System optimization for automated calibration of ECU functions

André Sell, Frank Gutmann, Tobias Gutmann

Abstract

Design of Experiments (DoE) is an important basis for the modelling of complex systems in modern calibration methods with the aim of increasing efficiency. However, DoE does not provide any generally applicable answers to the question of transferring the models to real-time ECU functions. These are often implemented by a plurality of dependent calibration parameters, which must be adapted successively in an iterative process.

A new approach to system optimization allows the automated calibration of ECU functions on the basis of measured or modelled data by simultaneously optimizing all calibration parameters. For this purpose, first a reference model is generated on the basis of the data. The ECU function with the parameters to be calibrated is also available in the form of a flow chart representation. An optimization then appropriately adjusts all the parameters to be calibrated in such a way that the deviation between reference and ECU system behaviour is minimized taking into account limits, smoothness and priority criteria.

This innovative method has been successfully applied by multiple OEMs in cooperation with the SGE Ingenieur GmbH. Functions such as load calculation, torque model or exhaust temperature model have been optimized with the help of the SGE ModelArtist software. The necessary development resources were more than halved. At the same time, potentials for future ECU development were demonstrated and verified by the automated and optimal calibration of alternative function proposals.

Kurzfassung

Design of Experiments (DoE) bildet eine wichtige Grundlage für die Modellierung komplexer Systeme in der modernen Applikationsmethodik mit dem Ziel der Effizienzsteigerung. DoE bietet aber keine allgemein anwendbaren Antworten auf die Frage nach der Übertragung der Modelle in echtzeitfähige Steuergerätefunktionen. Diese werden häufig durch eine Vielzahl abhängiger Applikationsparameter implementiert, welche nacheinander in einem iterativen Prozess angepasst werden müssen.

Ein neuer Ansatz zur Systemoptimierung erlaubt die automatisierte Applikation von Steuergerätefunktionen auf Basis von gemessenen oder modellierten Daten durch gleichzeitige Optimierung aller Applikationsparameter. Dazu wird zunächst anhand der Daten ein Referenzmodell gebildet. Ebenso steht die Steuergerätefunktion mit den zu applizierende Parametern in Form einer Flussdiagrammdarstellung zur Verfügung. Eine Optimierung passt anschließend alle zu applizierenden Parameter gemeinsam so an, dass die Abweichung zwischen Referenz- und Steuergeräte-Systemverhalten unter Berücksichtigung von Grenzen, Glattheits- und

Prioritätskriterien minimiert wird. Diese innovative Methode wurde mit Hilfe der SGE ModelArtist Software erfolgreich von verschiedenen OEMs in Zusammenarbeit mit der SGE Ingenieur GmbH angewendet, um z.B. Funktionen wie Lasterfassung, Momentenmodell oder Abgastemperaturmodell zu optimieren. Die notwendigen Entwicklungsressourcen konnten dabei mehr als halbiert werden. Gleichzeitig wurden Potentiale für eine zukünftige Steuergeräteentwicklung aufgezeigt und durch die automatisierte und optimale Applikation von Funktionsalternativen belegt.

1 Motivation

Modern development methods form the basis of projects with technical and economic success. Therefore Design of Experiments (DoE) is an important tool for modelling complex systems with the aim of increasing efficiency. However, so far this method has not provided any generally applicable answers to the question of transferring the models to real-time ECU functions. These are often implemented with a variety of interdependent calibration parameters, which have to be calibrated in an iterative process.

1.1 The challenge of calibration

The aim of calibration is to create a reliable working system under all ambient conditions over production tolerances and ageing behaviour. For this purpose, application-oriented, empirical methods are often used. The effort required for calibration thereby increases roughly proportionally with the number of variants and development stages as each time data is generated, evaluated and processed into calibration parameters in an identical manner. Only little synergy effects result for repeated calibrations. For this reason, specific software tools are developed on a regular basis that are tailored to the calibration of particular ECU functions.

Calibration is also made more difficult because an ECU function cannot yet represent the chemical-physical correlations of an internal combustion engine in a complete and real-time manner. Thus, often only main effects are implemented so that an entirely exact setting of the calibration parameters is no longer feasible and a compromise has to be made through prioritization.

Finally another challenge appears with calibration parameters whose output values cannot be determined directly or not in the entire operating range. For example, Otto engine torque models or exhaust-gas temperature models often contain parameters which apply to 100% ignition efficiency and lambda one. If these operating ranges cannot be measured for reasons of knocking limits or component protection, only an indirect determination is possible.

2 System optimization

A new approach of system optimization permits the automated calibration of ECU functions by simultaneously optimizing all calibration parameters. The aim is to minimize the deviation of the ECU system behaviour from a reference behaviour.

The reference behaviour describes the target state that the ECU function should map. It may be provided in the form of measured or simulated data or in the form of a data-based model.

The ECU function to be calibrated includes at least one, but in general, several calibration parameters, as well as one or more input and output signals in each case. These same signals also form the interfaces of the reference system. Therefore, it is only necessary to map the inputs and outputs of the function. Information about signals within the function is not necessary, consequently the above-mentioned problem of signals which cannot be directly determined is no longer relevant.

To determine the deviation between the ECU function and the reference system, the input signals of the reference system are applied to the ECU function and the resulting output signals are compared to those of the reference system. In the simplest case, the absolute differences for all the output signals are computed to a mean value that is used as a scalar quality criterion, which is then minimized by the optimization. Since the calculation of the quality criterion is freely definable, the user has the possibility to bias the optimization result. For example, weights can be defined depending on the operating point, the sign or the magnitude of the deviation. It is also possible to introduce empirical criteria to evaluate the calibration when it can be calculated from the input and output signals of the function. In this way, the well-defined calibration of functions is made possible, even if they cannot accurately represent the physical relations of the underlying system and thus do not permit a trivial evaluation on the basis of the deviation.

The quality criterion is minimized by means of an optimization algorithm that is simultaneously varying all the calibration parameters included in the function. If some parameters are not to be optimized, they can be excluded. An existing initial calibration can be taken into account as the starting point of the optimization, thus reducing the required time of the optimization.

Limitations and smoothness requirements can be considered for the calibration parameters as well. Limits are also used to achieve a reproducible result for under-determined functions. This need exists when calibration parameters are summed up or multiplied and an infinite number of combinations exists that provide the same result.

2.1 Implementation

The described method of system optimization was implemented as an extension of the SGE ModelArtist software. This tool, which is designed for visualizing, modelling and optimizing complex systems, supports the use of various data formats as well as extensive calculated channels. Thus, it offers direct access to the measurement and simulation data - usually without data preprocessing. Gaussian process models are then used as the basis for the optimization algorithms.

The essential components of the system optimization are the reference system, the ECU function to be calibrated and the quality criterion. The reference system may either be represented by the loaded data or by a model. While a model is generally preferred for its positive properties regarding plausibility, the data can be accessed directly in the case of very large data sets that cannot be modelled. To avoid unwanted effects resulting from extrapolation, the model can be restricted to the parameter space of the data. The ECU function to be calibrated is depicted in the form of a flow chart with its calibration parameters, which are set with initial values. Thus, the flow chart can be simply derived from the representation that is usually used for the ECU software development. It is also possible to directly integrate a Simulink system. The quality criterion is implemented in the same way and thus permits the described influence on the optimization results.

Before starting the optimization, the user configures smoothness criteria and limits for the calibration parameters using fixed values or maps/curves depending on the input signal values. A progress bar permits a quick evaluation of the current progression of the optimization. In addition, at any time during the optimization there is access to interim results of the calibration parameters to be optimized, which can be viewed and stored.

3 Application example

For an ECU torque model, the method of system optimization was used to calibrate the function, which is shown in Figure 1. The torque is depicted as a function of the ignition angle. The shape and position of the optimum of the function are to be calibrated in the form of maps and curves. Solely the friction map MAP_FRICT was excluded from optimization because it was retrieved from stationary measurements.

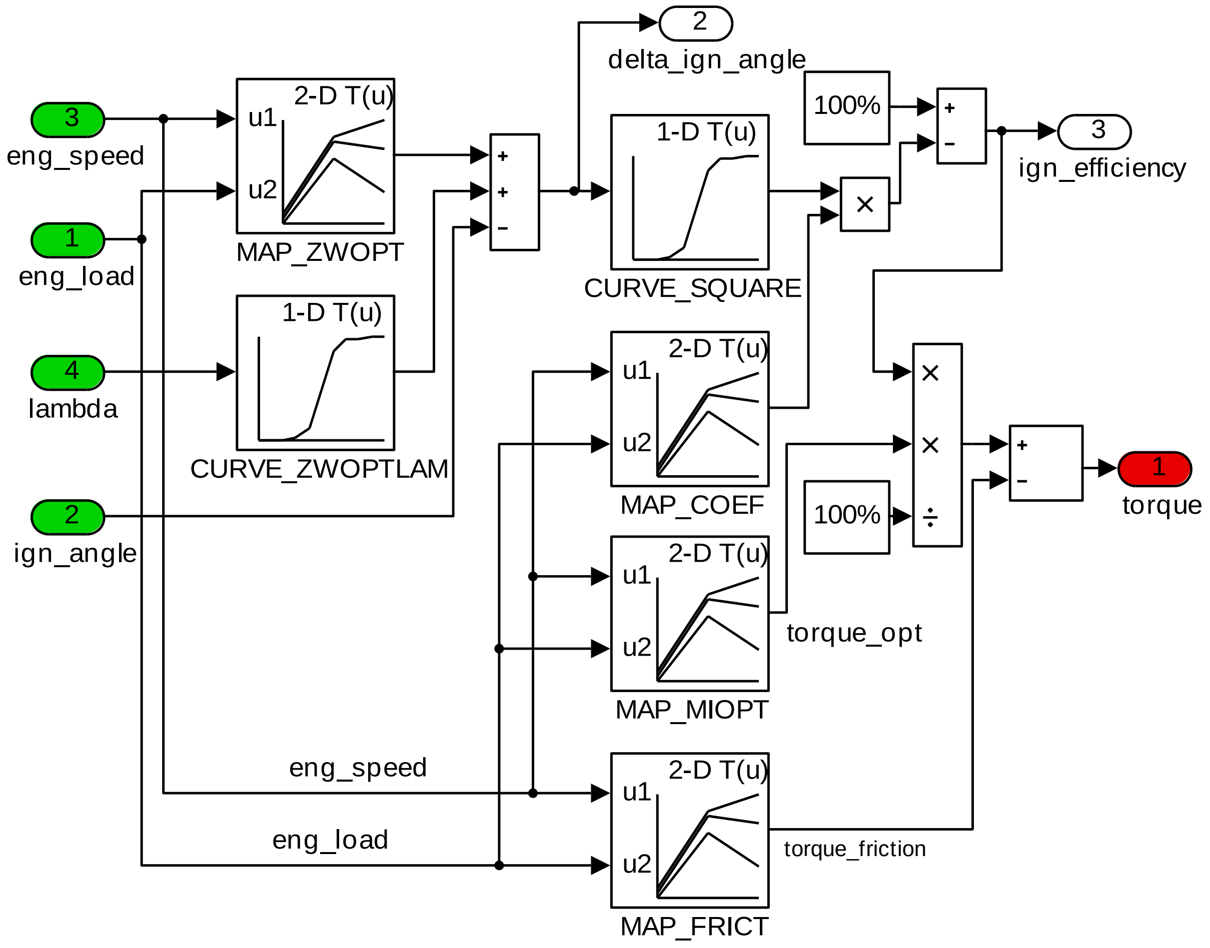

Figure 1: Torque model ECU function with parameters to calibrate

As a reference system, a Gaussian process model was trained within the input range of the data (16000 data points). Figure 2 and 3 show the models intersection and quality visualization. Because of a dynamic measurement procedure of only 0.5s measuring time per setting, the data is superimposed by some variation. This is compensated by the model and did therefore not affect the calibration optimization.

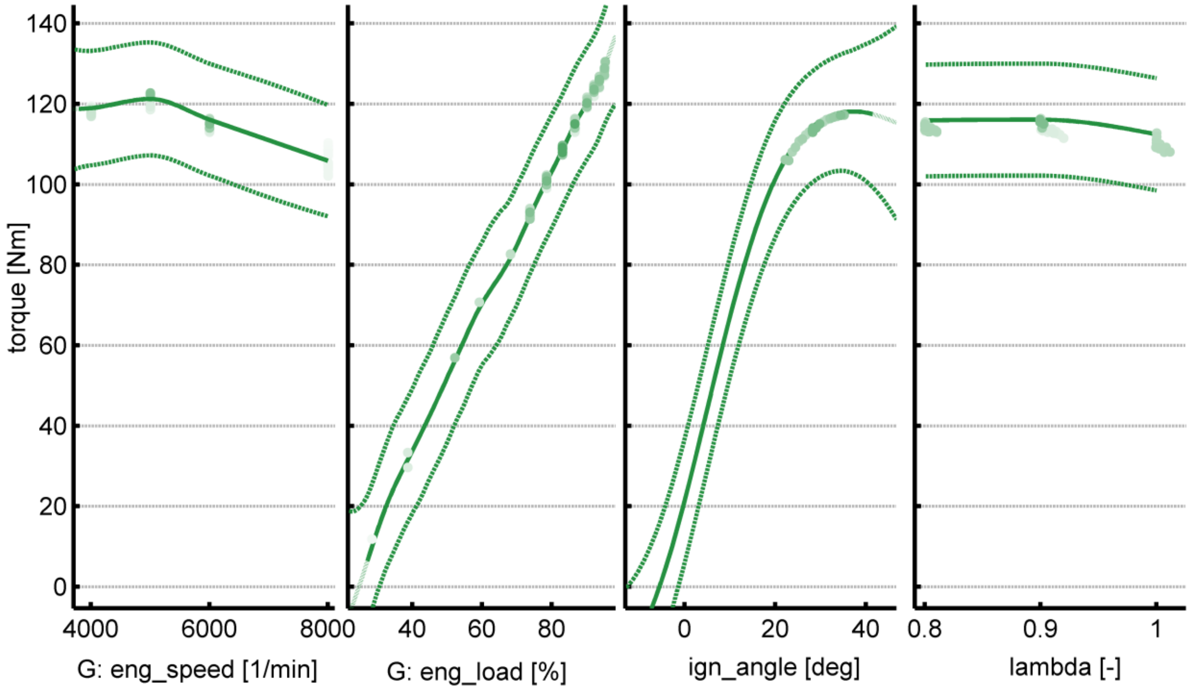

Figure 2: Torque model intersection visualization

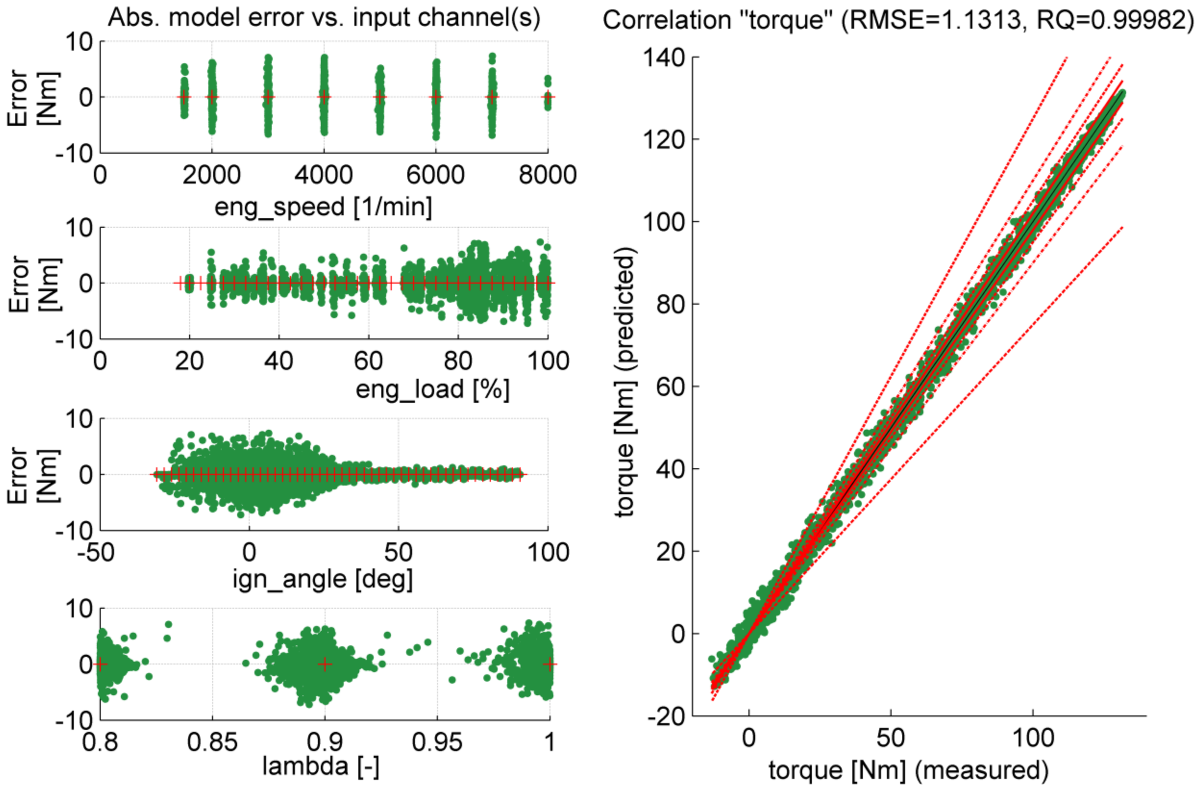

Figure 3: Torque model quality visualization

The quality criterion was implemented by integrating the Simulink system describing the ECU function and calculating the deviation from the model reference. The resulting signal is evaluated by the optimization to a scalar quality criterion. The calibration parameters are adjusted in such a way that this criterion is minimized.

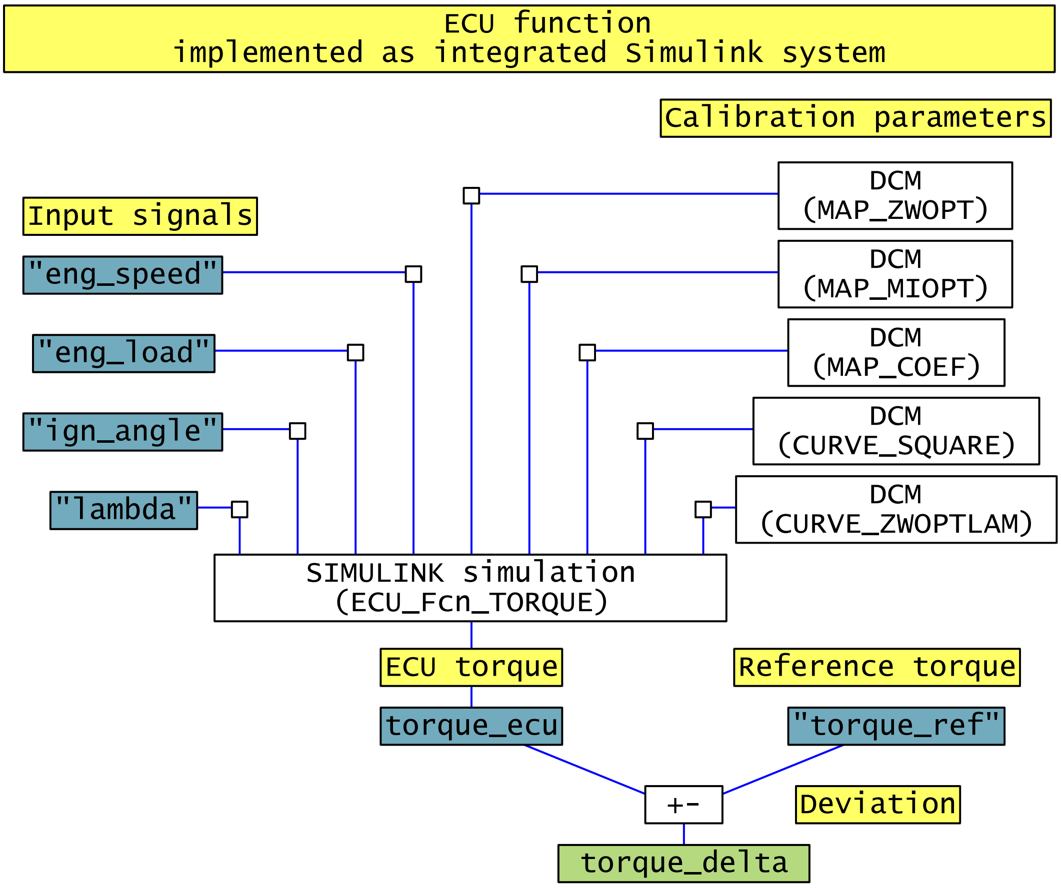

Figure 4: Quality criterion calculation for torque model optimization

For this function with 5 parameters and a total of 800 individual values to be calibrated, the optimization needed 9 hours of computing time. The result of the optimization created plausible maps, which could be transferred directly into the ECU after post-processing and extrapolation into non-measured areas. As an example figure 5 shows a comparison of the initial and optimized+postprocessed calibration of the map MAP_ZWOPT.

The efficiency gain when using system optimization increases disproportionately with the number of calibration variants, since the user only needs to make adjustments to the reference system and the quality criterion as well as post-processing of the calibration parameters if needed. The optimization itself is carried out independently without the user's intervention. In the present project the necessary development resources could be more than halved to achieve the high quality requirements regarding torque model accuracy.

At the same time, potentials for a future ECU development were shown and verified by evaluating alternative functions with an automated and optimized calibration.

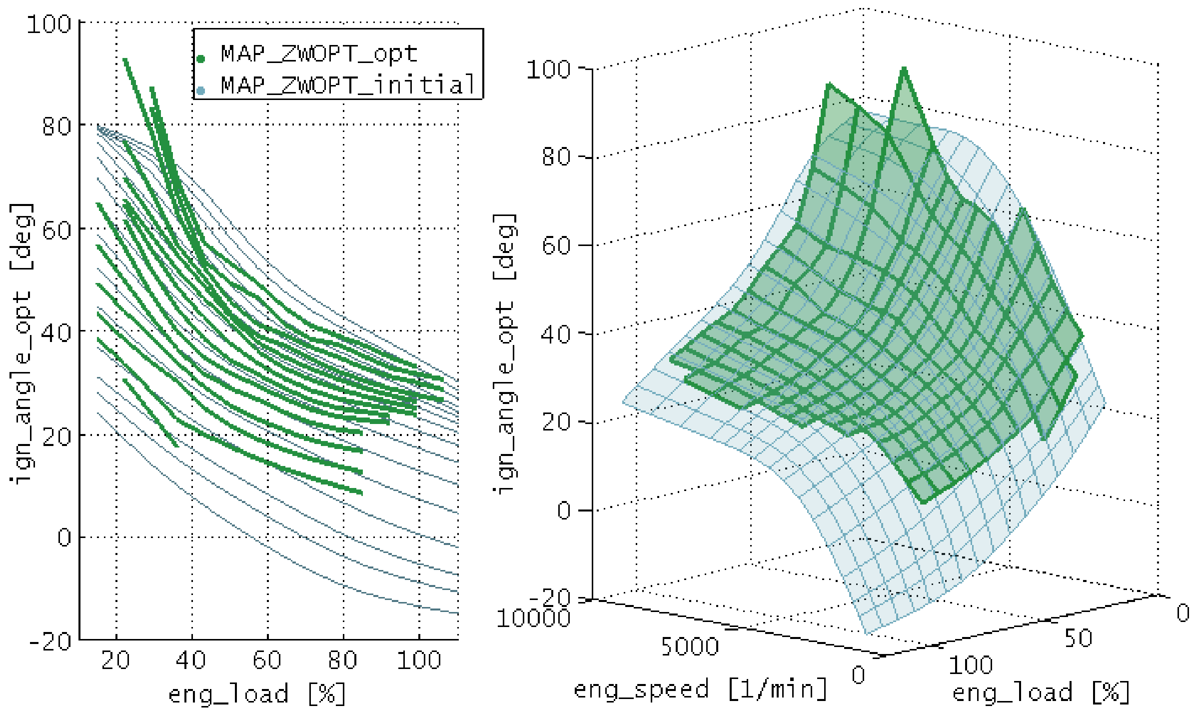

Figure 5: Calibration parameter MAP_ZWOPT. Comparison of initial and optimized+postprocessed calibration.

4 Summary

With the presented method of system optimization, the calibration engineer and software developer is provided with a universal tool for the automated calibration of ECU functions. The integration of the system optimization into a tool chain for model-based calibration ensures seamless processing of measured data into optimized calibration parameters.

The application of this method leads, besides significantly reduced effort, to an increasing quality and reproducibility of the calibration. Typical challenges of manual calibration processes are solved and there is no longer a need to develop specific software tools for single functions to calibrate.

This innovative method has been successfully applied by several OEMs in cooperation with SGE Ingenieur GmbH to optimize ECU calibration. It significantly reduced development resources and also showed the potential of further software development.

The Authors

Dipl.-Ing André Sell
SGE Ingenieur GmbH
Gräfelfing

M.Eng. Frank Gutmann
SGE Ingenieur GmbH
Gräfelfing

Dipl.-Ing. (FH) Tobias Gutmann
SGE Ingenieur GmbH
Gräfelfing