V-model, in order to follow standardized software engineering processes. There are a lot of tools like IRqA, DOORS or INNOVATOR to support these processes for larger projects with several participants. Due to the small size of the project, the V-model, as shown in figure 2, was used as guideline, but with simplifications.

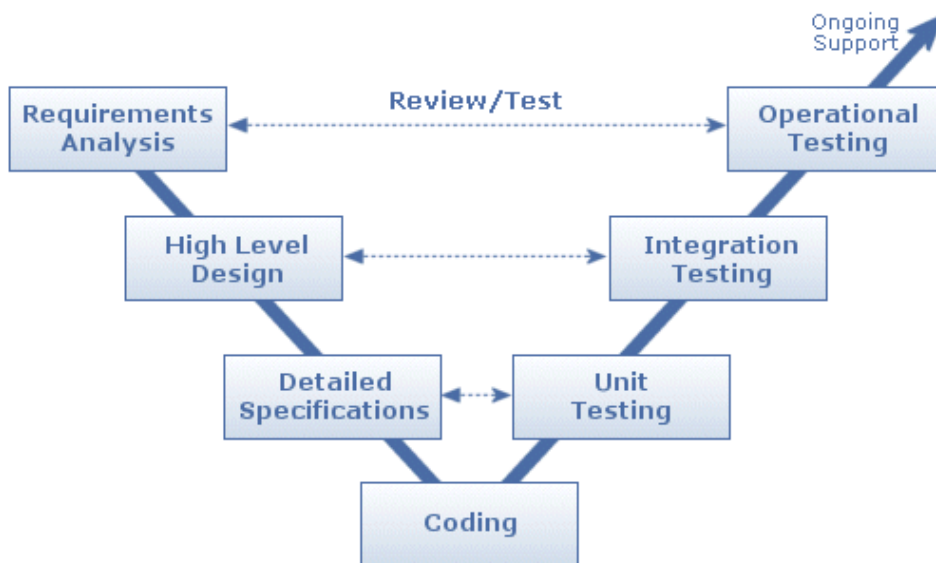


Figure 2: V-model [3]

2.2.1 Requirement analysis

First of all, a requirement analysis had to be made. Basis for this was the datasheet of the SCLS, to understand its behavior and features. Another source was the possibility to run a VHDL simulation of the real hardware, in order to solve ambiguities and vaguenesses in the datasheet.

A product of this analysis is a list of requirements, which are separated to the several modules of the SCLS. It was paid attention to the following criteria of “good” requirements:

- Atomic – a single description for each requirement
- Clear – no ambiguities
- Complete – explicit description of all requirements
- Correct – no discrepancies between different requirements

- Numbered – a unique identification for each requirement
- Testable – at least one test case per requirement

Table 6 shows an exemplary excerpt of the requirements list:

ID	Requirement	Source
3.1	The SCLS switches into fail mode if LIMP is logical 1 for more than 10ms (t_{LIMP})	datasheet
3.7	PWM is deactivated and the state of the output depends only on the ON bit if the frequency of the CLOCK input is less than 2.0kHz (f_{LCLK_det}).	datasheet
4.1	All outputs with ON=1 are switched on simultaneously at a rising edge of CLOCK if their phase settings are equal.	datasheet
5.4	The time measurement for the current thresholds starts with latching the ON bit into the input registers.	VHDL simulation
7.1	The SCLS is in sleep mode if $V_{BAT} < V_{BAT_POR}$	datasheet

Table 2: Requirements to the SCLS model

With the assignment between a requirement and a distinct module of the SCLS (as given with the first digit of the ID), it is even possible to verify the functionality of the subsystems at an early stage, without having them combined to the whole model. After the model is completed, it can be tested whether the parts fit together by applying the test cases again.

2.2.2 Used tools

2.2.2.1 Matlab

Matlab is first of all an environment for linear algebra and numerical analysis, created by The Mathworks. Its name stands for “MATrix LABoratory”, because the fundamental data type is a matrix. Matlab can perform various actions on matrices or vectors without using ‘for’ loops. The instruction set is optimized in speed and RAM usage for working on matrices. Because of this, Matlab allows a comfortable management of test vectors, including the possibility to plot and analyze the output vectors.

Automated sequences can be described in the Matlab script language and can be stored in so-called m-files. Matlab contains a lot of toolboxes for a wide area of usage, i.e. in control design, optimization, data acquisition or statistics. The

most famous add-on is the Simulink toolbox, which will be described in the following chapter.

2.2.2.2 Simulink

Matlab is a useful tool for preparing and analyzing test cases, but the modeling and the simulation are done in Simulink. This toolbox provides a graphical interface for “visual programming” of the information flow. It consists of a set of block libraries for various applications, such as for example signal processing, fuzzy logic or neural networks.

A block is the basic object in Simulink. Its attributes can be configured as constants or as variables from the Matlab workspace. Several blocks that are used for one task can be combined to a subsystem that has input and output ports. Thereby, it is possible to segment a model by building a hierarchy of subsystems. The Simulink solver is able to work with a variable- or fixed-step sample time. For discrete systems and code generation it is recommended to use a fixed sample rate with a discrete solver. Only this allows a sensible creation of test vectors, because every time step has a defined value.

2.2.2.3 TargetLink

TargetLink is a production-quality code generator created by dSpace, which is completely integrated in Matlab/Simulink. It mainly consists of special blocks, similar to the standard Simulink ones, but with additional settings for scaling, logging and overflow detection. Another important block is the TargetLink Main Dialog, which offers a lot of adjustments for the code generator. Subsystems that should be regarded for code generation have to be contained in a special TargetLink subsystem, which acts as interface to the remaining model in the different kinds of simulation.

TargetLink works with three different simulation modes:

- In model-in-the-loop (MIL) simulation, all calculations are done by using 64-bit floating-point variables. The model runs completely in Simulink, without regarding the scalings. This produces a reference for the following modes. It is also possible to detect overflows if limitations are correctly set.

- These features allow that the development of algorithms (often done in Simulink) and the implementation and coding (normally done by hand) can be accomplished without changing the toolchain.

The model of the SCLS is placed in a development environment for the high-level driver shown in figure 3. It contains the HLD itself, the SCLS model and instances of the bulb model for the six outputs.

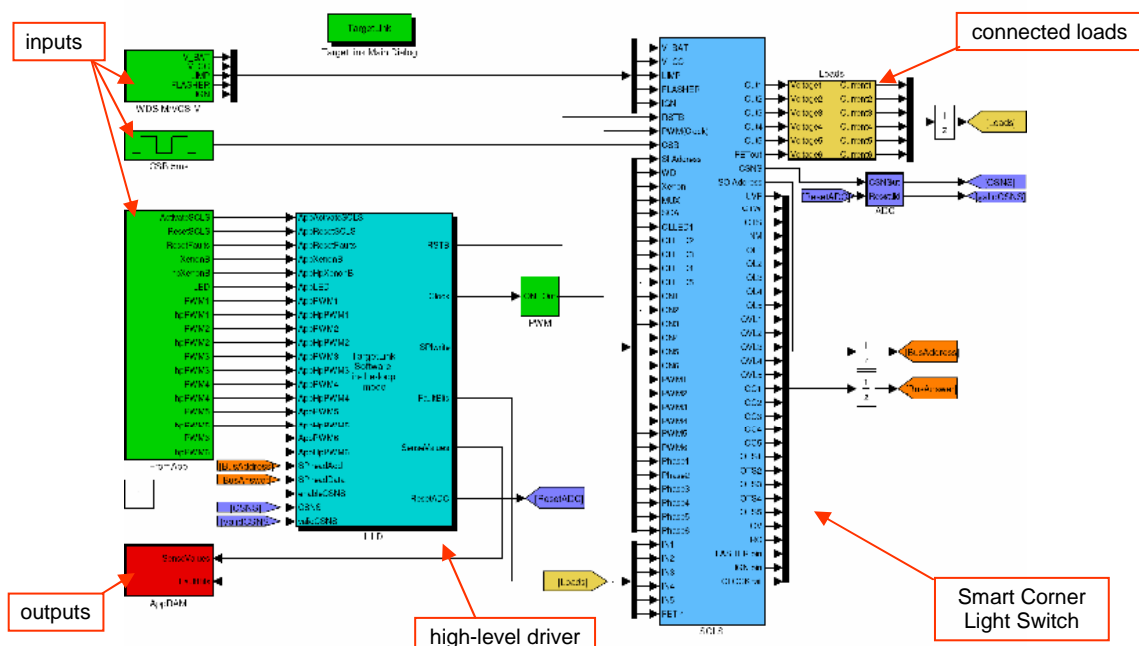


Figure 3: Development environment for the HLD

The green blocks on the left are stimulating the HLD with the test vectors of the Matlab workspace. They simulate the requests and instructions, which are normally sent by the application software. Fault bits and sense values are normally returned to the application. In the development environment, these values are saved to variables in the workspace. This is done by the red block on the lower left.

There is one closed loop between HLD that transmits the SPI messages and SCLS, which feeds back the answers. Another one is between SCLS and the bulb model, which calculates the current depending on voltage and temperature and returns these values to the SCLS.

2.2.4 Verification of the SCLS model

The quality of the SCLS model plays a very important role for the development of the driver, because the model-based approach is only sensible if the modeled system is free of faults. Otherwise, it could be possible that the driver works perfectly in the simulation, but not with the real hardware. Therefore, the model has to take a wide set of tests.

2.2.4.1 Creation of test cases

All developed test cases are directly derived from the list of requirements. It is documented which test case covers which requirement and vice versa. A test case describes the principle procedure of the test. These are the test steps and the expected results.

The real SCLS is tested with an automatic test rack. Some test cases are adopted from this automatic test specification, in order to have a possibility to compare between simulation and reality.

2.2.4.2 Explanation of the test environment

Matlab and Simulink are of course not able to work with this description in natural language. Therefore, every test case has to be converted into test vectors that have a defined value for each time step and for each input. For the

decision whether a test was correct or has failed, it is important to have vectors with the expected output values, too. Since the SCLS model has 42 inputs and 37 outputs, it is hard not to lose the overview.

To handle this complexity, a tool named CTE XL 1.6 was used. The term stands for “Classification Tree Editor eXtended Logics”. The classification tree method was developed in 1993 by Grochtmann and Grimm [3]. It requires the segmentation of all possible input vectors into different classes. For example, the input Phase1 has only 0°, 90°, 180° and 270° as possible values. The editor allows the creation of dependence rules, e.g. that PWM1 has to be zero if ON1 is equal to zero. Figure 4 shows the editor and explains the denomination “tree editor”:

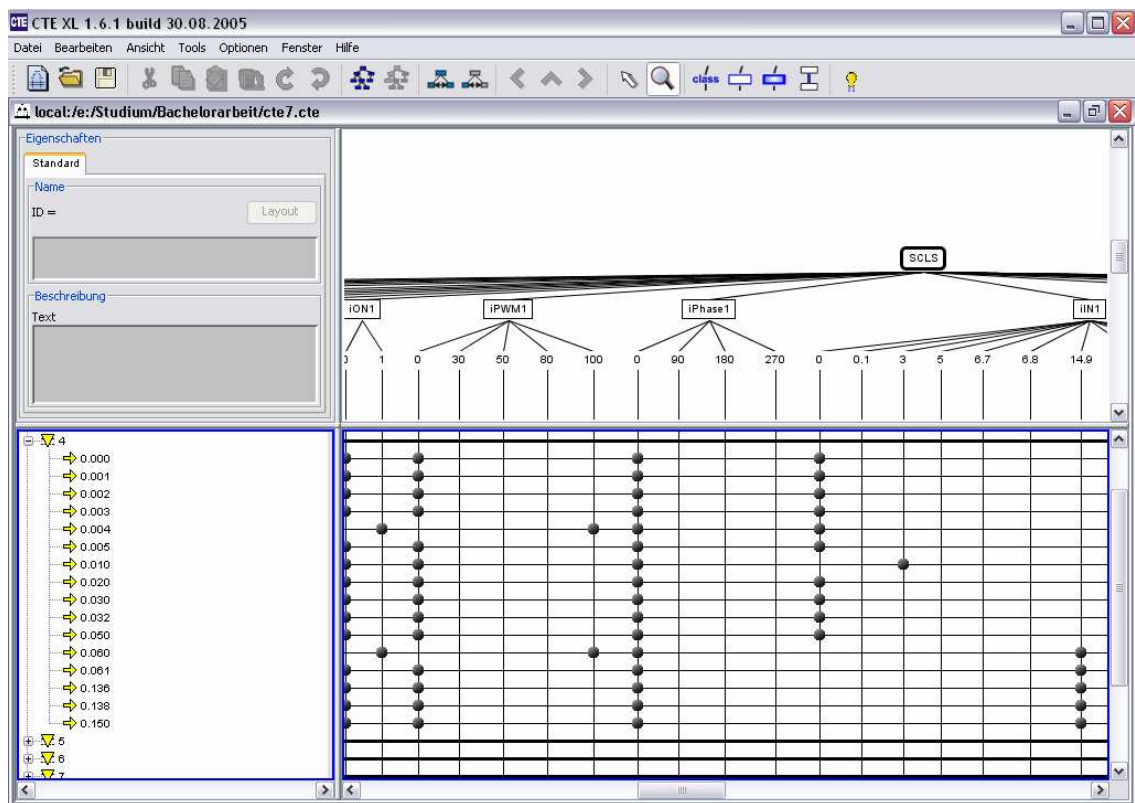


Figure 4: Screenshot CTE XL

Each class has its possible values as subnodes. Together with the time steps on the left frame, this forms a grid, where dots can be placed. Only one dot is possible per time step and variable. This sets the corresponding variable to the desired value at the desired time.

CTE XL allows the export of data to many different file formats. The export to Matlab generates an m-file that creates a structure in the Matlab workspace. This structure can be analyzed and segmented to the different test vectors with the help of a simple script.

Another script loads the parameters for the SCLS model and starts the simulation automatically. The resulting output vectors have to be compared with the expected vectors. Therefore, the script generates a figure with a plot of both signals for each output. The deviations can be analyzed by visual control.

Figure 5 shows an exemplary output of the test script. It plots the expected signal as a blue line and the real outputs as a dashed, red line. If the expected and the real signal are equal, both lines overlap each other to a red-blue dashed line.

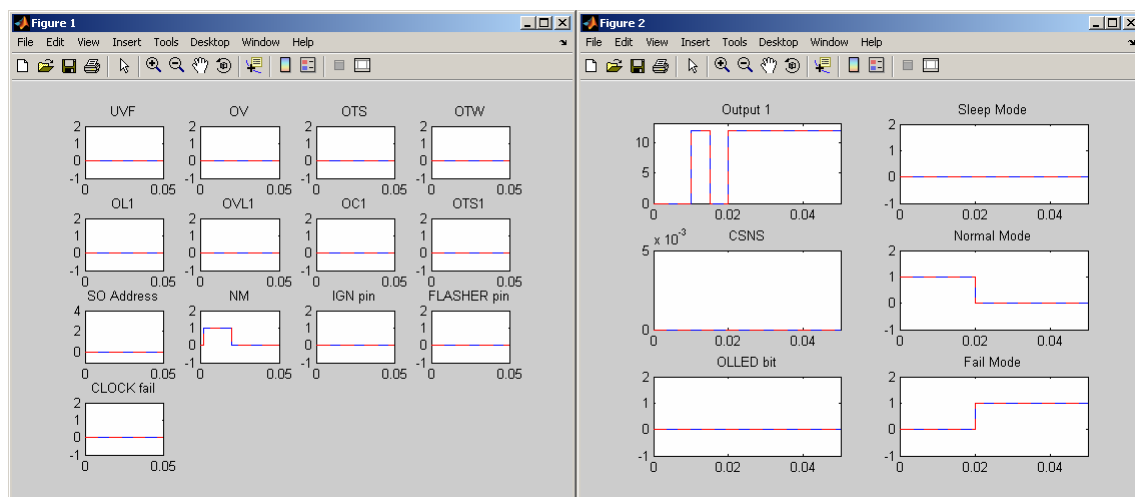


Figure 5: Plot of expected (blue) and real (red) outputs

It is also possible to create a script that runs all test cases in sequence and lists only the ones with differences between expected and real outputs.

3 Explanation of the bulb model

3.1 Reasons for using a bulb model

Normally, a bulb is regarded as a simple resistor, which is true as a first approximation. Its filament is made up of metal (tungsten) and Ohm's law is valid. But on closer examination, it can be seen that its resistance is not constant, but depends on the temperature. Halogen lamps heat up to about 2700K [4], which causes a huge difference between the resistance at room temperature and operating temperature. The effect to the current through the bulb is shown in figure 1. It can rise to about ten times the nominal current shortly after switching on the voltage. This is quite normal and must not be treated as short circuit. To validate the behavior of the software in this case, all tests in the development of body controllers are done with original loads and not with ohmic resistors.

For the modeling in Simulink, these original loads have to be replaced by a bulb model. This offers a wider range of feasible tests. For example, it is possible to simulate the switching of a lamp at an ambient temperature of -40°C – simply by changing a parameter.

Another decisive factor for the current curve is the duty cycle. If a bulb is driven with a very low duty cycle at low temperature, it might perhaps not heat up fast enough to have a current, which is below the third overcurrent threshold (OCLO). The ECU software has to avoid that by heating the bulb with higher duty cycle in the first milliseconds and setting the lower duty cycle afterward.

The model of the SCLS needs a feedback of the output current, because it only computes the voltage and the current depends on the connected load. Of course, the values of the current inputs can be defined in the test vectors. But it is easier and closer to reality if the values are calculated by a bulb model. Real short circuit and open load conditions can thereby be simulated by routing back either the bulb current, no current or an extremely high current.

This method of reconnecting the outputs to the inputs is called closed-loop simulation, because the feedback is done in the model itself and is not determined by external input vectors.

3.2 Physical basics

Behind the bulb model are a few formulas of thermodynamics and electrical engineering. They are based on three simplifications:

- (1) All electrical energy is converted to heat. Normally, about 5% of the whole energy is emitted as light.
- (2) There is no additional heating by the other bulbs in the headlights. All heat comes from the own electrical power.
- (3) The only mass that is heated up is the tungsten filament in the lamp. It is assumed that the proximate environment (e.g. the glass of the bulb) is not heated up.

The aim of the calculations is to get a current depending on voltage, temperature and time. First of all, current depends on voltage and resistance according to Ohm's law:

$$I = \frac{U}{R} \quad (3.1)$$

The resistance of a metal varies with changing temperature as shown in the following equation where R_{20} is the resistance at 20°C and α is the temperature coefficient of the material. The temperature of the filament in °C is the variable ϑ .

$$R = R_{20} \cdot [1 + \alpha \cdot (\vartheta - 20^\circ\text{C})] \quad (3.2)$$

By considering the different forms of energy, it is possible to get a correlation between power and temperature. According to the first law of thermodynamics, the energy flowing into a system is equal to the sum of the increase in the internal energy of the system and the work done by the system. This is valid under consideration of simplifications (1) and (2) and leads to equation (3.3):

$$W_{el} = Q_{heat} + Q_{out} \quad (3.3)$$

The electrical energy in a resistive load is determined by voltage, current and time:

$$W_{el} = P_{el} \cdot t = U \cdot I \cdot t \quad (3.4)$$

The increase of internal energy, which heats the filament, can be described as follows:

$$Q_{heat} = m \cdot c \cdot \Delta T \quad (3.5)$$

Variables of this equation are the mass m of the filament, the specific heat capacity c of tungsten and the difference ΔT between the initial temperature and the temperature of the hot filament.

A part of the energy is emitted as heat. Its magnitude depends on the thermal resistance R_{th} between bulb and ambience. Since the initial temperature of the filament is equal to the ambient temperature, ΔT in equation (3.5) is the same as in equation (3.6).

$$Q_{out} = \frac{\Delta T}{R_{th}} \cdot t \quad (3.6)$$

Applying this to equation (3.3) leads to:

$$P_{el} \cdot t = m \cdot c \cdot \Delta T + \frac{\Delta T}{R_{th}} \cdot t \quad (3.7)$$

It is possible to get a first-order differential equation after division by an infinitely small time step Δt :

$$P_{el} = m \cdot c \cdot \frac{d}{dt} \Delta T + \frac{1}{R_{th}} \cdot \Delta T \quad (3.8)$$

By application of the Laplace transform and setting all initial conditions to zero, a transfer function can be set up:

$$H(s) = \frac{L\{\Delta T\}}{L\{P_{el}\}} = \frac{1}{m \cdot c \cdot s + \frac{1}{R_{th}}} \quad (3.9)$$

Since the simulation is a discrete system, a Z-transform of this continuous function has to be used. This can for example be done with the Tustin approximation (also called bilinear transform):

$$s = \frac{2}{T_{sample}} \cdot \frac{z-1}{z+1} \quad (3.10)$$

Inserting this in equation (3.9) leads to the final discrete transfer function used in the bulb model:

$$H(z) = \frac{z+1}{z \cdot \left(\frac{1}{R_{th}} + \frac{2 \cdot m \cdot c}{T_{sample}} \right) + \left(\frac{1}{R_{th}} - \frac{2 \cdot m \cdot c}{T_{sample}} \right)} \quad (3.11)$$

Since it is known that the temperature of the filament is approximately 2700K in steady state [4], it is possible to determine the thermal resistance. This can be calculated by setting the derivative of the temperature difference ΔT in equation (3.8) to zero, which leads to the following formula:

$$R_{th} = \frac{\Delta T}{P_{el}} = \frac{2700K}{55W} \approx 50 \frac{K}{W} \quad (3.12)$$

The following list gives an overview of the used constants:

Temperature coefficient of tungsten:	$\alpha = 4.8 \cdot 10^{-3} \frac{1}{K}$	[5]
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Specific heat capacity of tungsten:	$c = 143 \frac{J}{kg \cdot K}$	[5]
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Mass of the filament:	$m \approx 35mg$	(estimated)
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Thermal resistance (bulb to ambience): $R_{th} \approx 50 \frac{K}{W}$ (calculated)

R_{20} of a 55W halogen bulb (H7): $R_{20} \approx 0.24\Omega$ (measured)

3.3 Translation into Simulink

Modeling the bulb in Simulink is not difficult if the above shown equations are known:

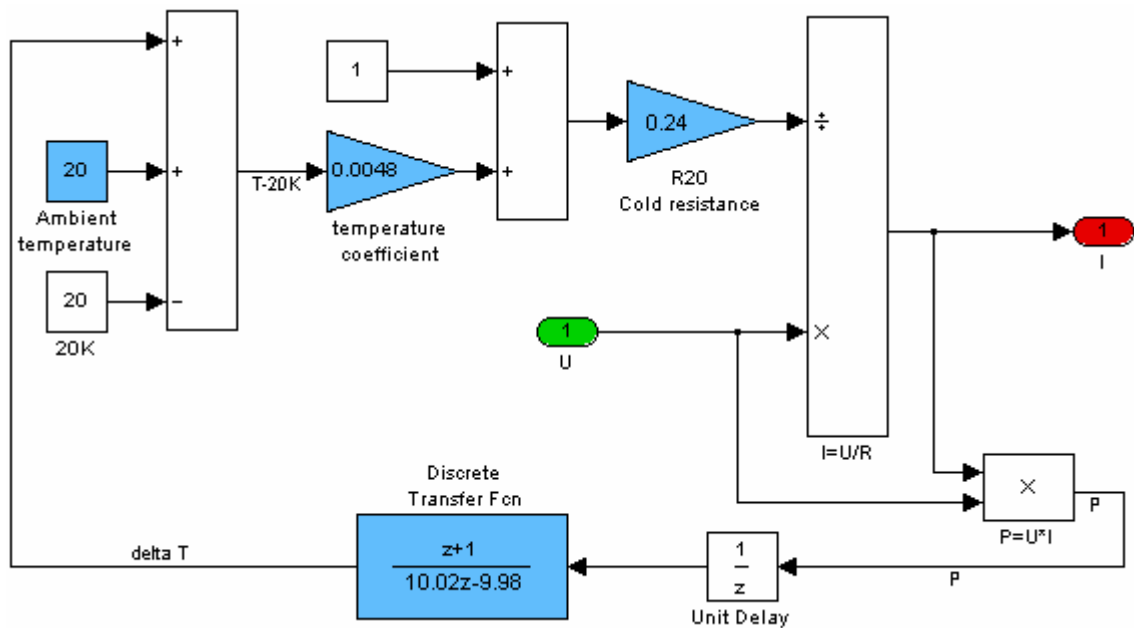


Figure 6: Model of a 55W bulb

The voltage U is divided by the resistance, which depends on temperature. Result of this division is the current I that is multiplied with the input voltage to get the electrical power. Calculating the temperature difference from the power is done by the discrete transfer function. Testing the behavior at different temperatures is possible by changing the value of the ambient temperature.

The current curve is determined by four parameters. The magnitude of the peak depends on R_{20} and the ambient temperature, because initially after switching the bulb on, it has not heated itself and the resistance is mainly determined by these two values. A lower temperature or a smaller resistance increases the initial peak.

Decisive for the time, until a steady state is reached, is the value of $\frac{2 \cdot m \cdot c}{T_{sample}}$ in

the transfer function. A higher mass extends this time, because more energy is necessary to get the same operating temperature. The used value of 10J/Ks with a sample time of 0.001s leads to a mass of the filament of 35mg. This estimated value is confirmed by the technical support of the bulb manufacturer OSRAM. Typical values for the filament's mass in halogen bulbs are between 23mg and 35mg.

If the steady state is reached, the derivation of the temperature in equation (3.8) becomes zero. This causes a linear correlation between electrical power and temperature, determined by the thermal resistance R_{th} as described in equation (3.12). The model uses a value of 50K/W. Increasing it leads to less current in steady state, because the temperature (and thus the electrical resistance) rises, since the transfer of heat is hampered.

Knowing the effects of these parameters allows testing the SCLS driver e.g. with bulbs that need a longer time to reach the steady state.

3.4 Exemplary outputs

This chapter shows the output (current vs. time) of the model for a battery voltage of 12V, which is switched on at $t=0.05s$, and different duty cycles. The current peak, when the bulb is switched on, is clearly visible.

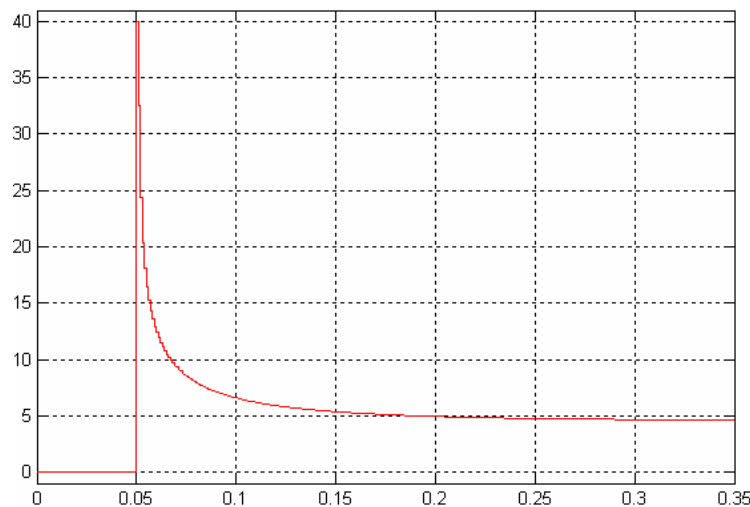


Figure 7: Output of bulb model (100%)

If the voltage is pulse width modulated, the filament cools down in the off-time of PWM. This can be seen in figure 8, where the current at the beginning of one pulse is higher than at the end of the pulse before, if the temperature has reached its operational value.

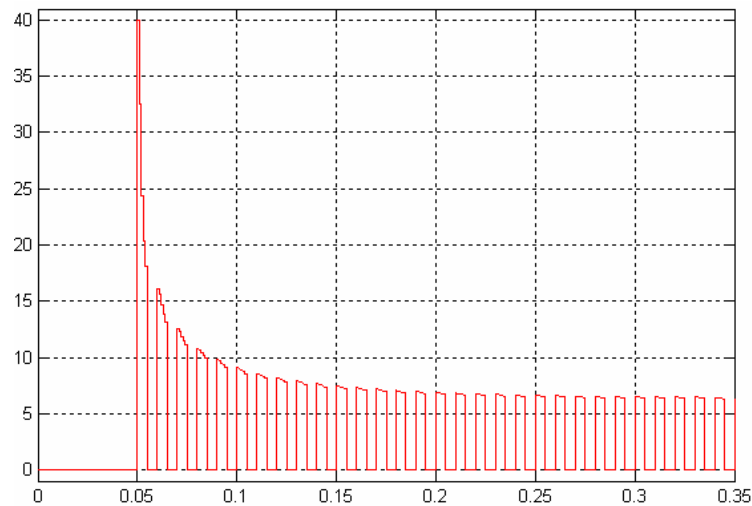


Figure 8: Output of bulb model (50%)

More detailed diagrams and a comparison to real bulb currents are given in chapter 5.

4 Driver description

4.1 Task system

Controlling the SCLS requires four functions that have to be called in defined time intervals:

- The high-level driver itself, which prepares the data to send.
- The SPI driver, which manages the transmission to e.g. four Corner Light ICs by using daisy chain.
- The AD converter that reads the current sense value.
- The application, which controls the HLD.

The SPI driver can not be called from the HLD, because the HLD function is only written to control one device. In contrast, the SPI driver has to wait until all four HLDs have set up their commands. Since the SCLS resets its fault

registers after sending their content to the microcontroller, and buffering the data requires a lot of memory, it was determined to call the SPI driver exactly once between two calls of the HLDs. Hence, a loss of data is avoided.

This method even works in an OSEK system, if both functions are invoked in one task. The application and the AD conversion run independent of the drivers. Realistic values are an interval of 5ms between the driver calls and an execution of the application every 20ms. Timing of the AD conversion depends on the sampling method.

Another problem is multiplexing the current sense. To save the few AD channels of the microcontroller, all current sense outputs are connected to the same pin of the microcontroller. Therefore, it has to be ensured that only one SCLS delivers its sense current at any given time. Since the HLD function is only an instance that doesn't know about the other ones, a superior logic is necessary to determine, which instance is able to route one of its outputs to the processor.

Figure 9 shows the chronology of function calls:

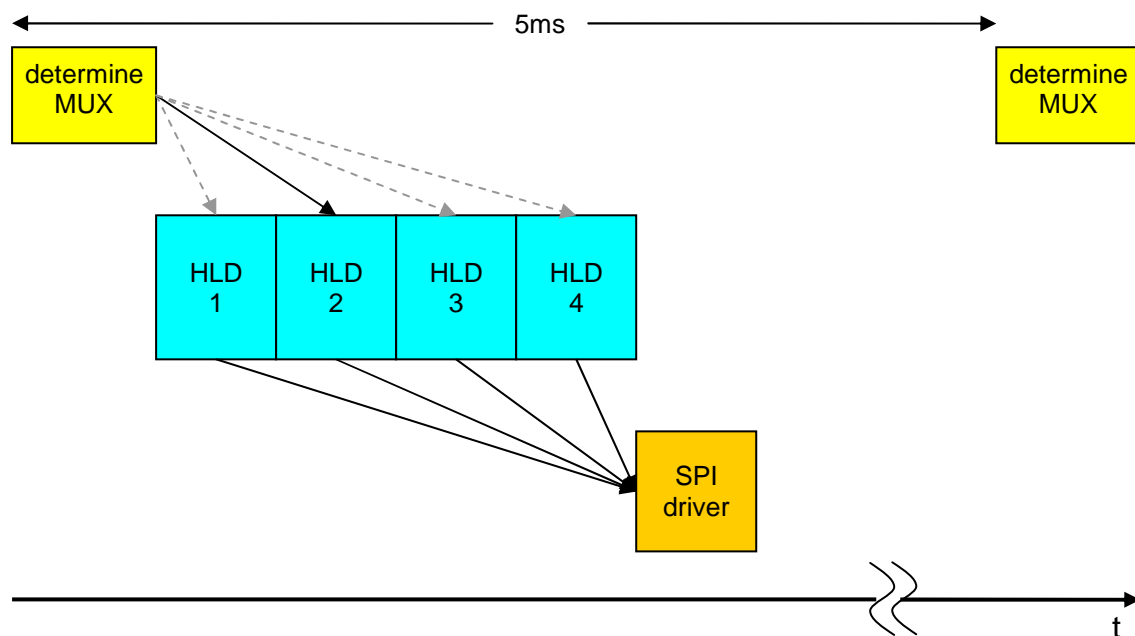


Figure 9: Sequence of function calls

4.2 Initialization and reset

After switching on its supply voltage, the SCLS needs a defined initialization procedure:

- Waking the device by setting the reset pin (RSTB) to high level and applying the clock signal.
- Sending an initialization message with WD=1 to trigger the watchdog and SOA=2 to clear an eventually set Clock-fail flag. This message also contains the XenonB bit.
- Sending a message to configure the outputs as LED or bulb.

Since the driver has outputs for RSTB, Clock and message address that are only calculated once in one step, it is not possible to change them frequently within one function call. For example, the SIA can only have exactly one value in each simulation step, because it is only one output of the model. It is not possible to assign SIA=0 (Initialization message) and SIA=1 (Config OL message) in one function call. Thus, the driver needs to be called three times to perform the complete initialization procedure.

If the microcontroller switches into sleep mode, the SCLS has to sleep, too. Otherwise it would recognize fail mode (because the SPI watchdog is no longer triggered) and activate the emergency light. Therefore, the driver has to take care that the RSTB pin is pulled to low level in this case.

To satisfy these requirements, the driver provides two inputs, called AppActivateSCLS and AppResetSCLS. The former named is the more important. If it is zero, the SCLS is set to sleep mode. A transition from zero to one starts the initialization. As long as it does not return to zero, the driver is ready for use. This is accomplished by holding a state counter that is increased in each initialization step and remains constant if the normal operational mode is reached. If using just the activateSCLS bit, the application can perform a reset of the SCLS (e.g. after detecting a fault) only by resetting it to zero and increasing it to one in the next cycle, which would be approximately 20ms later.

This is the typical use case for the resetSCLS bit: Setting it to one resets the state counter and thereby the SCLS. Thus, the re-initialization of the device can

start with the next call of the HLD, i.e. 5ms later. In this case, activateSCLS stays at logical one for the whole time and resetSCLS is set back to zero within the following execution of the application. Since the integrator is only reset after a positive edge, it is no problem that the value of resetSCLS remains one until the next application call.

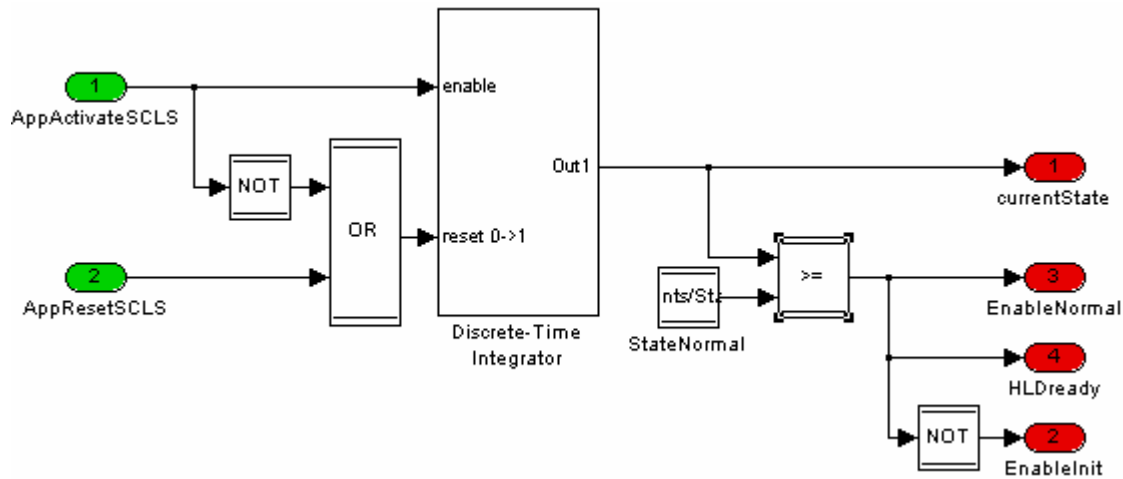


Figure 10: State machine

The following figure shows a timing diagram with the different signals. Setting activateSCLS to one enables the modified integrator (a standard integrator would increase currentState one step after its enable input is set to one), which has its output limit set to three. When currentState has reached the value three, enableNormal is set to one and enableInit is reset.

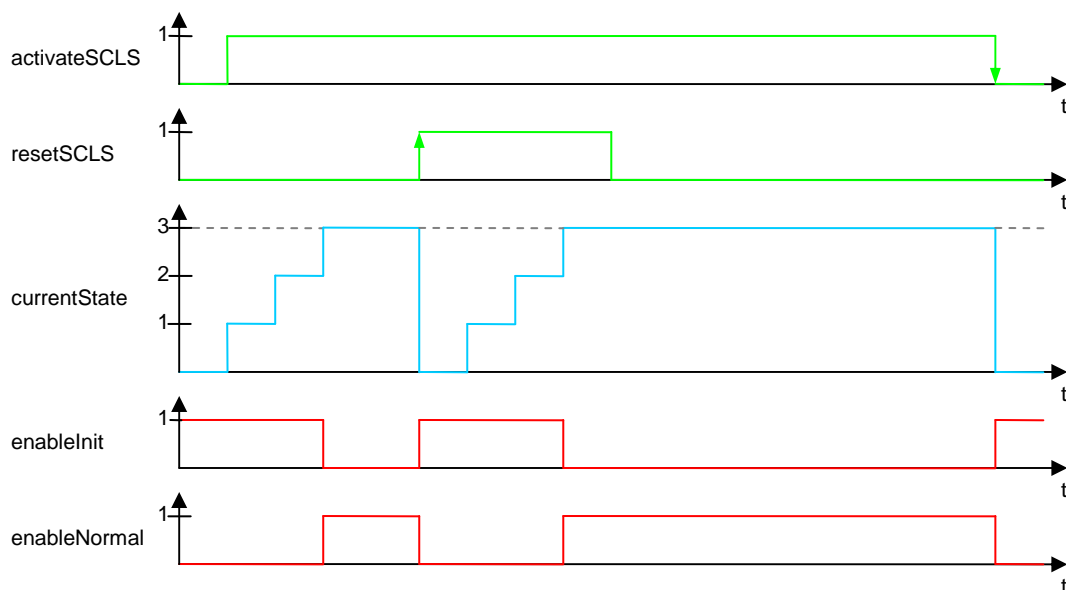


Figure 11: Timing diagram

The outputs enableInit and enableNormal control the execution of two other subsystems of which only one is processed in one simulation step. One performs the initialization procedure and the other one works in the normal operational mode. Figure 12 below shows the Init subsystem:

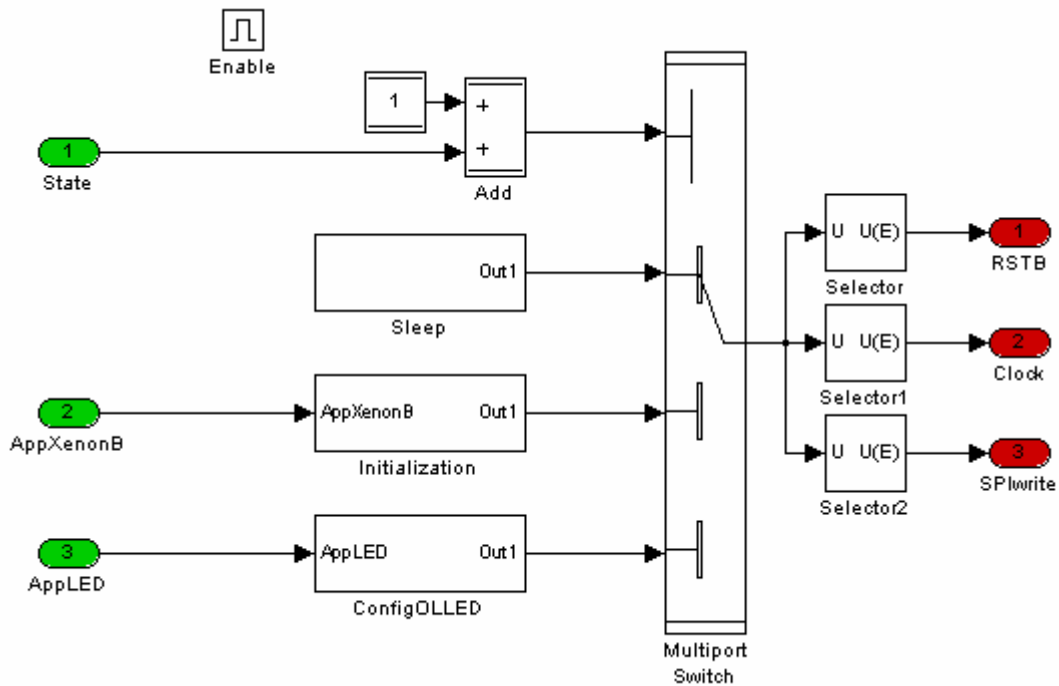


Figure 12: Init subsystem

It again consists of three subsystems that are routed through the switch, according to the state counters value. They simply set the values for RSTB, Clock and the SPI message that has to be transmitted. This performs the above shown initialization procedure. The inputs for Xenon and LED configuration make sure that the corresponding bits are set during the init phase.

4.3 Message scheduling

As described above, it is difficult to send more than one message between two HLD calls, since this would require the use of buffers for the received messages. Therefore, a compromise has to be found to manage the various duties that have to be fulfilled:

- Output states have to be updated according to settings given by the application (Control Out x message).

- Alternating requests for the three different answer messages have to be made (Initialization message).
- The channel of the internal multiplexer must be changed after a time that was long enough to sample the complete signal of one output (Initialization message).

These requirements are obstructing each other, because e.g. during the output states are updated, it is not possible to change the answer message or the multiplexer channel. Therefore, a schedule of messages, which considers all requirements, was set up:

Schedule nr.	Time	Message	SIA	SOA
0	0.000	Initialization	0	0
1	0.005	Control Out 1	9	
2	0.010	Initialization	0	1
3	0.015	Control Out 2	10	
4	0.020	Initialization	0	2
5	0.025	Control Out 3	11	
6	0.030	Initialization	0	0
7	0.035	Control Out 4	12	
8	0.040	Initialization	0	1
9	0.045	Control Out 5	13	
10	0.050	Initialization	0	2
11	0.055	Control Out 6	14	

Table 3: Normal schedule of messages

The advantage of this sequence is that a fault is reported at least within 25ms after its occurrence. For example, if open load happened at $t < 0.010\text{s}$, it is reported in the message received at $t = 0.010\text{s}$. If it appears later, it is definitely acquainted at $t = 0.035\text{s}$ as answer to the Initialization message at $t = 0.030\text{s}$. If SOA is not changed, because another message than Initialization is sent, the answer would have the same SOA as in the step before.

Alternating with the Initialization, the messages to control the outputs are sent, independently of whether the request has been changed or not. This approach assures that, when the SCLS has lost its settings (e.g. if it was reset), all outputs are working correctly not later than 60ms afterwards.

These are quite good values, but it could happen that an output has to be switched on faster. Therefore, the schedule was enhanced to regard so-called high-priority messages. It is possible to set a high-priority bit for each output and

for Initialization, which discontinues the normal sequence to send a distinct message.

To prevent the other messages from starving out, only three high-priority messages can be sent between two regular Initialization messages. Three conditions need to be fulfilled, to interrupt the schedule: The high-priority bit of a message is set, less than two high-priority messages were sent since the last regular Initialization message and the settings of the addressed output have to be unequal to those already sent.

Table 4 shows the worst-case were the schedule is interrupted as much as possible:

Schedule nr.	Time	Message	SIA	SOA
0	0.000	Initialization	0	0
	0.005	<i>high priority message</i>		
	0.010	<i>high priority message</i>		
	0.015	<i>high priority message</i>		
1	0.020	Control Out 1	9	
2	0.025	Initialization	0	1
	0.030	<i>high priority message</i>		
	0.035	<i>high priority message</i>		
	0.040	<i>high priority message</i>		
3	0.045	Control Out 2	10	
4	0.050	Initialization	0	2
	0.055	<i>high priority message</i>		
	0.060	<i>high priority message</i>		
	0.065	<i>high priority message</i>		
5	0.070	Control Out 3	11	
6	0.075	Initialization	0	0
	0.080	<i>high priority message</i>		
	0.085	<i>high priority message</i>		
	0.090	<i>high priority message</i>		
7	0.095	Control Out 4	12	
8	0.100	Initialization	0	1
	0.105	<i>high priority message</i>		
	0.110	<i>high priority message</i>		
	0.115	<i>high priority message</i>		
9	0.120	Control Out 5	13	
10	0.125	Initialization	0	2
	0.130	<i>high priority message</i>		
	0.135	<i>high priority message</i>		
	0.140	<i>high priority message</i>		
11	0.145	Control Out 6	14	

Table 4: Worst-case sequence of messages

This could only happen if the settings for the duty cycles are changed in every application call. Considering the timing, it is shown that a fault is acquainted at the latest after 55ms. This is short enough for diagnosis, because the main protection is done in the SCLS. The time after which all outputs are surely updated is 150ms. Through the possibility to set the high-priority bits for more time-critical outputs, this should be short enough, too.

There is no explicit high-priority bit for the 'Config OL' message, because it is internally set to one. Since this message does not appear in the schedule, LED configuration is always handled as high prioritized task.

Figure 13 shows the subsystem that is enabled after the initialization was performed. It gets the desired duty cycles (AppPWMx) and the already transferred ones (PWMx). According to the set high-priority bits, it determines the SIA and fills up the message with the correct values.

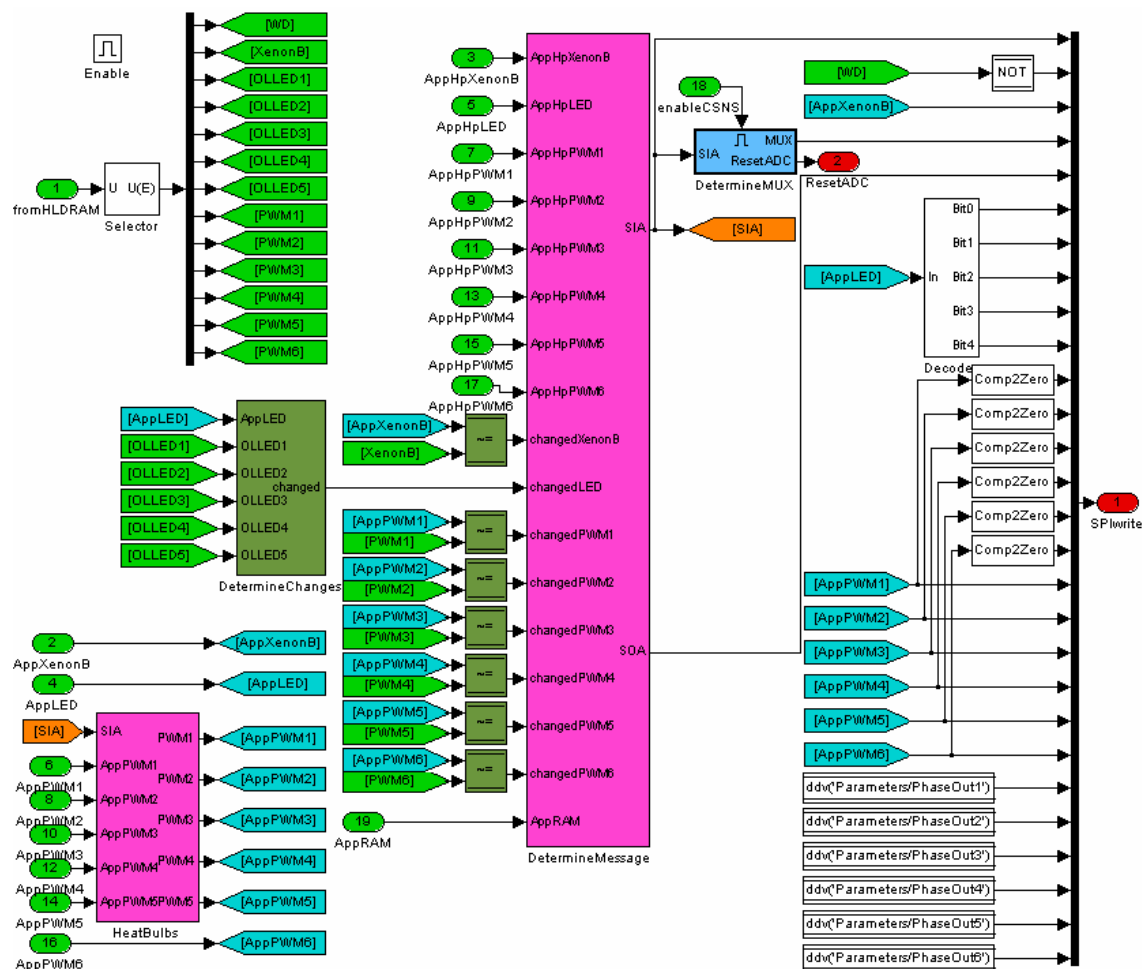


Figure 13: Normal subsystem

The most important block in figure 13 is the DetermineMessage subsystem. It manages the above described decision, whether to send a high-priority message or to continue with the normal schedule. Therefore, it handles a variable called HpCounter, which is increased after each high-priority message and reset after a regular Initialization message. The Merge block feeds through its most recent updated input, i.e. the current enabled 'if/else' subsystem.

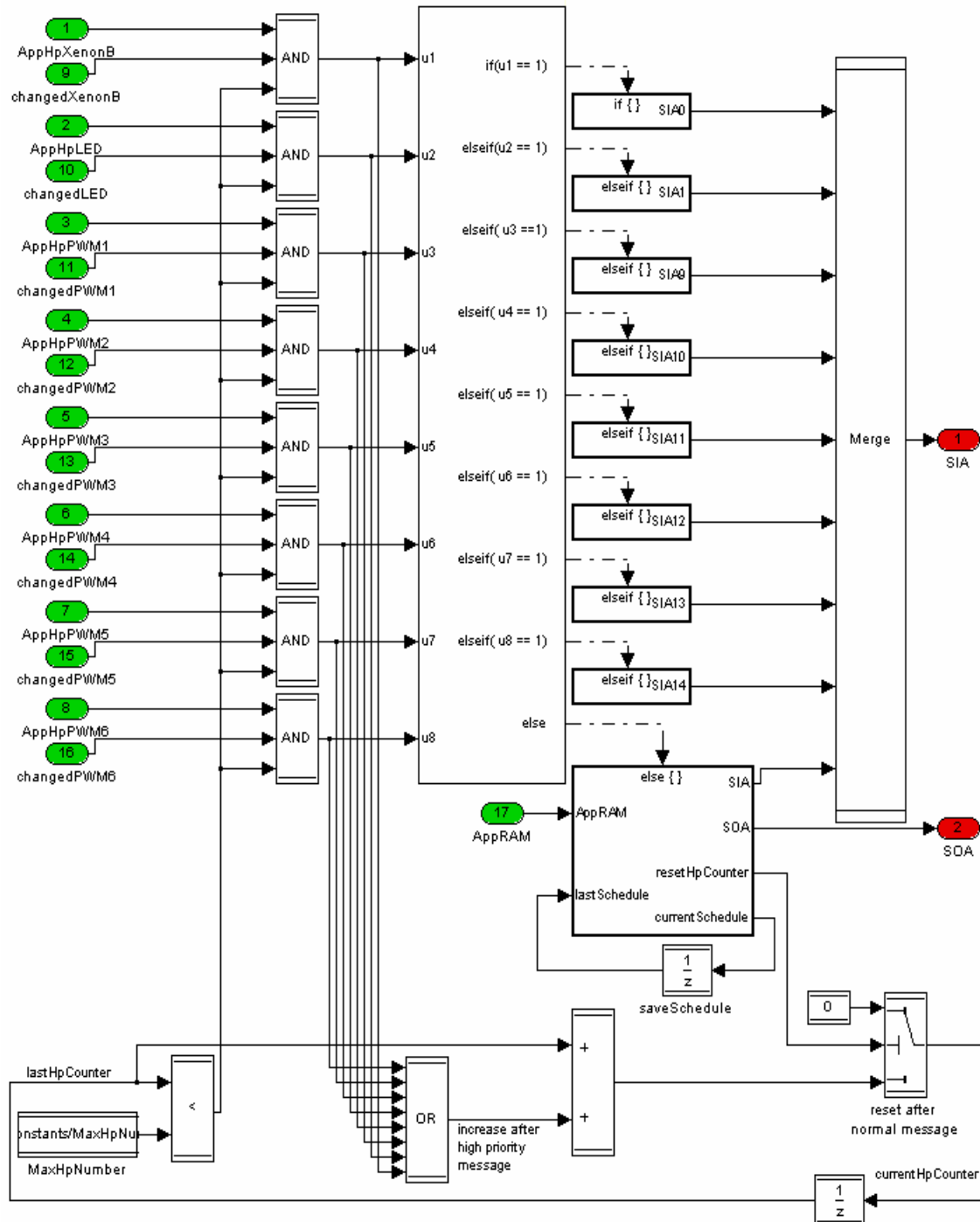
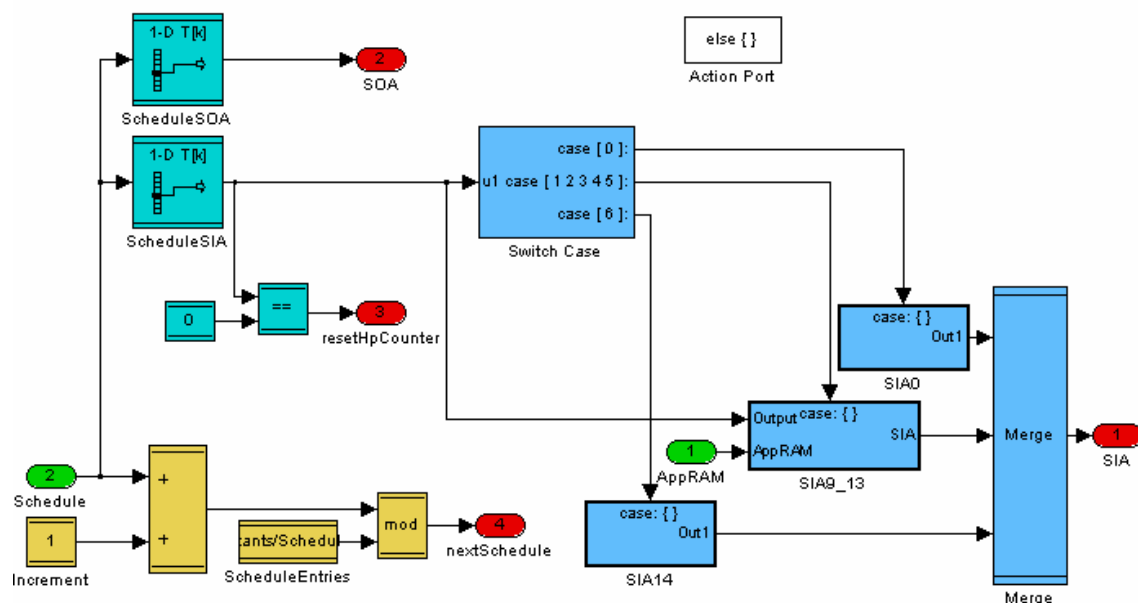


Figure 14: DetermineMessage subsystem

If there are more high-priority messages at the same time, the order of execution is defined by the positions in the 'If' subsystem. Anyway, only one message per simulation step is possible and the others have to wait until the next step (perhaps even until the next regular Initialization message was sent). The 'If' block enables the first subsystem, whose condition is true. All the other blocks are then disabled in this step, even if their condition is fulfilled, too. For example, if the inputs 'u2' and 'u5' are both logical true, the 'elseif' block for 'u2' will be enabled first.

The scheduling is done in the 'else {}' block. The current schedule index is stored in a Unit Delay block outside the subsystem, because otherwise its state would be reset if the block is disabled during sending of a high-priority message.



It is mainly divided into three parts. The yellow part on the lower left increases the index of the schedule and resets it when the maximum value is reached. The green part determines the current SIA and SOA, according to the schedule index. Furthermore, it decides whether the high-priority counter should be reset. To do this, it uses discrete look-up tables. A normal Simulink look-up table would cause a huge overhead in the generated code, because special search and interpolation functions will be inserted, although they are not needed for these integer variables. A discrete look-up table, in contrast, generates an array, which is accessed by the schedule index.

Another way could be the calculation of SIA and SOA out of the index by using integer divisions and modulo operations. This would decrease the amount of ROM needed, since the entries of the tables need not to be stored. A disadvantage is, modifying the schedule would cause a complete exchange of the calculation procedures. Therefore, the usage of the look-up table was considered to be more comfortable.

A reset of the HpCounter is performed after a regular Initialization message (SIA=0).

The blue part on the right side of figure 15 avoids retries on outputs that were shut down. Therefore, it eventually replaces the calculated SIA.

5 Hardware-in-the-loop tests with CANoe

5.1 Reasons for HIL tests

Until now, all tests were accomplished by using models of the real hardware. In order to eliminate failures in the models, it is useful to test the developed system with real hardware, too. In the present test environment, the SCLS and the bulbs are simulated. Therefore, it would be the optimal way to test the HLD with a real SCLS and a real bulb by setting the border between HLD and SCLS as shown below.

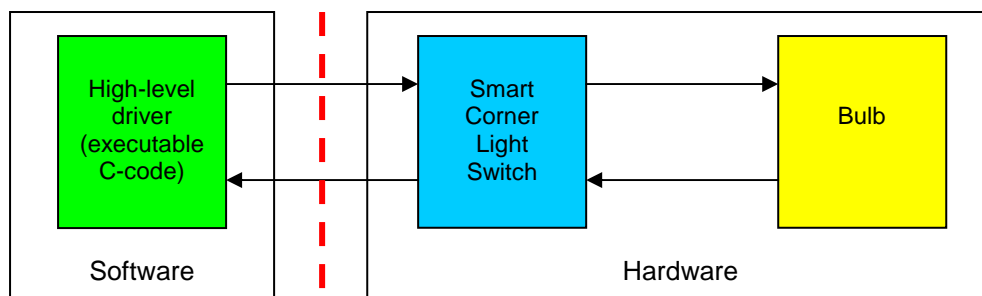


Figure 16: Method 1 for HIL tests

This would mean that the Simulink model has to control the SCLS via a real SPI interface between PC and SCLS. The interface needs to be able to transmit the data and receive the answer simultaneously within one simulation step. One possible solution, which exists at Continental Temic, is a microcontroller board that is connected to the PC via USB. Furthermore, it has an SPI interface to control an SCLS. This means that a message would have to be transferred first of all via USB and then via SPI. After that, the answer would have to be returned in reverse order.

Since it is hardly possible to achieve this in the correct time intervals, it was considered to set the border between the SCLS model and a real bulb. It is not possible to increase the sample time, because the SIL simulation needs to have the sample time, which is later used in the ECU. Figure 17 visualizes this method.

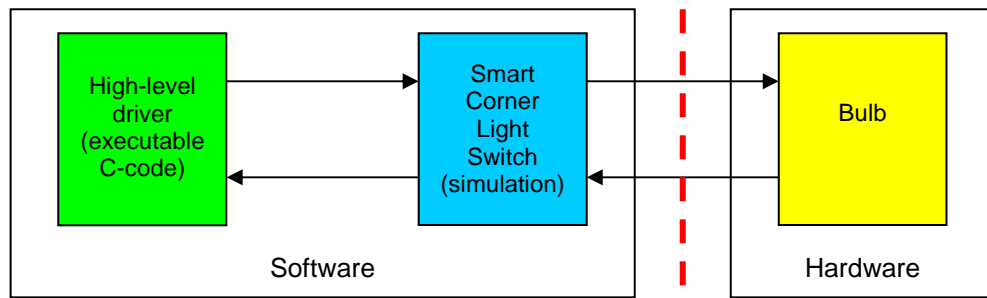


Figure 17: Method 2 for HIL tests

By using the shown way, it is possible to test the processing of the read sense values even with corrupted signals. Therefore, the real current can be measured with a clamp-on ammeter and can be compared to the value delivered by the HLD. Furthermore, the reaction of the HLD if it has to control a cold bulb can be tested.

An important advantage is the possibility to test the same C-code, which is later executed in the microcontroller.

A special reason, concerning this thesis, was the opportunity to examine the interaction between Matlab/Simulink and CANoe, e.g. timings and possible sample rates.

5.2 Test setup

5.2.1 Interface between Simulink and CANoe

CANoe is normally used to log and send CAN messages via a CANcab, which contains a CAN transceiver. It is possible to create GUIs (so-called panels), which allow the user to view the received signals and to change the data that should be transmitted. For the exchange of data, CANoe uses so-called environment variables (EV).

There is a special Simulink library, named canolib, which contains several blocks for the data exchange with CANoe. These blocks work similar to the 'From/Goto' blocks and have direct access to CANoe environment variables. There is one block that gets a Simulink signal and writes its value to the corresponding EV. Another block is used for the other way round.

5.2.2 Interface between CANoe and IOcab

Instead of the CANcab, it is possible to use an IOcab, which has several digital and analog in-/outputs. This device is controlled via environment variables, too.

The IOcab contains:

- 8 digital inputs or 4 digital outputs (two ports are combined to one output)
- 4 analog inputs or outputs (each port's direction is configurable)
- a PWM module or a capture/compare unit

It is configured in the Port Link Configuration menu of CANoe. The mapping between the EVs and the ports has to be done there, too. To control the PWM and CAPCOM module, two EVs are needed: One for frequency and the other one for duty cycle. The frequency is set to a constant value, while the duty cycle depends on the current state of the SCLS.

5.2.3 Description of the complete test setup

Normally, the SCLS controls the bulb model. For the HIL tests, one of the SCLS models outputs is redirected to the CANoe environment variable, which controls the duty cycle of the PWM module in the IOcab. This signal can be gripped at a box that distributes all IOcab ports. It is used to control a MOSFET, which switches a load, e.g. a bulb (55W).

The current through the bulb leads to a voltage drop at a shunt (0.01Ω), which is amplified by an operational amplifier (TLC272). Its output voltage is measured by one of the IOcab's analog inputs. Another input is used to measure the supply voltage. After the AD conversion, these values are available as environment variables and can be returned to Simulink.

The SCLS model analyzes them and reacts, for example, with overcurrent or undervoltage shutdown. Furthermore, it returns its status to the HLD.

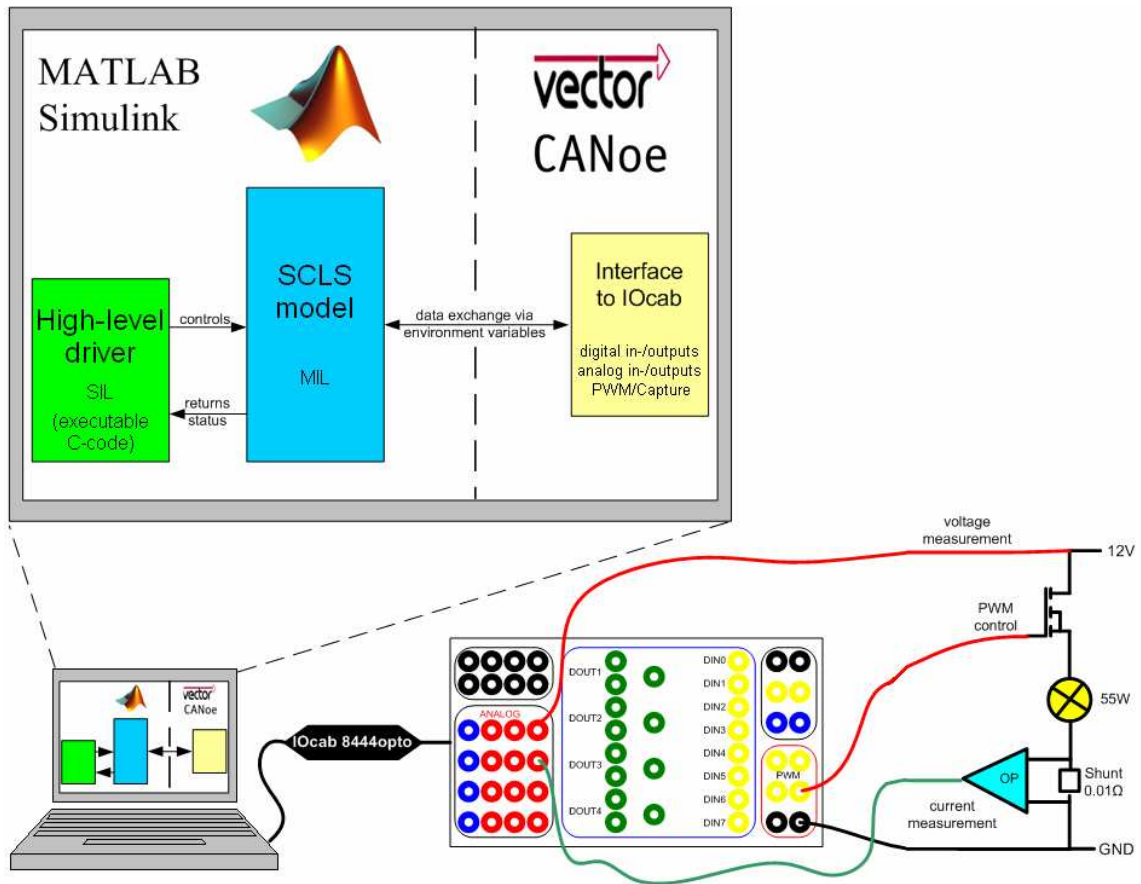


Figure 18: HIL test setup

In TargetLink, the simulation mode of the HLD is set to SIL. This means that this setup can test how the real C-code of the HLD works with real loads in real-time, including all possible fixed-point faults and quantization errors. The calculation of the SCLS model is done in floating-point arithmetic, since it is still a normal Simulink subsystem.

The real-time behavior can be achieved by inserting a 'real-time' block of an additional library named rtlib. This increases the priority of the Simulink process in Windows. It is even possible to connect digital inputs of the IOcab to the LIMP, FLASHER and IGN inputs of the SCLS. This allows activating fail mode and switching on emergency light.

Figure 19 shows the real test setup at the workstation. The oscilloscope is used to compare the real voltages to those returned from CANoe. Since the power supply is not capable to deliver more than 50A, a battery was connected in parallel, in order to buffer the current in the moment of switching the bulb on.

Between laptop and oscilloscope, the IOcab and the box, which distributes its signals, can be seen.

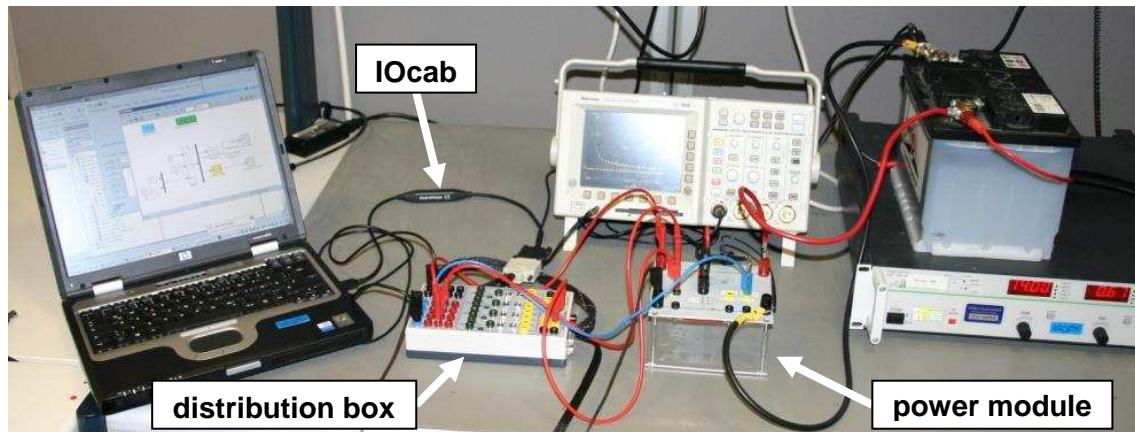


Figure 19: Real HIL test setup

Both, distribution box and power module were built up at Continental Temic. The power module, where the bulb is connected to, is shown in detail in figure 20. It was designed specially for these HIL tests and contains two amplifier circuits, in order to deliver the current in two different measuring ranges. Since the analog inputs are capable to measure voltages up to 8V and the typical currents were estimated to be about 70A (when switching the bulb on) and 5A (in normal operational mode), it was considered to have one range from 0A to 8A and another one from 0A to 80A.

By removing the bridge between bulb and shunt, it is possible to simulate open load or to connect e.g. a LED or an electronic load.

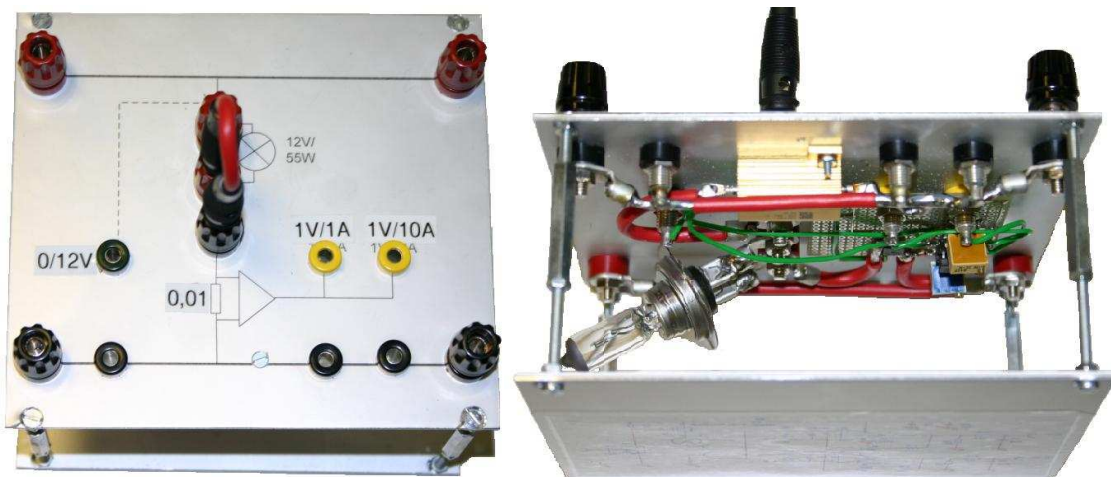


Figure 20: Power module for HIL tests

5.3 Test results

5.3.1 Accuracy of the current measurement

First of all, it is important that the current is measured correctly. To verify this, a clamp-on ammeter was used to get a reference, to which the results of the shunt measurement can be compared.

The clamp-on ammeter was inserted at the bridge between bulb and shunt and connected to channel 4 of the oscilloscope. The voltage at the amplifier with the higher range was measured at channel 1. Results can be seen in the figure below, where the left plot shows the current at 100% duty cycle and the right one at 50%.

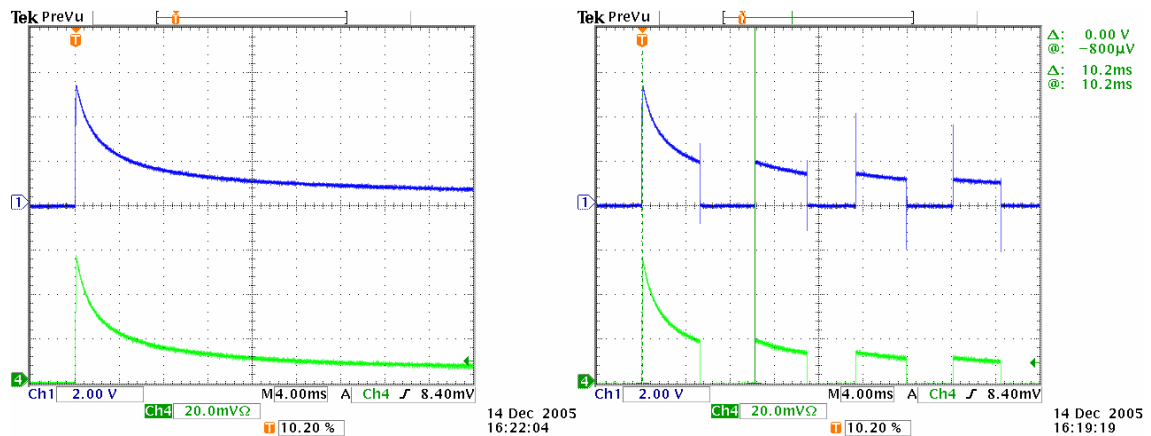


Figure 21: Comparison between shunt (ch. 1) and clamp-on ammeter (ch. 4)

It can be seen that both channels approximately show the same curve. The peaks in the right picture are supposedly caused by the operational amplifier, but can be neglected, since they are too short to be acquired by the ADC.

Unfortunately, the IOcab works very inexactly in this frequency range. To get the above shown frequency of about 100Hz, the corresponding environment variable has to be set to 140Hz. Even with this value, the frequency dithers between 90Hz and 110Hz.

The next possible source of error is the AD conversion in the IOcab. Therefore, its results have to be compared with the real current, as shown in figure 22. The course of both signals is nearly the same. Only the peak value differs from 54.2A (real) to about 46A (measured by IOcab). This is due to the sampling frequency of the IOcab, which is 3kHz. This makes a period of more than

300 μ s. Since the peak is very short, it is very likely that its largest value is not exactly hit.

The sample time of the SCLS model is 1ms. It is not possible to reduce this time, since it is needed for the complete calculation in real-time. The IOcab delivers three samples in this time, of which only one is recorded. In order not to get a falsification, the current curve was recorded with a smaller Simulink model, which can be calculated within every 200 μ s in real-time. Therefore, all values, delivered by the IOcab, can be recorded.

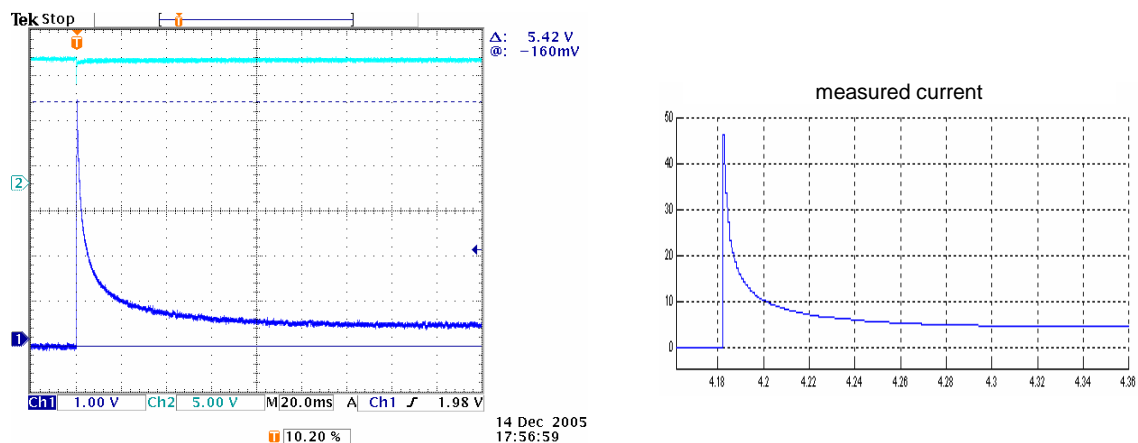


Figure 22: Comparison between real current and ADC values

Channel 2 shows the supply voltage, which has a break-in from 14V to about 11V in the moment of switching the bulb on, although it was buffered by a battery. This indicates that the real current peak could be still higher.

5.3.2 Comparison between real current and bulb model

It is possible to compare the recorded current values to the simulated signal of the bulb model, which was used in the previous tests. This can easily be done by using TargetLink plots. The comparison is done at different ambient temperatures and duty cycles.

5.3.2.1 Normal ambient temperature

Figure 23 shows the current at room temperature with 100% and 50% duty cycle. For the same reason as mentioned above, the measured current does

not reach the maximal value of the simulated bulb. The decline time of both signals is nearly the same.

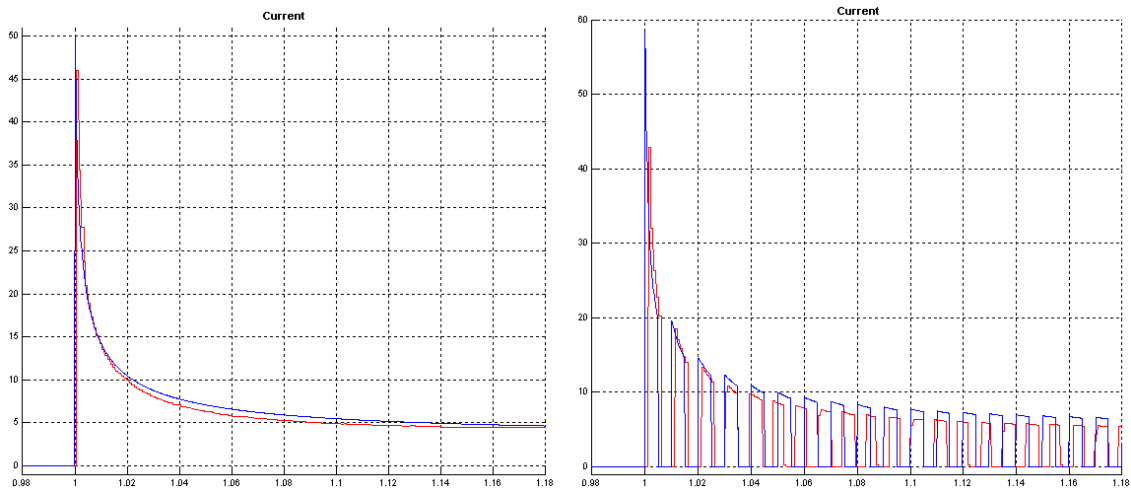


Figure 23: Comparison between real current (red) and bulb model (blue) at 20°C

The diagram on the right shows the inexact and varying frequency of the IOcab. Furthermore, the output values of the model are a little bit higher than the real ones. This indicates that the real temperature is higher than the simulated one. This can be caused by the IOcab, too. The correct number of pulses in the plotted time interval is 18. As it can be seen, there are 20 pulses of the real current. This additional power might have caused the higher temperature.

5.3.2.2 Ambient temperature 70°C

A higher ambient temperature reduces the current peak. Since this parameter can be specified in the bulb model, it is possible to simulate this behavior. The results are shown in figure 24. Both signals, real and simulated one, nearly have the same amplitudes.

Conspicuously is the worse resolution of the real signal in contrast to the model. The simulation has been executed with a sample time of 200µs. But the values stay constant for about 1ms, which leads to bigger stairs in the plot. This indicates that Simulink is supplied too slowly with new information. The real-time simulation causes a higher CPU load. In order to get more system resources for the Simulink solver, the priorities in the Windows schedule system are changed. This can be seen, for example, by a significantly higher response time (e.g. for changing the active window). It is also possible that the

Windows message handling, which does the data exchange between different applications, is hampered by the higher priority of the simulation in real-time mode. Supposedly, the CPU load in the moment of recording the values of figure 24 was too high. Therefore, the data exchange between CANoe and Simulink was slowed down.

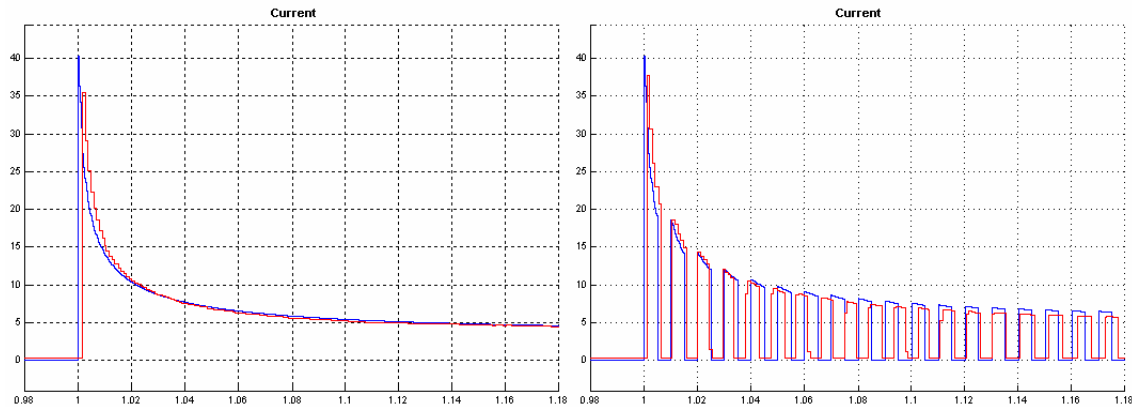


Figure 24: Comparison between real current (red) and bulb model (blue) at 70°C

5.3.2.3 Ambient temperature -40°C

More critical than a high ambient temperature is a low one, because this leads to an increase of current. As it can be seen in the simulation results, the current can be up to 70A. The real current is limited to about 50A by the power supply.

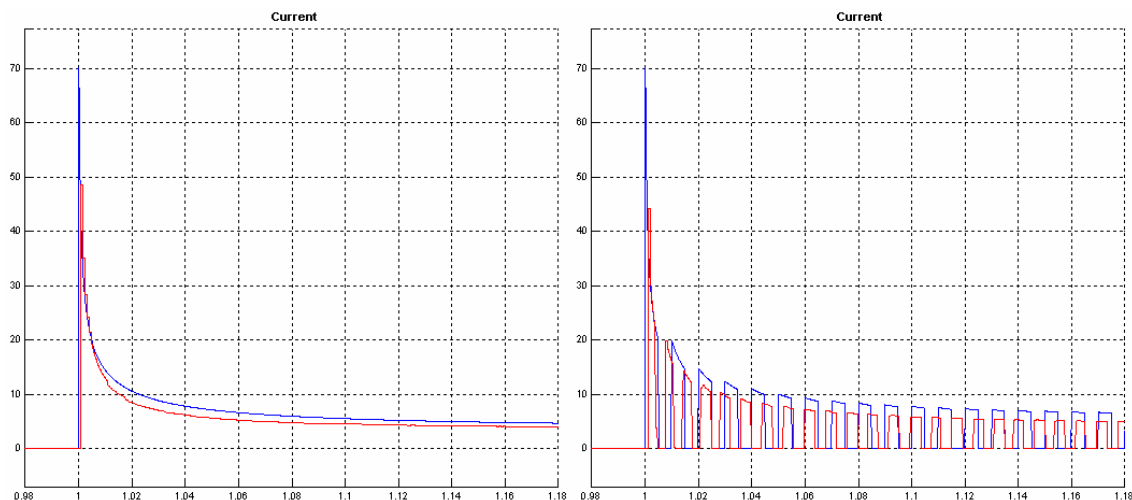


Figure 25: Comparison between real current (red) and bulb model (blue) at -40°C

The left part of figure 25 shows that the real current declines faster than the simulated one. This denotes a higher temperature of the real bulb. In the model, the ambient temperature stays constant at -40°C. It is assumed that the

ambience is not heated up by the emitted energy. In reality, the glowing bulb is going to heat its immediate environment. For example, the glass of the bulb has a temperature of at least 600°C in steady state. To simulate this, the bulb model would require a second transfer function, which describes how the glass is heated by the emitted energy of the filament. Furthermore, the hot glass again emits energy to the ambience. These details are not modeled in the simulation, since the currently used model is accurate enough for testing purposes.

In reality, the hot glass reduces the temperature difference between filament and ambience and therefore the transfer of heat. When the filament has reached a higher temperature, the discrepancy between model and reality is less significant and both currents are nearly the same.

Finally, it can be seen that the bulb model is useful as a first approximation to the real behavior, even in different temperature ranges.

5.3.3 Measurement of delays

In order to measure the delay time, after which the output of the IOcab's PWM module is updated after a changing value in Simulink, the time between a logical one at LIMP and the activation of emergency light was examined. Furthermore, the behavior of the SCLS model in fail mode can be tested, too.

Therefore, the IGN input is permanently set to logical one, by connecting the supply voltage to a digital input of the IOcab. To start the test and activate emergency light, the LIMP input is connected to supply voltage, too.

Normally, 10ms after a positive edge at LIMP, the SCLS should switch on emergency light, as shown in figure 26, where the following signals are recorded:

- The LIMP input of the SCLS model in Simulink (diagram on the upper left).
- The current calculated by the bulb model (diagram on the lower left).
- The voltage at the digital input of the IOcab (channel 2 of the oscilloscope).
- The current measured by the shunt (channel 1 of the oscilloscope).

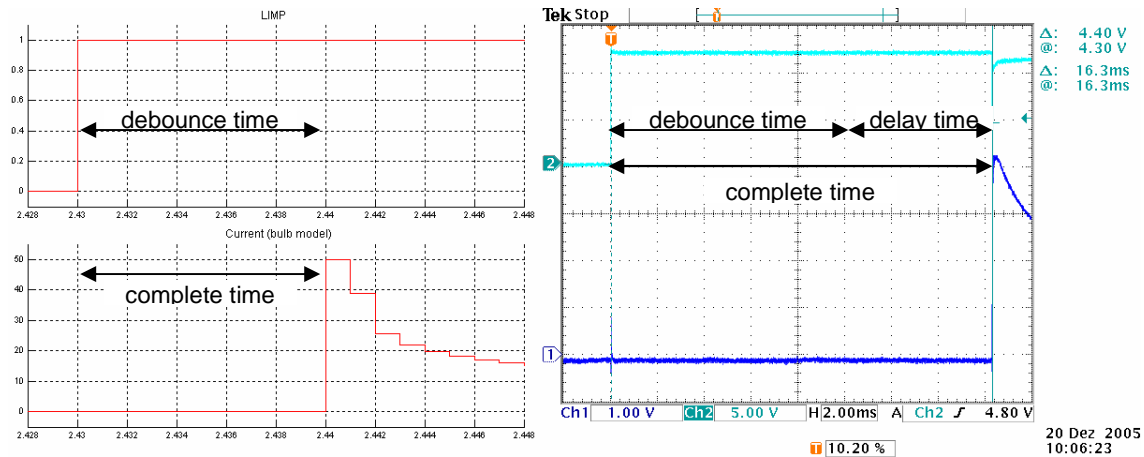


Figure 26: Measurement of the delay time

As it can be seen on the oscilloscope plot on the right, the time to activate the real bulb was 16.3ms. Normally, the complete time should be equal to the debounce time (i.e. 10ms), as shown in the left diagram. The measured time leads to a delay time of 6.3ms caused by reading in the input, transferring the environment variables from CANoe to Simulink and back and updating the duty cycle of the IOcab.

This delay time varies from 2ms up to 11.8ms. One reason for these high and differing times may be the Windows message handling. Furthermore, it is possible that the IOcab's PWM module works similar to the one of the SCLS and uses a timer, which determines the switch-on time. This would mean that it can take one period of this timer until the new value is valid.

6 Considerations for future projects

To conclude this paper, some steps, which could simplify or shorten similar projects in the future, should be mentioned. For this purpose, the most time-consuming stages are examined in detail. These are the development of the SCLS model and the tests of all models.

Since a specification sheet of the SCLS existed at least a year before starting the development of the HLD, it would have been possible to model the SCLS much earlier. Perhaps, it would even be possible, to let such models develop by student-trainees that got an introduction to Matlab/Simulink. Since the

development can start much earlier, it would not matter if it is slightly delayed due to the lack of skills of the trainee.

Another problem concerns the different simulation modes in TargetLink. A comparison between MIL and SIL simulation is only a verification of the fixed-point arithmetic. It is not verified whether the model itself works according to the specification. For these tests, it is necessary, to include additional blocks, which have to be removed for the SIL tests. Therefore, both methods require different files, which can lead to inconsistencies.

Testing is a big problem due to the huge complexity of the model's interfaces and the test vectors. Tools like CTE try to simplify the handling of this complexity. Nevertheless, even in CTE it is hard not to lose the overview if the model grows larger. Conventional tests specify signals that have to be changed at distinct points of time. Model-based test cases require the value of every signal at every time step. A tool, which could generate test vectors out of normal test sequences, would be a great advantage. The tool has to consider special, programmable rules, e.g. that the watchdog bit has to be toggled every 75ms, even if the interval between two instructions in the test specification is longer. Hence, it would be possible e.g. to switch a bulb on at a defined point of time and switch it off after one minute, without specifying the time steps for toggling the watchdog bit. This would lead to an enormous simplification in the creation of test vectors.

Due to the growing importance of model-based development, it can be expected that such tools will be developed in the future.

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