2008-01-1292

Combining Passion with Fundamentals - Applying Model-Based Design to Education

Marc E. Herniter, Zachariah Chambers
Rose-Hulman Institute of Technology

Elizabeth Callanan, Sameer M. Prabhu
The MathWorks, Inc.

ABSTRACT

Model-Based Design is increasingly prevalent in industrial sectors including aerospace and automotive, but lacking from college and university curricula. The need for students to be adept at the modeling of systems, their associated subsystems, and overall system controller as per the standard industry practice is the impetus for The MathWorks, Freescale, and MotoTron to partner with Rose-Hulman Institute of Technology to address the lack of students familiar with this industry standard practice. Rose-Hulman Institute of Technology has created the Model-Based-System Design Center with the express purpose of introducing the philosophy of Model-Based Design to the educational community. This paper describes the function of the Center and the teaching materials currently being generated.

1. INTRODUCTION

Everyone can remember a teacher or two from their years in school who managed to take everyday subjects and topics and brought them alive with insightful, deep knowledge and inspired story telling. This helped build a vision in the minds of the students about how the subject of discussion related to other things in the universe and thereby built a lifelong passion in the minds of the students for that subject. Thus, great teaching gives students an in-depth understanding of a subject and simultaneously ignites an interest to pursue that subject with a lifetime of continued learning and understanding. The relentless pace of technological advances allows students ample opportunities to explore newly emerging areas that lie at the intersection of engineering and scientific disciplines that traditionally have been considered as separate educational disciplines and thus serve to fire up a student's desire to be innovative and creative. Automotive engineering, especially with the recent focus on the research and development of hybrid and alternative fuel vehicles, provides one example of fertile ground in which to capture and grow a student's imagination for a lifetime. The convergence of mechanical, electrical, electronic, and control systems that is necessary to make these advanced vehicle concepts work, allows students to see how these different disciplines and physical phenomena interact with each other to make complex system functionality possible. This however does necessitate a change in the traditional teaching mechanisms employed in universities and colleges.

Traditionally, educational institutions use a bottom up approach and focus on understanding the physics of individual components without showing how the components fit into a larger system. This creates a disconnect because students come from a world where they can relate to and understand the purpose of the system. Introduce information by describing the system, and you can capture a student's imagination. Focus on the component without relating it to a system and you lose a student's attention and passion. As educators, we agree that an understanding of the fundamentals and an understanding at the component level is necessary to be a successful engineer. However, we also recognize that students need context in which to apply those fundamental skills. Students see the application of systems all around them. They do not, however, see that systems are made up of smaller subsystems. When we talk about subsystems and basic physics in class, students lose interest.

To solve this problem, we propose to apply Model-Based Design, a technique used in industry to design large systems, to bridge the gap between a student's familiarity of a system to a physical understanding of its inner workings.

With Model-Based Design, models of individual components are developed and then the components are interconnected to form a system that solves a problem. Developing models of individual components gives students a physical understanding of the components and allows us to cover engineering fundamentals. Connecting the component models together to form a non-trivial system provides context. If the system is chosen correctly, it is a non-trivial system that the student has seen before and the student knows why it is important.

As participants in the Challenge X Hybrid Vehicle competition, we have seen the passion students exhibit when learning about a system in which they are totally engrossed. [1] We also learned that a formal modeling technique is needed to successfully produce a working hybrid vehicle. We are combining passion with fundamentals by applying and teaching Model-Based Design to systems based courses. We have formed a consortium of several companies, including software providers, hardware providers, and system integrators, to support the development of these courses. In this paper we discuss the Model-Based-System Design Center and the development and content of the courses it is charged to create. The paper is organized as follows. In section 2 we introduce Model-Based Design and its importance in industry. We then discuss in section 3 how the need to bridge the gap between industry and academia in adopting Model-Based Design has driven the creation of Model-Based System Design Center at Rose-Hulman Institute of Technology. The courses developed at the Center and the mechanisms for dissemination of knowledge are discussed in Section 4 and the conclusions of the paper are outlined in Section 5.

2. MODEL-BASED DESIGN

2.1 Model-Based Design in Industry

Given competitive pressures, developing a product on time and within budget requires a systematic approach to the design and realization process. The design and realization process in the aerospace and automotive industries is typically represented by a V diagram as shown in Figure 1. [2]

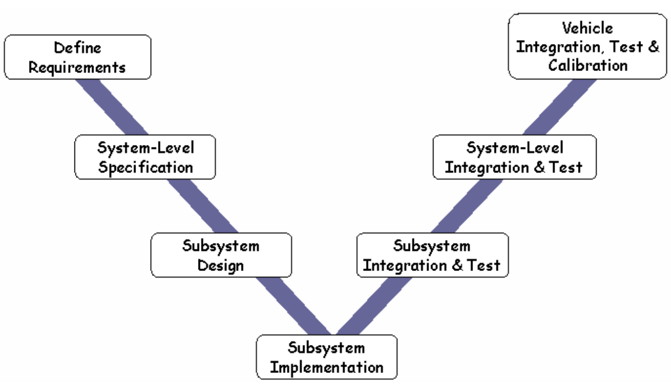

Figure 1: A V Diagram of the System Design and Realization Process

The two sides of the V correspond to uniquely different activities. The left branch captures the decomposition of the initial system requirements into subsystems and components that are specified and implemented at a detailed level. The right branch represents the realization of the subsystems and components specified in the left branch and their integration.

In a traditional product development process, engineering teams would observe strict boundaries between the various design activities in the process. Teams would communicate by passing text-based design documents back and forth. This method has several drawbacks such as document synchronization with the current state-of-the-art of the design, errors introduced with recording and understanding the design functionality in the form of a text-based document, and the need to manually code the application. Furthermore, when documents are used as deliverables and shared electronically, engineers often duplicate efforts and it is difficult to trace the source of errors along a paper trail.

Engineering teams in the automotive, aerospace, communications, power systems, and other industries have turned to Model-Based Design to address these problems. [3,4] Model-Based Design enables engineering teams to effectively manage the ever-increasing complexity of products, more demanding performance requirements, and tighter product development cycles. By using models early in the design process, engineers can create "executable specifications" that enable them to immediately validate and verify specifications against the requirements. Instead of communicating with documents, engineers can share models that capture the performance of subsystems and components. With early and continuous modeling and simulation, errors can be detected and eliminated earlier in the design process when the cost to fix them is less.

Model-Based Design uses automatic code generation to facilitate hardware-in-the-loop testing, thus eliminating errors introduced during manual implementation and realization. Automatic code generation shortens the path to product delivery by generating code for testing, calibration, and final production.

2.2 Need for Model-Based Design in Academia

Model-Based Design is not formally taught in the typical undergraduate setting because students do not have the opportunity to work on large systems (e.g., a complete automobile, communication system, or power system) in a conventional classroom setting. Students are exposed to models as part of a typical electrical engineering curriculum; however, the emphasis of such courses is on the model and how it represents the physical component. Schools do not teach the philosophy of Model-Based Design, how to apply it to the design of engineering systems, nor the rationale for adopting Model-Based Design for the design of complex systems. Students typically learn about pieces of a subsystem, focusing on small parts of the whole without appreciating the effect a piece or subsystem can have on the total system.

Academics traditionally introduce an understanding and mastery of the “building blocks” and then use the block in the context of an example. The use of the blocks as part of a larger system, or the analysis of a large system is typically not practical in a classroom setting. As a result, engineering graduates entering the workforce must negotiate a steep learning curve in terms of learning, mastering, and then applying Model-Based Design, which is increasingly prevalent in industry. To ease the transition for engineering graduates and bridge the gap between industry and academia, students and faculty must be introduced to Model-Based Design at the undergraduate level.

Model-Based Design is a philosophy which allows one to attack a complex system from all levels: from the basic physics of the system components, through the interaction between components, to the overall behavior of the system. This philosophy takes a system from basic physical models to implementation and demonstration of the solution. Model-Based Design allows students to:

- Understand basic physics of components in the context of the overall system.
- Understand component interaction.
- Understand and work at the system level.
- Understand and investigate control methods.
- Troubleshoot the overall system.
- Embrace a process adopted by OEMs
- Use state-of-the-art software and hardware tools.

The need for students to be adept at the modeling of systems, their associated subsystems, and overall system controller is the impetus for The MathWorks, Freescale, and MotoTron to partner with Rose-Hulman Institute of Technology to address the lack of students familiar with this industry standard practice.

3. MODEL-BASED SYSTEM DESIGN CENTER

3.1 Introduction to the Center

To address the issues discussed above, Rose-Hulman has created the Model-Based-System Design Center to introduce the academic community to the industry standard practice of Model-Based Design. The principal materials to be developed are academic courses, webinars, academic and professional workshops, and establish a national information center for faculty and professionals seeking to learn about and implement Model-Based Design. Course content will be implemented in two pilot interdisciplinary technical electives. Educational and technical conferences will be targeted for faculty and professional workshops. Collaboration with industry partners will ensure that the technical content is relevant and current.

The materials developed will focus on undergraduate students who have completed at least two years toward a four-year degree in electrical or mechanical engineering. Additionally, workshops will target faculty that teach undergraduates with the goal of teaching faculty how to teach Model-Based-System Design.

Model-Based-System Design addresses the design of large systems that are inherently multidisciplinary and span a large cross-section of technology. Engineers working on large systems must work with a large cross-section of suppliers and technologies that span traditional engineering disciplines. To model this, a Model-Based-System Design Center and the curriculum it develops must necessarily be supported by a wide range of companies. To date, our center is supported by software and hardware manufacturers (The MathWorks, MotoTron, and Freescale), system integrators, and component suppliers. This collaboration ensures that the activities of the center produce curriculum that educates undergraduate students with the skills needed to design the complex systems of the future.

3.2 Activities of the Model-Based-System Design Center

The Model-Based-System Design Center was created to introduce the academic community to the philosophy of Model-Based Design. Activities of the Model-Based-System Design Center include:

- Generation of full-length academic courses on Model-Based Design (both introductory and advanced) that can be incorporated into the curriculum.
- Generation of academic workshops to teach faculty how to teach Model-Based Design.
- Generation of industry-focused short courses on Model-Based Design (both introductory and advanced).
- Presentation of workshops on Model-Based Design at academic conferences.
- Presentation of workshops on Model-Based Design at professional conferences.
- Establishment of a national information center for faculty and professionals seeking to learn about and implement Model-Based System Design.

The Model-Based-System Design Center intentionally has a strong relationship between industry and academia. Traditionally, academic courses and projects are limited in scope and the number of interdisciplinary fields that they can span. This is a requirement usually imposed by the fixed length of a course. Companies that produce large systems or suppliers that work with those companies, require engineers to work on large multidisciplinary systems. A disconnect exists between the skills requirements of industry and the skills of students produced in a traditional curriculum. This disconnect has resulted in two problems that we propose to solve: (1) Companies must educate incoming engineers in Model-Based-System Design and incoming engineers must negotiate a steep learning curve. (2) Faculty are not familiar with teaching the design of large systems or the recent methods adopted by industry to design large systems.

We propose to solve these problems by a strong collaboration between industry and the Model-Based-System Design Center. The Center is currently supported by several companies such as The MathWorks, Freescale, and MotoTron. Continued support from these companies requires the center to use state-of-the-art tools and techniques as well as produce students and curriculum relevant to the design of large systems. The center will offer industry short courses to engineers at companies that work on large systems. Offering these courses keeps the center abreast of the skills demanded by industry. These skills will also be taught in the academic courses to undergraduates. Faculty workshops will be taught at both academic and professional conferences to teach faculty how to teach Model-Based-System Design. Possible conferences are ASEE Annual Conference, the Frontiers in Education conference, Freescale Technology Forum, and MathWorks Automotive Conference. The Center will also offer faculty workshops at Rose-Hulman Institute of Technology. A major function of the Center will be the development of courses in Model-Based-System Design and to make the course materials available to faculty interested in teaching the subject. Materials currently available are course slides and laboratory exercises.

3.3 Industry Support of the Center

The design and realization of a large system requires products and support from a wide range of companies covering a large spectrum of engineering disciplines. Accordingly, the Model-Based-System Design Center is supported by several companies. Present supporters and the critical piece of the puzzle they provide are listed below:

- The MathWorks – Supply the modeling software for the life of the design cycle, including simulation, real-time simulation, automatic code generation, and design of experiments.
- Freescale – Supplies the hardware and software for implementing solutions on hardware targets. Hardware includes various evaluation boards that can be used to realize system level controllers. Software includes licenses for compilers used in the automatic code generation process and Simulink® toolboxes that allow easy access to hardware resources.
- MotoTron - Supplies the hardware and software for implementing solutions on targets. Hardware includes targets that can survive in an automotive environment and the tools needed to tune controllers in real-time. Software includes licenses for Simulink toolboxes that allow easy access to hardware resources and tools for real-time system monitoring and tuning.

4. COURSE DEVELOPMENT AND KNOWLEDGE DISSEMINATION

4.1 Model-Based Design

Two quarter-long academic courses and two academic/professional two-day workshop courses are currently under development by the center. The workshop courses are condensed versions of the academic courses and have been presented several times to students through the Challenge X competition and locally to Indiana State University faculty. The academic courses will be offered for the first time at Rose-Hulman in the Winter and Spring quarters of the 07/08 academic year. Rose-Hulman uses the quarter system where three 10-week terms are offered during the academic year. In a traditional semester system, two 15 week courses are offered during an academic year.

The first course, “Introduction to Model-Based-System Design,” is a junior level technical elective. This course applies the principals of Model-Based-System Design to a simple motor-generator system so that students can focus on the process of Model-Based Design rather than become lost in the physics of a large and complex system. The course takes students from basic modeling of components, through real-time simulations and deployment on real-time targets, to testing a solution on a physical system. All of the steps used in industry to model, simulate, and realize a solution are introduced in this course. A brief outline is given below:

- Model-Based Design for a Small System
  - Motor Model
  - Generator Model
  - Controller Model
  - SimDriveline Intro
- Simulink Simulations
  - Explore the System Response Using Different Control Methods
  - Tune the System
  - Explore System Limitations
  - Understand and Refine Motor Models
- Real-Time Simulations with xPC
  - Plant and Controller Implementation on Single Target
- Implement Controller on MPC5554 Target
  - Install Hardware and Software
  - Use Freescale RAppID Toolbox
  - Familiarize Students With Pin Outs
  - Explore Analog Inputs, Digital and PWM Outputs
- Processor-in-the-Loop Real-Time Simulations
  - Controller on Freescale Target
  - Plant on Real-Time Target
  - Display Performance on Virtual Gauge Display
  - Data Collection of Performance
- Test Controller on Real System
  - Observe System Performance
  - Observe the Effect of Different Control Methods.
  - Tune the System

- Model Verification
    - Data Collection of Physical Model Response
    - Comparison of Physical Plant Response to Model Response
- Design Of Experiments to Collect Data on Motor and Generator
    - Automatically Generate Test Schedule to Obtain Data
    - Run Experiments and Collect Data
    - Generate Models for Components
        - Table-Look Up
        - Curve Fits
- Model Refinement and Re-Verification
    - Update Models to Include Measured Data
    - Comparison of Updated Physical Plant to Model
    - Further Exploration of Alternate Control Methods

The second course, “Advanced Model-Based-Systems Design,” applies Model-Based Design to a series hybrid-electric-vehicle. This course applies the concepts introduced in the junior-level course to a much more complicated system. Models are more in-depth and repeatedly refined, verification and validation processes are introduced and applied, communication protocols and their effect on the system are discussed, and test plans and data collection are covered. If student teams can demonstrate that the controller they have developed can safely control a hybrid-electric-vehicle, the controller is deployed on an actual series hybrid-electric-vehicle and tested. A brief outline is given below:

- Introduction To Modeling Tools
    - Simulink
    - Vehicle Model Blocks
    - Create Vehicle Model with Rear Diff, Constant Torque Motor, and Tires
    - Create Electric Motor Using Look-Up Table
    - Creating a Model Initialization File
- Modeling Large System
    - Create a Model Hierarchy
    - Electric Motor Model
    - Battery Model
    - Driver Block
- Troubleshooting A Large System
    - Identify and Correct Model Physical Problems
    - Run Simple Drive Cycles
    - Read Drive Cycles from Files
    - Simulate Standard Drive Cycles
    - Enhanced Motor Model
- Modeling Internal Combustion Engines
    - Investigate SimDriveline Engine
    - Create Detailed Engine Model
        - Fuel Consumption
        - Torque Versus Rpm
        - Braking Torque
        - Engine Off Torque
- Designing A System Controller
    - Create Controller with Complex Logic Structures
    - Maintain Battery State of Charge
    - Develop Engine Starting Method
    - Calculate Fuel Efficiency
- Model Enhancement and Observation
    - Identify and Eliminate Model Problems
    - Identify and Eliminate Hazards
    - Observe the Effects of Changing Component Properties

These courses have been implemented using two methods. Pilot courses have been taught as two-day workshops several times, and full-length academic courses are being taught for the first time during the 2007-08 academic year. The workshops have been taught four times to students and faculty participating in the Challenge X Crossover to Sustainable Mobility competition [1] and three times to Rose-Hulman students involved in senior design projects and student competition design projects such as Challenge X and Rose Efficient Vehicle. These workshops have been used to refine and improve the course content.

An example model used in the first class is shown in Figure 2. This model is used to develop controller and plant models for a simple motor-generator system. This simple system is then used throughout the course in simulations, real-time simulations, real-time targeting, and verification and validation.

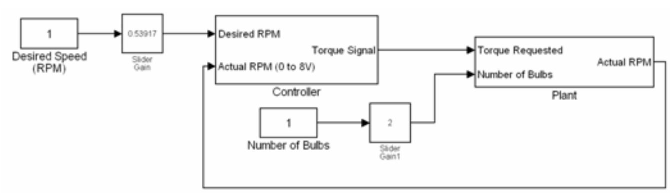

Figure 1: Top level of the motor-generator system.

The plant model contains subsystems for the motor and generator. An evolved version of the generator model is shown in Figure 3. This model allows us to understand the generator from a physical point of view, a terminal characteristic point of view, and as a component in a larger system.

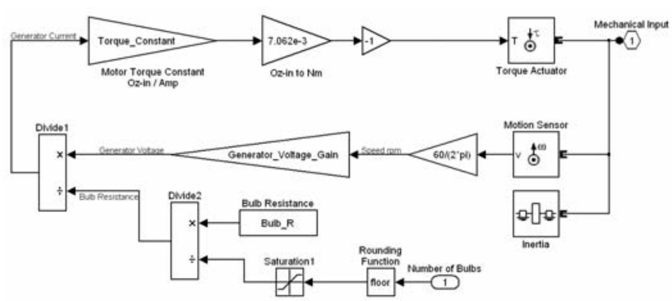

Figure 1: Generator subsystem model.

One major advantage of this model over that used in a traditional control course is that students understand the physics and operation of the physical plant. From this understanding, a controller is generated and the system performance is observed. Understanding the system from a control point of view and a physical point of view is not typically covered in a traditional control systems course where the plant is usually given and specified as a system of equations or a transfer function with no understanding of where the equations originated.

4.2 Model-Based Design Center Knowledge Dissemination

The goal of the sponsors of the Model-Based-System Design Center is to make the information generated by the Center as widely and freely accessible. The information will be disseminated in several ways including websites, workshops at academic and professional conferences, papers at academic and professional conferences, professional and academic workshops at Rose-Hulman Institute of Technology.

Websites: Rose-Hulman Institute of Technology will develop a dedicated website where all generated educational material will be available for download. Additional, web pages at the major sponsor's sites such as The MathWorks, Freescale, and MotoTron will be created to increase the exposure of the materials. Available material will include webinars, course slides, laboratory exercises, and homework assignments and projects.

Teaching Workshops: Workshops with the goal of teaching educators how to teach Model-Based-System Design will be held at national academic and professional conferences. Targeted academic conferences are the Annual ASEE Conference & Exposition and the annual Frontiers in Education conference. Proposals for workshops at both conferences will be submitted. Because of the Center's close relationship with Freescale, an academic workshop will be held at the the Freescale Technology Forum. This workshop will allow educators to learn about large system design using the Model-Based-System Design philosophy and network with practicing engineers in a field requiring the design of large systems. The Freescale Technology Forum is an annual professional conference. Although the focus of the conference is technical, the conference includes an educator track for the first day of the conference. Invited educators may attend the conference free of charge. Depending on the conference, workshops would be anywhere from ½ to 1 day long.

Challenge X Workshops: As part of the Challenge X – Crossover to Sustainable Mobility university competition, the Model-Based-System Design center will present annual workshops to the faculty and students participating in this competition. Challenge X is a 4 year competition where 17 universities design and build a hybrid-electric vehicle. A hybrid-electric-vehicle is a very large and complex system, and all teams are encouraged to use Model-Based Design to design their vehicle. Rose-Hulman Institute of Technology has presented four two-day workshops to the Challenge X teams over the past two years. We see this form of dissemination continuing in the future at upcoming Challenge X competitions.

Rose-Hulman Institute of Technology Workshop: Following a model pioneered by the University of Minnesota to promote a philosophy for teaching Electric Power Engineering, we will conduct an NSF sponsored workshop to be held at Rose-Hulman Institute of Technology. [5] This will be a two day workshop where educators are invited to learn how to use Model-Based-System Design in their classes. The workshop will be free of charge and educators will receive a travel stipend to help encourage their attendance. Teaching Model-Based Design in a university setting will allow students to quickly ramp-up into their post academic careers as many industries have adopted Model-Based Design as a foundation for their product development process.

One way to gauge the success is to monitor the number of students who register for subsequent advanced technical electives in Model-Based Design. Rose-Hulman will also track the career paths of students who graduate and measure the impact the courses have on reducing the learning curve new hires might otherwise encounter in industries that use Model-Based Design.

5. CONCLUSION

Applying Model-Based Design to the design of large systems is an industry standard practice that has not yet been adopted by the academic community. The Model-Based-System Design Center was created to bridge the gap between industry and academia. This center is supported by a wide range of companies that span a variety engineering disciplines. The collage of companies was chosen to model a similar requirement in industry where the design of large systems requires products from a wide range of suppliers. Thus far, the Model-Based-System Design has produced two short courses and is developing two full-length academic courses. The results of these courses will be the topic of a future paper.

ACKNOWLEDGMENTS

The authors would like to thank The MathWorks, Freescale, and MotoTron for their support of the Model-Based-System Design Center. Without their foresight into the future of education, this endeavor would never have been realized. Not only have they provided state of the art tools, but they provided training and support so that we could effectively use the tools and disseminate the information to students and faculty. We are grateful for their support. The authors would also like to thank General Motors, Argonne National Laboratory, and the Department of Energy for supporting the Challenge X competition. Without this competition and their encouragement, we would never have been introduced to Model-Based Design.

REFERENCES

[1] http://www.challengex.org/

[2] Prabhu, S. M., and Mosterman, P.J., “Model-Based Design of a Power Window System: Modeling, Simulation, and Validation,” Proceedings of the Society for Experimental Mechanics IMAC XXII, 2004.

[3] “Nissan Develops Emission Reduction System for Mass-Production Vehicles Using The MathWorks Tools”,http://www.MathWorks.com/mason/tag/proxy.html?dataid=4388&fileid=20542

[4] “BAE SYSTEMS Controls Develops Autopilot for Unmanned Aerial Vehicle Using The MathWorks Tools” http://www.MathWorks.com/mason/tag/proxy.html?dataid=2886&fileid=21724

[5] N. Mohan et al, Success with NSF CCLI-EMD and CCLI-ND Grants, “Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition, American Society for Engineering Education”, 2004.

CONTACT

Marc Herniter, (812) 877-8512
Marc.Herniter@ieee.org
5500 Wabash Avenue
Terre Haute, IN 47803

Zac Chambers, (812) 877-8904
Chambez@rose-hulman.edu
5500 Wabash Avenue
Terre Haute, IN 47803

Elizabeth Callanan (508) 647-7417
Liz.Callanan@MathWorks.com
3 Apple Hill Drive
Natick, MA 01760

Sameer Prabhu (248) 596-7944
Sameer.Prabhu@MathWorks.com
Crystal Glen Office Centre
39555 Orchard Hill Place
Suite 280, Novi, MI 48375