Physical Modeling Considerations for Control System Development

2014-01-0310
Published 04/01/2014

Thomas Egel and Scott Furry
MathWorks Inc.

CITATION: Egel, T. and Furry, S., "Physical Modeling Considerations for Control System Development," SAE Technical Paper 2014-01-0310, 2014, doi:10.4271/2014-01-0310.

Abstract

A mature process for the development of embedded controls and systems using Model-Based Design relies on libraries of validated models for the physical system components. These models are used throughout the design process and are readily available to the system and controls engineers for design and validation tasks. Models are created at various levels of abstraction to accommodate analysis needs at various stages of the design process. Abstract models are used early in the process for quick assessment of design tradeoffs, while higher fidelity models are used as the design progresses to account for the dynamics that affect system performance. Once acceptable system performance is achieved with desktop simulation, the models are moved to a real-time platform for final verification. Creating real-time capable plant models typically requires making assumptions and compromises to achieve acceptable performance. The end result is successful deployment of the embedded controls system with minimal reliance on expensive prototype hardware during the bulk of the design process. This paper outlines the necessary requirements and key considerations in using plant models as part of Model-Based Design.

Introduction

Model-Based Design is widely used for developing complex embedded control systems and has been proven to significantly decrease development time while reducing design defects [1]. Although it is most commonly associated with control algorithm development and automatic code generation, Model-Based Design can also be applied to system design including the physical system (the "plant" in control theory terminology). In fact, a plant model of some kind is required to properly test the control algorithm within a model-based environment. As illustrated in Figure 1, plant models are often relatively simple in the early stages of design, increasing in fidelity and complexity as the system design matures.

There are numerous methods for creating physical models, and the applicability of these methods varies with the stage of the design process. A primary challenge is determining what physical effects need to be included in the model to provide a suitable representation of the system dynamics while maintaining acceptable simulation times. Modeling tools are necessary but not sufficient, as engineering judgment is also required to determine the appropriate level of model fidelity for the task at hand. For embedded control systems development, it is important to use an environment for Model-Based Design that provides the flexibility to create physical models using a wide range of methods for a variety of applications. This allows the user to apply the most appropriate modeling technique based on the analysis needs. This paper discusses a structured approach to modeling physical systems and components, along with some best practices for determining the appropriate level of model detail when using Model-Based Design.

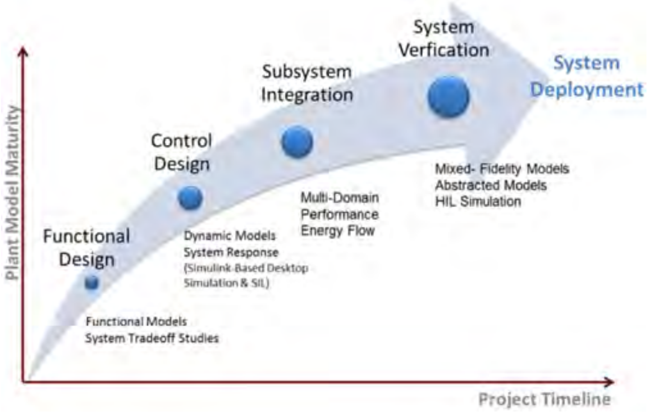

Figure 1. Maturity of plant models with Model-Based Design

The paper is organized into three main sections:

1. Establishing the organizational infrastructure necessary to enable effective plant modeling

2. Employing a plant model development strategy
3. Using plant models with Model-Based Design

In the first section we discuss the challenges organizations typically face when tasked with developing plant models of physical system and components. Some guidelines are provided by answering common questions about plant model development including:

- What changes are required to develop a modeling culture?
- How will an increased emphasis on plant modeling affect the organization?
- What additional investments are required?
- How do you balance modeling needs with other priorities?

In the second section we provide some best practices for plant model development. To apply these, we recommend a structured approach and provide guidance by answering additional questions:

- When do you begin developing plant models?
- What plant modeling techniques are available?
- How do you balance model fidelity vs. speed?
- How do you maximize model reuse?

In the final section we discuss how to maximize the effectiveness of plant models when using Model-Based Design:

- Employing “in-the-loop” simulation
- Migrating from desktop to real-time simulation
- Verifying and validating the model

Establishing the Organizational Infrastructure

Develop a Modeling Culture

To be successful using Model-Based Design, it is important to instill a modeling culture throughout the organization [2]. Some companies take a top-down approach by dictating process changes, which is quick and far reaching; others allow the culture to grow organically, which can result in a higher level of buy-in to the concept by participants.

Indeed, a culture embracing Model-Based Design should naturally develop in most science and engineering-centric businesses. Imagine a small engineering company faced with developing their next product with limited assets and resources. Schedules and budgets are tight and the company cannot help but perform research and engineering design in parallel-in fact, vendor sourcing, patent protection activities, marketing, sales, and more are probably all happening at the same time. Furthermore, these efforts are interdependent, which leads organizations to adopt Model-Based Design. Before purchasing can send for quotes, they need answers from engineering, which needs answers from the lab or research. Prototyping hardware is often a costly method to get those answers-especially in terms of time; so, somebody models the hardware in software. When research encounters new findings, the model is refined. This cross-discipline dependence in which prototype models permit groups to accomplish their tasks plays itself out on numerous fronts. For example, piping engineers depend on hydraulic engineers for pressure profiles, loads engineers depend on strength engineers for component mass properties, instrumentation engineers depend on controls engineers for I/O requirements, purchasing depends on mechanical engineers for material requirements, and so forth. Modeling and simulation are often the only practical means for finding those answers-especially early on.

The act of basing decisions on models is natural. When a company establishes a modeling culture, a wealth of benefits accrue from proper and efficient modeling through model reuse and other best practices, which allow the models to scale in size and complexity as systems become more defined and behaviors better understood. In turn, the answers provided through modeling and simulations improve as the design evolves and the effort to develop the product that follows has a head start.

In some organizations, there is a perception that plant modeling is too difficult and time-consuming and ultimately not worth the effort. However, even the simplest of models can provide value early in the design process if used correctly. Engineers do not have to wait for high fidelity models to begin to apply knowledge gained from simulation studies. Simple models that provide “trend-correct” behavior can be extremely useful in the conceptual stages of the design by developing the engineering team's intuition about system performance. For example, many engineering organizations have extensive repositories of measured data from previous design iterations. This data can be easily incorporated into lookup table models or used with system identification techniques to create high-level, functional models for early design verification. Relying exclusively on the existence of physical hardware in the absence of a plant model results in added costs and should be avoided whenever possible. Involving other modeling experts within the organization can accelerate the adoption of best practices. For example, engineers who are already comfortable with Model-Based Design for control design can help extend this approach to the discipline of system level plant modeling.

Invest in Modeling Resources

Creating a high-fidelity model of a physical system is not a trivial task, so it is important to have dedicated plant modeling resources throughout an organization. Too often, plant modeling is done in an ad hoc manner with a focus on short term benefits. Resources include not only skills at the engineering level, but also a mechanism in place to qualify models for their defined use. Qualified models should be placed under source control within a library to maximize reuse. This library infrastructure should be scalable to accommodate models for different applications created with varying levels of fidelity. Justifying the necessary time and expense to achieve this may require highlighting internal successes where plant modeling has been beneficial. Since it is unlikely that all required models will be available, it is also important to allow individual users to contribute to the model library. This will help increase modeling expertise and instill a modeling culture throughout the organization.

Emphasize Documentation

When establishing the organizational infrastructure, is it essential to emphasize the importance of documentation. It is also important to understand the difference between model developers and model users in regards to content, interfaces, and execution time. The model user needs to understand each model's limitations so that performance expectations are properly set. Model documentation is critical to this understanding and where possible should include test models that capture the capabilities and limitations. As the number of available models increases over time, having an infrastructure that enables engineers to easily find what models are available along with documentation of their technical attributes is essential.

Broadcast Successes (and Failures)

There is a tendency among engineers to resist new design methods and view them with some skepticism. While it is clearly important to understand the limitations of simulation results, it is not uncommon to encounter an attitude in engineering organizations towards modeling and simulation that can be summed up as: *"No one believes model results except the one who performed the calculation … everyone believes observed or measured data except the one who performed the measurements."* Engineers typically need tangible evidence before embracing a new design methodology, so it is important to communicate progress with the rest of the organization by highlighting successes and understanding failures and limitations. This can be done through regularly scheduled meetings among engineering and management to communicate the return on investment from modeling efforts and steadily build the business case for continued investment of resources in this area. It is just as important during the review process to communicate the limitations of the modeling methods to ensure expectations are properly set and a transparent engineering methodology is maintained.

Employing a Plant Model Development Strategy

Start Early

With a model-based culture, modeling begins at the very early stages of the design process. Using models for early verification has been shown to pay significant dividends, as design errors found early are much easier and less costly to correct [3]. As is often the case when adopting new processes, getting started with plant modeling can be a challenge due to uncertainty about the effort required and a lack of tangible benefits that will result. A common way to begin is to define the simulation goals and create a statement of work to serve as an agreement between the model developers and model users. This could be facilitated by extending the concepts used in the controls requirement specification to include plant models. It is important to recognize that plant model development time often increases significantly with increasing fidelity and to properly plan, prioritize, and scope the required modeling effort. The planning process should include defining the interfaces for the component models, understanding where domain interactions occur, and providing for the inclusion of sensor and actuator dynamics as needed. A challenge here is having access to all the information required to begin the modeling efforts. Reliance on engineering judgment along with past experience is essential.

Understand and Apply Different Modeling Techniques

This paper focuses on physical modeling techniques for control design and system design. It does not cover modeling methods used for detailed component design that are typically too computationally intensive for system-level simulation. While there is not necessarily a distinct line between models useful for system and control design and those useful for component design, an increasing amount of detail will have diminishing returns for system simulation. Figure 2 lists some of the common techniques for modeling physical systems and shows where they fit in the modeling spectrum.

It is important to understand the strengths and weaknesses of various modeling techniques and to know when to apply them. The attributes of some of the common techniques for plant modeling for system and control design are summarized below:

1. **Signal flow models** - This is the traditional method for graphically expressing first principles equations as part of a block diagram. While this can be used for detailed plant modeling, it is typically most effective for modeling control algorithms.
2. **Transfer functions** - This approach is used within signal flow models and is common for simpler systems where the input/output relationship is easily derived from first principles equations.
3. **Multi-dimensional lookup tables** - This is a common but powerful modeling technique that enables engineers to incorporate measured data into a model to define the input/output relationships.
4. **Statistical models** - This technique employs statistical methods using measured data to create input/output relationships derived from the data.
5. **State-space models** - This approach is similar to transfer functions; a state-space model is typically created by linearizing a more complex model at a specified operating condition.
6. **Embedded functions** - This approach involves reuse of predefined functions written in a common language (for example, C/C++) by incorporating them into your system model.
7. **Physical network approach** - This is a non-causal method with domain-specific physical connections that allow the energy exchange between physical components to occur.

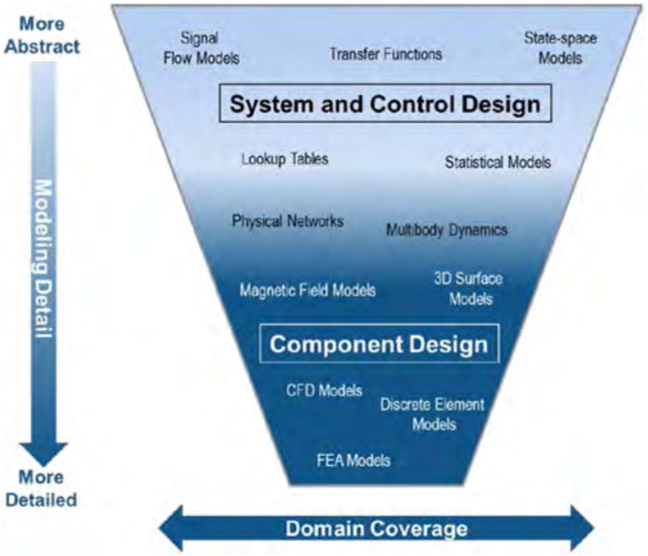

Figure 2. Modeling Techniques for System, Control, and Component Design

Data driven models using lookup tables can be useful when equations are unknown, but these models lack the dynamic behavior of models based on first principles models. It is possible to use first principles models with signal flow methods as system level models, but this approach is often impractical due to the difficulty in deriving and implementing the system-level equations. The physical connections employed by physical modeling tools handle the subsystem boundaries and result in less rework as the models are elaborated. Linear models can be useful when operating conditions are constrained and can be automatically generated from complex non-linear models at different operating points. High frequency pulse-width modulation is computationally expensive and can be replaced with averaged models for closed-loop control design. Statistical models can be derived from multiple datasets to provide insight into performance variance. Since they are derived directly from data measured to characterize the plant, statistical models have a higher degree of accuracy. They also have the advantage of much faster execution times when compared to first principle models. Making simulation models real-time capable for hardware-in-the-loop (HIL) studies typically requires making some simplifications to enable them to execute within the fixed computational resources. Another method is to replace complex components with statistical models. For example, higher fidelity models like those developed in GT-Power [6], can be used to generate response data. That data can then be used to develop statistical models for HIL testing. It is important to understand what simplifications are acceptable and be comfortable with these compromises.

Keep It Simple, Elaborate as Needed

It is most efficient to keep plant models simple at first and elaborate only as required for the specific analysis task. For system-level simulation, all that may be required initially to represent the plant is a transfer function or look-up table. As the design progresses, additional fidelity will be necessary, but this should be determined by the requirements or application, not necessarily by the model developer. The technique chosen for the plant model will play a critical role in the ability to elaborate without unnecessary model rework. As an example, consider the two models for an electronic throttle body mechanism [4,5] shown in Figure 3 and Figure 4. The throttle system includes a DC motor, throttle plate, gear, and mechanical spring.

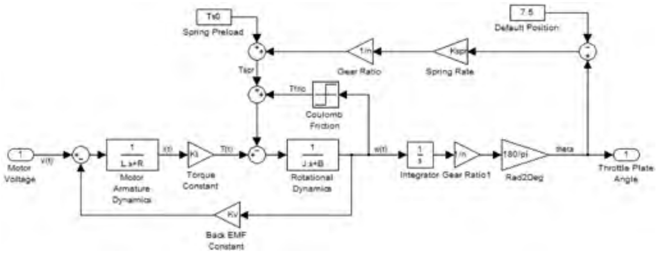

Figure 3. Signal Flow Plant Model for Electronic Throttle Body

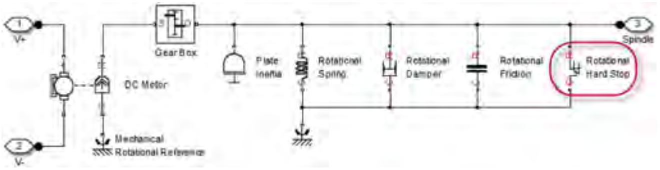

Figure 4. Physical Network Plant Model for Electronic Throttle Body with Hard Stop Added

The signal flow technique using transfer function blocks, while not uncommon for system-level modeling, begins to introduce added complexity when applied to a multidomain physical model. This is primarily due to the methodology of graphically modeling the system equations and having to account for the flow direction of energy. By contrast, the topology of the physical network model [7] more closely represents the structure of the physical throttle mechanism by connecting models of individual components or effects (motor, gearbox, inertia, friction, and so on). Using this technique, the overall model fidelity is determined by the equations used to represent each of the individual physical components and the system equations are formulated automatically from the model topology. Consider adding a non-linear spring to the throttle system model. Using the network approach, this can be done by simply modifying the equations inside the spring component model, requiring no change to the overall model topology. Furthermore, if model topology changes are required, the physical network approach again makes this task much easier. For example, the signal flow model shown here does not include travel limits of the throttle plate. To add this non-linear effect would require reformulating the system equations resulting in significant rework to the graphical signal flow representation. Using the network approach, this can be easily added by inserting a rotational hardstop block (circled in Figure 4) that contains the desired equations and material properties-again with minimal disruption to the overall model topology.

A key aspect of the physical network approach is the bidirectional flow of energy between connected components. This makes it easy to model interactions that occur within multidomain physical systems. The ability to easily modify the physical network model also encourages engineers to experiment with the model, testing different designs and gaining a deeper understanding of system behavior.

Match the Model Fidelity and Technique to Analysis Needs

To make effective use of plant models, the model fidelity as well as the modeling technique must match the analysis requirements. When relying on simulation models to make design decisions, the user must keep in mind the adage *"All models are wrong; some are useful"* [8]. Any physical model is an approximation of the actual behavior of the component or system. Using the wrong model for the analysis task typically results in either inaccurate results due to insufficient fidelity or prohibitively long simulation times due to unnecessary detail. Success here depends on good requirement definition and the proper documentation methods mentioned earlier. This enables potential users to be aware of the capabilities and limitations of the model. It can be tempting to use whatever model is available in an effort to save time, but investing in creating the proper model will typically prove more cost-effective in the long run. Figure 5 shows the range of approaches for plant modeling.

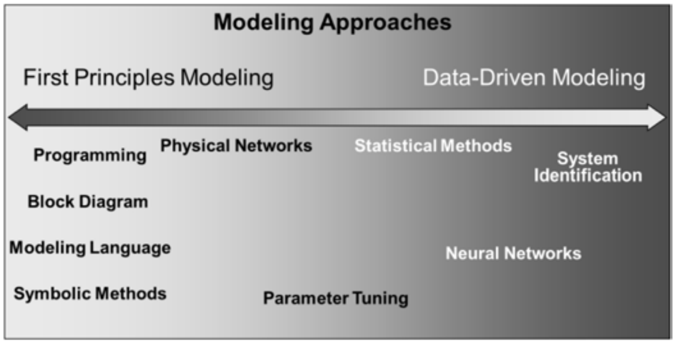

Figure 5. Modeling Methods Applicable to Plant Modeling

Typically a combination of different approaches are employed for a given system model and the modeling approach for a given subsystem or component often changes as the design progresses. More complex systems will often require a variety of different modeling approaches. Consider the engine model shown in Figure 6, modeled in Simulink. Here the physical network approach was selected for modeling the engine pneumatics and the thermal convection process. The throttle body and exhaust system consist of pneumatic valves to model the air flow dynamics; the intake manifold consists of pneumatic volume with convective heat transfer. The core engine combustion process is modeled using statistical methods from Model-Based Calibration Toolbox [9] to create Simulink models that optimize air-fuel ratio and output brake torque.

The models were carefully selected to achieve the desired fidelity and simulation speed. Any infrastructure created to search for existing models should include model fidelity as an attribute of the database. A set of common model classifications should be incorporated as part of this infrastructure.

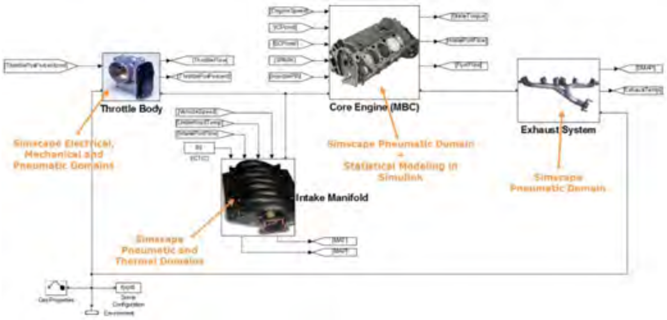

Figure 6. Spark Injected Dual-Independent Variable Cam-Phased Engine Model

Plan for Reuse, Begin with the End in Mind

Architecting models so that fidelity can be adjusted without major rework will save considerable effort as the design progresses. To help scope the modeling tasks and maximize reuse, ask critical questions during the planning process such as: Who can benefit from the model and how will they use it? Does a model already exist that meets the needs or can an existing model be easily modified? Can an existing high-fidelity plant model be used to parameterize a lower fidelity model? What additional effects may be required (for example, thermal effects, tolerances, or degradation)? Will this model need to run in real time? How does this model interact with the rest of the system? Developing a standard model architecture ties back to the organizational infrastructure needs and could include a combination of modeling guidelines, best practices, and style guides. A clearly defined specification also facilitates model reuse.

The type of analysis to be performed will most certainly affect the model requirements. It is important to determine if existing models are sufficient for the desired analysis task. Operating a model outside its intended region of operation will often result in invalid simulation results. For example, it does not make sense during simulation to vary a parameter or input over a large range of values if the resulting non-linear behavior is not incorporated into the model. Keep in mind that model developers and model users are not necessarily one and the same and often have different needs. As mentioned previously, it is important to sufficiently document the model's intended use along with any assumptions that were made. Properly documenting a model's intended use is essential for the end user to understand its limitations and correctly set their expectations for how the model will perform during simulation.

Use Automation to Decrease Development Time

Repetitive tasks that are essential yet time consuming are good candidates for automation. Examples include model documentation, model validation, and even some aspects of model development. Creating scripts that use model templates can help automate the creation of a common model structure. This enables developers to focus on the model content and helps establish a systematic development methodology. Using a standard model structure also helps to automate reuse of existing components. This approach can even be used to automate the creation of low-fidelity models from existing detailed models or measured data. Creating a common documentation format will also save time and effort by eliminating any potential confusion about the capabilities of a model. Model validation can be performed using data collected from a physical component or system, and common test benches can be created to exercise models to compare their performance to test data. These processes can be easily automated using optimization for parameter tuning, parallel computing to expedite the processing, and automatic report generation. A mature process for Model-Based Design will provide all of these opportunities for automation. Automation, however, is not substitute for regular review of models to ensure integrity of the development process.

Using Plant Models with Model-Based Design

Use Existing Models for More than One Application (The Rule of Two)

There are well-established industry best practices for applying Model-Based Design to embedded control system development [2]. Among these is the practice of using a model for at least two different purposes (also known as the “Rule of Two”). A significant amount of effort goes into developing simulation models of physical systems. Planning for model reuse will help ensure a maximum return on investment for the effort expended. For example, the model could be designed to test the control algorithms in simulation and then reused to test the software running on an ECU in a real-time HIL environment. Alternatively, applying parameter optimization along with statistical analysis methods could be useful for model verification and validation.

As the computational power of embedded controllers increases, plant models are often repurposed as observers implemented as part of the larger control strategy. This is typically justified when hardware costs can be reduced by eliminating a sensor or when emissions and fuel consumption can be reduced. The technique can vary depending on the secondary usage. One recent trend is to use models as part of a virtual calibration process. Often such models are used in conjunction with optimization techniques and therefore must not only be accurate but also execute rapidly, since base calibrations are derived from them. As a result, these models' characteristics make them good candidates for reuse in a real-time application, such as a HIL plant model used for testing [10]. Keep in mind that the modeling method chosen will play a large role in the ability to reuse the physical models. This is discussed further in the next section.

Employ In-the-Loop Simulation

To maximize their value, plant models should be capable of being used during all stages of the process. Desktop simulation, sometimes called model-in-the-loop (MIL) is typically used for initial design investigation all the way through the final parameter tuning using optimization techniques. Software-in-the-loop (SIL) enables engineers to simulate the control algorithm software with the plant model as a step in the verification process. Processor-in-the-loop (PIL) is the next level of verification; it integrates the production microcontroller and the plant model in a non-real-time debugging environment. Finally, in hardware-in-the-loop simulations the plant models are executed on a real-time operating system in communication with the production controller and other physical hardware. The real-time requirements of HIL simulation make it the most challenging of these methods to achieve. Fortunately, through a structured process typically involving some model simplifications and the selection of robust fixed-step solvers, real-time simulation of complex physical models is practical [11].

Verify and Validate Models

Plant model performance should be validated, preferably against measured data. Automatic parameter tuning using optimization techniques is efficient and can be used at the individual component level as well as the system or subsystem level. Model verification and validation is a continuous process that must be an integral part of the entire development process. A robust and well-documented validation process instills confidence in users of the models and properly sets expectations in what results can be achieved.

Summary/Conclusions

Developing plant models for embedded controls and systems is a critical part of Model-Based Design and reduces reliance on physical prototypes. When modeling the physical system and components, engineers must achieve the appropriate accuracy with a reasonable amount of computational resources. This paper discusses various approaches to plant modeling along with some practical considerations to keep in mind while undertaking the task of modeling physical systems. The different approaches discussed (block diagrams, transfer functions, lookup tables, statistics, and physical networks) each have benefits and limitations. Achieving a mature plant modeling process with Model-Based Design requires understanding the strengths and weaknesses of each approach and knowing when to apply them for maximum benefit.

References

1. Dillaber, E., Kendrick, L., Jin, W., and Reddy, V., “Pragmatic Strategies for Adopting Model-Based Design for Embedded Applications,” SAE Technical Paper 2010-01-0935, 2010, doi:10.4271/2010-01-0935.
2. Smith, P., Prabhu, S., and Friedman, J., “Best Practices for Establishing a Model-Based Design Culture,” SAE Technical Paper 2007-01-0777, 2007, doi:10.4271/2007-01-0777.
3. Murphy, B., Wakefield, A., and Friedman, J., “Best Practices for Verification, Validation, and Test in Model-Based Design,” SAE Technical Paper 2008-01-1469, 2008, doi:10.4271/2008-01-1469.
4. Pursifull, R. and Keener, H., “Motorized Throttle Positioning Simulation Model,” SAE Technical Paper 2003-01-0222, 2003, doi:10.4271/2003-01-0222.

5. Yang, C., “Model-Based Analysis and Tuning of Electronic Throttle Controllers,” SAE Technical Paper 2004-01-0524, 2004, doi:10.4271/2004-01-0524.
6. Maloney, P., “Objective Determination of Minimum Engine Mapping Requirements for Optimal SI DIVCP Engine Calibration,” SAE Technical Paper 2009-01-0246, 2009, doi:10.4271/2009-01-0246.
7. Simscape Users Guide (R2012b), Basic Principles of Modeling Physical Networks, http://www.mathworks.com/help/physmod/simscape/index.html.
8. Box G., Draper N., Empirical Model-Building and Response Surfaces. Wiley. pp. 688, p. 424. ISBN 0471810339, 1987.
9. Maloney, P., “Objective Determination of Minimum Engine Mapping Requirements for Optimal SI DIVCP Engine Calibration,” SAE Technical Paper 2009-01-0246, 2009, doi:10.4271/2009-01-0246.
10. Raman S., Sivashankar N., Milam W., Stuart W., and Nabi S., Design and Implementation of HIL Simulators for Powertrain Control System Software Development, Proceedings of the American Control Conference, 1999.
11. Miller S., Wendlandt J., Real-Time Simulation of Physical Systems Using Simscape, http://www.mathworks.com/products/simscape/technicalliterature.html.

Contact Information

Tom Egel
MathWorks Consulting Services Group
tom.egel@mathworks.com

Scott Furry
MathWorks Consulting Services Group
scott.furry@mathworks.com

ISSN 0148-7191

http://papers.sae.org/2014-01-0310