Development of an Introductory Course on the Modeling and Control of Advanced Electric Vehicles

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***Abstract*— In January of 2010 the University of Detroit Mercy began offering a Graduate Certificate in Advanced Electric Vehicles. This program was intended as a means to quickly and effectively educate practicing engineers in the skills that they would need as the number of electric and hybrid-electric vehicles being produced increases. The program was initiated with the support of Ford Motor Company who has committed to sending at least 125 engineers through the program in its first five years of existence. A central element of this program is a course on the modeling and control of advanced electric vehicles. This paper describes the structure and content of this course, as well as the lessons learned and what they mean for the introductory system dynamics and control curriculum in general.**

I. INTRODUCTION

The University of Detroit Mercy began offering a Graduate Certificate in Advanced Electric Vehicles (AEVs) in January of 2010. The program was developed at the direction of Ford Motor Company with the purpose being to quickly and effectively educate some of Ford's existing engineers in the skills that they would need to participate in the production of modern electric and hybrid-electric vehicles [1]. The program as a whole was developed for an audience of practicing engineers that are currently or soon will be members of AEV programs. While these engineers won't necessarily be experts in the design or implementation of any of the subsystems that are particularly unique to AEVs, it is expected that they will need to interface with some of these new AEV technologies as part of their everyday duties.

The graduate certificate program is structured to be completed in one calendar year over the course of three semesters. It is expected that the students will maintain full-time employment while enrolled in the program. Five courses must be completed with a cumulative B average to earn the certificate. The course offerings and their proposed ordering are shown in Fig. 1. Three of the seven courses are required core courses with one offered in each of the three semesters of the program. The core courses and the order in which they are offered are an introductory AEV course (AEV 5010), a course on the modeling and control of AEVs (AEV 5020) and a course on electric drives (AEV 5050). In the first and third semesters the students are also scheduled to choose an elective course. There are in general two tracks available: (1) a technical track consisting of an elective in energy storage systems (AEV 5030) and an elective in power electronics, and (2) a product development track consisting of an innovation and systems architecture course (AEV 5060) and a systems engineering course (AEV 5070).

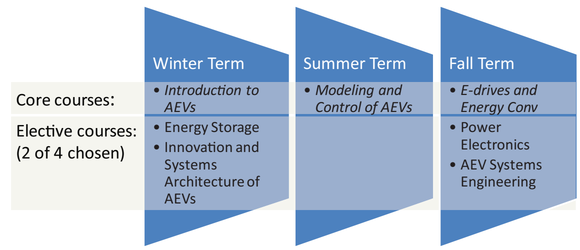

Fig. 1. AEV Graduate Certificate Course Plan

While the program has been developed to be completed in one calendar year, some students may choose to spread the program out over a longer period of time and take only one course per semester. The focus of this paper is the course AEV 5020: Modeling and Control of AEVs. This course is intended to follow the introductory course AEV 5010 and to be taken in a semester on its own since many students regard it to be the most technically challenging course in the program. The introductory course AEV 5010 serves as a high-level overview to the systems and challenges unique to AEVs. The modeling and control course AEV 5020 is a good follow-up to AEV 5010 since control is important to the operation of most AEV subsystems as well as the vehicle system as a whole. AEV 5020, however, approaches these systems with much more mathematical rigor than AEV 5010. AEV 5020 is also a good pre-cursor to the power electronics (AEV 5040) and motors (AEV 5050) courses, and to a lesser extent the batteries course (AEV 5030), since AEV 5020 addresses the subsystems from a first principles perspective, while the other courses are focused more on practicalities and implementation heuristics, including control.

The first cohort of Ford engineers began the certificate program in January 2010 with approximately 30 of them having successfully completed the program so far. An additional 34 Ford engineers from the second cohort have completed the program and a third cohort of 30 engineers began the program in January of 2012. In addition to the Ford engineers, off-cycle offerings of these courses have been taught for the benefit of other working and displaced automotive engineers. The certificate program has been certified by the Michigan Academy of Green Mobility Alliance (MAGMA) that supports the training of automotive workers for the emerging green economy. In the first three offerings of AEV 5020 a total of 87 students have completed the course.

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This paper will focus on the structure and lessons learned from the first three offerings of AEV 5020: Modeling and Control of AEVs. In particular, the implications of these lessons for the introductory systems modeling and control curriculum in general will be discussed. The remainder of this paper will be organized as follows: Section II discusses the topics covered in the course including modeling, analysis and controller design, Section III discusses the laboratory component of the course and Section IV concludes the paper with a summary and a discussion of future plans.

II. COURSE TOPICS

The course, AEV 5020: Modeling and Control of AEVs, has content that closely resembles the introductory systems modeling and control course common to the undergraduate curricula of many engineering disciplines. As the course is part of a larger certificate program on AEV engineering, many of the applications and practical lessons are geared toward electric vehicles and their particular subsystems, however, the mathematical tools and theory are not fundamentally different from other more commonly offered courses.

A challenge posed by this course is that the background of the students is quite diverse with many students having completed their last university degree many years prior. For example, there have been students in the course with backgrounds such as chemistry and computer science that have little engineering background at all, while there have also been students with advanced degrees who primarily work in a controls area. Of the 78 students surveyed, only 30 had taken a control systems course prior to taking AEV 5020, and many of those that had did so many years ago. Interestingly, 40 of the 78 students surveyed stated that they had at least some experience with control systems through their jobs. The limited background of the students in the course means that instruction must start with basic mathematical tools such as a review of differential equations and the Laplace transform. Not only must the course start from the fundamentals, but the course must cover more material than a typical undergraduate course in order to address those topics particular to AEVs and in order to justify the graduate credit the students receive for completing the course. In order to address these conflicting requirements, while not exceeding approximately 40 hours of meeting time, it was necessary to adjust the way the course was taught as compared to a more traditional introductory course in system dynamics and control. Specifically, less emphasis was placed on hand calculations and more emphasis was placed on concepts and the use of software tools, such as MATLAB and Simulink.

While the schedule and number of class meetings may vary from semester to semester, Table I depicts an example schedule for AEV 5020.

TABLE I
EXAMPLE SCHEDULE FOR AEV 5020

Lec #	Topics	Time (min)
1	Introduction to modeling and control, differential equations, the Laplace transform and properties	165
2	Mechanical system models, transfer functions	165
3	Electrical system models, power electronics, blackbox modeling, batteries, simulation	165
4	Electromechanical systems, sensors, motors (DC & AC), first-order system response	165
-	Quiz #1	45
5	Stability, second-order system response, extra poles and zeros, system ID, nonlinearities	120
6	Block diagram manipulation, introduction to control and specifications, PID control	165
7	Laboratory introduction and modeling review	45
-	Laboratory Activity #1	120
-	Midterm Exam	120
8	Steady-state error, root locus basics, root locus for controller design	165
9	Introduction to frequency response and Bode plots, relative stability, system identification	165
10	Frequency response approach to controller design, different architectures, robustness, optimality	165
-	Quiz #2	45
-	Laboratory Activity #2	120
11	Discrete logic design, system-level considerations, control system implementation, advanced topics	165
-	Final Exam	120
	Total time in minutes Total time in hours	2220 37

A. Modeling

Approximately the first third of the course is spent on the modeling of dynamic systems. This includes the introduction of various mathematical formalisms for representing systems, as well as techniques for generating these models.

1) Mathematical Formalisms: Since the students typically do not recall many of the mathematical fundamentals necessary for this course, instruction begins with the basics. There is, however, some movement to push some of this instruction on fundamentals back to the introductory course (AEV 5010). In the AEV 5020 course differential equation and transfer function models are taught. The state-space modeling formalism is not introduced and the content of the course remains primarily focused on Single Input Single Output (SISO) systems. In the solution of differential equations and the generation of transfer function models, the Laplace transform and its properties are also introduced.

In order to reduce the amount of hand calculations necessary for the course, only relatively simple differential equations are solved by hand. Rather than exactly solving a forced, high-order differential equation, the focus is placed on predicting the character of the solution based on the roots of the characteristic equation (poles of the transfer function) and the type of forcing function. That is not to say that the Laplace transform and its inverse are not used, it is just that the examples and assigned problems focus on first- and second-order systems and more commonly encountered forcing functions (step, ramp, sinusoid). For example, only very simple partial fraction expansions are ever demonstrated or required in a problem. The use of MATLAB to determine residuals, however, is taught. Along the same lines, the algebra required to generate a transfer function model from a given set of differential equations is also kept to a minimum.

While the hand calculations are kept to a minimum, a great deal of emphasis is placed on the character of different models and the tradeoffs associated with their application. For example, the differences between employing a differential equation model as compared to a transfer function model are emphasized. Also, the tradeoffs associated with including more or less complexity in a model are discussed. For example, when are the dynamics of a particular mode "fast" enough that they can be considered constant, or when are the values of individual parameters changing slowly enough that they can be treated as time-invariant? More generally, an understanding of what a dynamic model provides as compared to what a static model provides is emphasized. For the example of a motor, Fig. 2 demonstrates how a dynamic model illustrates the transient torque response of the motor (or speed response) for a given input, while Fig. 3 depicts how a static motor model captures the steady-state behavior in a torque-speed curve (or efficiency map). The basic lesson here is that there is a tradeoff between the level of accuracy provided by a model and the ease with which a model can be used for analysis and design.

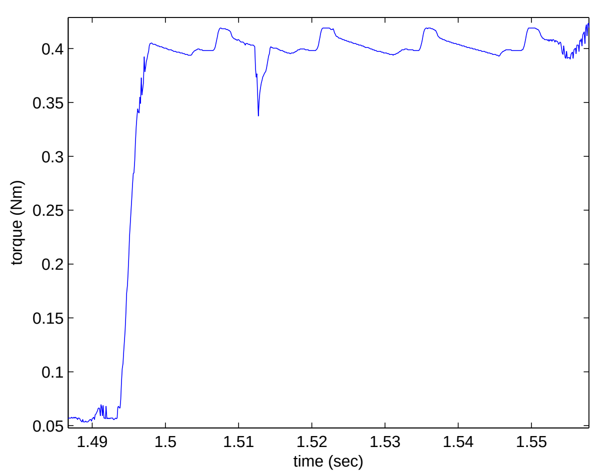

Fig. 2. Motor from a dynamic viewpoint: Motor Torque Time Response

Another area where mathematical rigor is sacrificed in favor of greater conceptual understanding is the modeling of nonlinearities. In the course, how to linearize a nonlinear model is not taught. However, understanding why a linearized model is useful and the conditions under which it is accurate are explained and demonstrated.

2) Model Derivation: Students in AEV 5020 are taught to derive models of physical systems from first principles and from empirical data. The techniques themselves are similar to those taught in standard introductory system dynamics courses. The difference here is that an emphasis is placed on modeling systems that are specific to automotive applications in general and to electric vehicles in particular.

The first class of systems addressed in the course are purely mechanical systems, both translational and rotational.

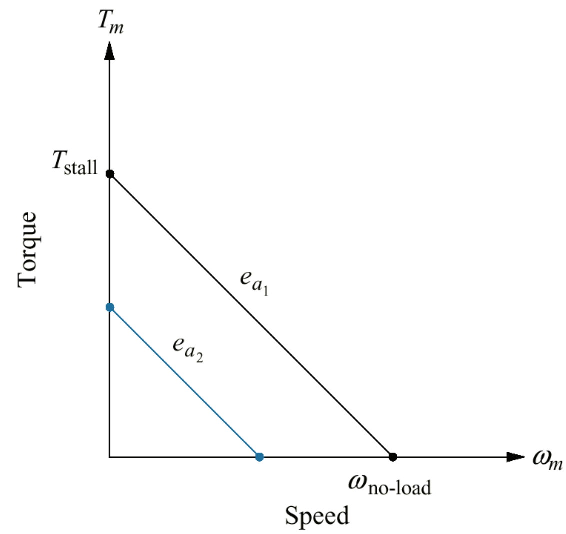

Fig. 3. Motor from a static viewpoint: Torque-Speed Curve

These systems are modeled from first principles in the course using a Newtonian mechanics approach. Traditional automotive examples employed in the course include modeling chassis dynamics, suspension and wheels. An example that is stressed that is particularly relevant to electric vehicles is modeling of the driveline. At its simplest, a driveline can be modeled as a torsional spring with damping taking the form of viscous friction in a transmission or bearing. The modeling of a driveline is particulary relevant to electric vehicles since driveline oscillation is a common problem [2]. Such oscillation is prevalent because of the fact that an electric vehicle driveline has less damping as compared to a conventional vehicle due to the absence of a clutch and torque converter. Furthermore, an electric motor can generate almost instantaneous torque which can have the effect of exciting high frequency driveline modes.

The transmission of power and motion via geartrains is also introduced. In particular, approaches for coupling multiple power plants, as in a hybrid-electric vehicle, is discussed. Examples include *torque coupling* via different configurations of gears and pulleys and *speed coupling* via a planetary gear set. The analysis of the coupling of power plants is done in the context of discussing different hybrid-electric vehicle architectures and the number of degrees of freedom they offer [3].

The next class of physical systems addressed in AEV 5020 are electrical systems. The models for these types of systems are analyzed from first principles employing Kirchoff's laws and complex impedances. There are many examples of circuits that are particulary applicable to electric vehicles. Among these include the power electronics employed by electric vehicles. In AEV 5020, simple DC-DC boost and buck converters (such as shown in Fig. 4 with no filtering capacitor, an ideal switch, and an ideal diode) are modeled from first principles and the time response is solved for under operation of the switch. This exercise is in contrast to the type of heuristic analysis performed in the power electronics course (AEV 5040) where the time response is analyzed by balancing the power in the ON and OFF modes of the converter assuming the voltage across the load is constant [4]. The power electronics course also begins to address complicating factors like inefficiencies in the switching, choosing components, and the operation of other types of conversion circuits such as rectifiers and inverters.

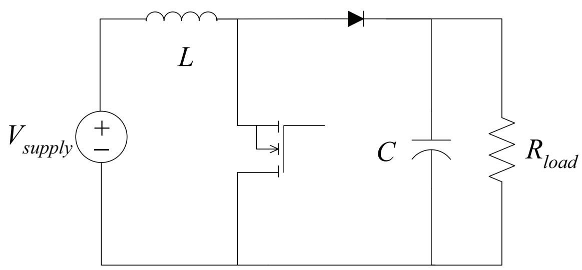

Fig. 4. Simple DC-DC Boost Converter

The fact that a subsystem, like a DC-DC converter, is addressed in three different courses helps to improve understanding of the system and provide intuition for the underlying mathematics. Material on DC-DC converters is first presented in the introductory course (AEV 5010) where their uses and the concept of their operation are discussed. The modeling and controls course (AEV 5020) then treats them from a first-principles point-of-view under simplified conditions, and finally, the power electronics course (AEV 5040) addresses some of the complicating factors associated with real converters from a practical standpoint.

Batteries are another subsystem common to electric vehicles that are modeled in AEV 5020. While the electrical properties of a battery are fundamentally derived from chemistry, it is common to model the electrical behavior of a battery as an equivalent electronic circuit [5]. This serves as a good example for students of a model that is derived empirically based on observed inputs and outputs, rather than based on a first-principles understanding of the underlying physics/chemistry. The energy storage systems course (AEV 5030), however, does discuss the fundamental battery chemistry [6].

In AEV 5020, the modeling of thermal and fluid systems are not discussed directly, however, analogous circuit models do allow them to be analyzed in the course. For example, students have performed an analysis of the temperature response of a battery system under different conditions. A more detailed presentation of how to model from first principles the heat transfer that takes place in a battery is presented in the energy storage systems elective (AEV 5030) [6].

The final class of physical systems modeled from first principles in the course are electromechanical systems. The concept of operation of many electromechanical sensors (resolver, optical encoder, Hall-effect sensor) and actuators (solenoid, motor/generator) are presented in the course that have specific relevance to electric vehicles. Motors receive the most attention in AEV 5020 of any type of sensor or actuator. Specifically, simplified versions of DC motors are modeled based on the student's understanding of the underlying mechanical and electrical aspects of the motor. There is some brief discussion of the electromagnetic properties of the motor, but the necessary mathematical relationships are basically given to the students without requiring any derivation. Separately excited DC motors are primarily discussed including armature-controlled and field-controlled arrangements. Furthermore, one type of AC motor that is of particular importance to electric vehicles, the Permanent Magnet Synchronous Machine (brushless DC motor), is introduced and is modeled under the specific condition that the orthogonality of the magnetic-field vector and current-space vector is maintained.

Electric motors represent another type of system that is covered over the course of multiple classes in the graduate certificate program. As was the case with power electronics and batteries, the AEV 5020 course models and analyzes simplified versions of these systems using rigorous mathematics. The course, electrical drives and electromechanical energy conversion (AEV 5050), discusses motors in greater detail with an emphasis on practical considerations. For example, in AEV 5050 the construction of various types of motors is considered as well as practical considerations such as motor selection and sizing. Furthermore, complicating factors such as multiple poles, distribution of windings and motor inefficiencies (iron losses, flux leakage, friction and windage, etc.) are discussed. The AEV 5050 course also discusses the underlying electromagnetic principles of motors with greater depth.

Another approach to model derivation that is emphasized in the course is a blackbox approach to modeling, that is, how to fit a model to a system based on its response to some known input(s) rather than based on a first-principles understanding of the underlying physics. The details of such an approach will be described in the next section.

B. Analysis

The middle third of the course focuses on the analysis of the physical models after they have been derived. Specifically, students are taught how to interpret a given mathematical model to determine how a system will respond to different types of inputs. For example, students learn how to determine how fast a system will respond, how much oscillation it will exhibit and what the response will be in steady state. The same time-domain and frequency-domain techniques that are common to most any introductory control systems course are taught, where again the primary difference here is that examples relevant to electric vehicles are drawn from to build intuition for the techniques and to motivate their usefulness.

1) Time-Domain Analysis: The extent to which the solution of a system's time response to arbitrary inputs and initial conditions is taught in AEV 5020 has already been discussed. In addition to the general solution of a system's time response, students are taught to recognize and characterize the response of standard types of systems to standard types of inputs. Due to time constraints, students are only introduced to the step responses of standard first- and second-order systems. The character of these step responses reinforce the students' understanding of how transfer function poles (characteristic equation roots) relate to system behavior. Additionally, these standard responses are used to build a qualitative understanding of the behavior of higher-order systems and to illustrate when reduced-order models may be employed. Students are also taught to qualitatively understand the effect of zeros, including nonminimum-phase zeros. One example from earlier that exhibits nonminimum-phase behavior is the boost DC-DC converter.

Recognizing the character of a standard first- or second-order step response also allows the students to derive black-box models of various subsystems, such as batteries. Within the AEV 5020 course, students derive a blackbox model of a DC motor as part of the laboratory component of the course described in Section III. This exercise additionally helps students to understand the conditions under which reduced-order models may be employed. Specifically, students observe what appears to be a standard first-order step response even though the first-principles model they had derived in class was second-order. This observation derives from the well-understood fact that the electrical dynamics of the motor are significantly faster than the mechanical dynamics of the motor and, therefore, can in effect be neglected.

2) Frequency-Domain Analysis: The concept of a system's frequency response is also taught within the course. The property of linear systems to generate a scaled and shifted sinusoidal output in response to a sinusoidal input of the same frequency reinforces the students' understanding of the character of the solution of a forced linear differential equation. Students are taught the concept of how to experimentally determine a system's frequency response. Furthermore, students are taught to represent the resulting data in the form of a Bode plot. An empirical frequency-response approach is commonly employed in practice for modeling power converters [7]. Due to time constraints, no other graphical representations are introduced.

In addition to the empirical determination of a system's frequency response, students are also taught how to draw a straight-line approximation of a system's Bode plot from its transfer function. Keeping with the practice of limiting the amount of hand calculations, students are required to plot by hand Bode plots of only relatively simple systems. The primary purpose of learning to sketch the Bode plot by hand is simply to build the students' intuition of how a system's Bode plot can be modified to achieve a desired shape. This knowledge will be useful for the students when they attempt to design controllers using a frequency-response approach.

In addition to teaching the students how to generate a system's frequency response, the students are also taught to understand from a very basic level what the frequency response tells them about a system's behavior. Even a question as simple as, "does the system amplify or attenuate signals of this frequency?," can be illuminating. For example, students can derive meaning from the Bode plot of a lightly-damped electric vehicle driveline by identifying the resonant frequency. Similarly, students can understand the behavior of various types of filters they may have encountered in their jobs for which they may have had an intuitive, but not a mathematically rigorous, understanding. Other examples of applications of frequency response analysis that are relevant to electric vehicle subsystems is how to choose the pulse-width modulation (PWM) frequency for controlling a DC motor or how to choose the switching frequency for a DC-DC converter when feeding a load like a motor. In each case, the students are able to clearly see how the motor can filter a switched input. Therefore, from an analysis standpoint, the PWM methodology can achieve the same behavior as a smoothly changing control signal. Similarly, students can observer how a linear, averaged model of a DC-DC converter can produce the same behavior as a nonlinear, switching model [8].

The qualitative relationship between a system's open-loop frequency response and its closed-loop step response in the time domain is also emphasized. Specific relationships, such as for a standard second-order system, are not taught, but general trends are demonstrated. For example, the relationship between gain crossover frequency and speed of response, between phase margin and overshoot, and between low-frequency magnitude and steady-state error are explored. Furthermore, frequency response is the primary vehicle by which the property of robustness is analyzed. Stability margins are taught, but also the response of specific systems to undesired inputs such as disturbances and noise are investigated. In particular, students learn how modifications to a system to improve its response to one type of input may adversely affect its response to another type of input.

3) Numerical Analysis/Simulation: Simulation provides another venue for the "analysis" of system behavior in this course. Simulation allows the students to gain a practical understanding of some complicating factors and advanced topics that they do not have the background or time to address analytically. For example, while the students are not taught how to generate a linearized approximation of nonlinear model, they are able to explore the limitations of such an approximation through simulation. Simple examples include actuator saturation, air drag experienced by an automobile, some friction models and the switching present in a DC-DC converter. These simulation exercises in general provide an illustration of the tradeoff between model complexity and accuracy. For example, the effect of replacing a dynamic battery model with a static resistive model can be seen in terms of the speed with which the simulation runs and the resulting accuracy of the results. It is especially illustrative when a simplification to the model doesn't perceptibly affect the results of the simulation.

Simulation also provides a medium for understanding some properties of control systems that are typically not addressed in an introductory course. For example, while students are not taught about sensitivity in a precise mathematical sense, they are able to observe through simulation how robust their system is to uncertainties in their model. Additionally, students are able to quickly observe various signals in a given simulation so that they may consider, for example, how changes to their system affects the control effort required by their controller. This enables introduction of the concept of optimality without getting into any formal discussion of optimal control techniques.

Simulation as a subject in of itself is also relevant to the students since it has become such a prevalent aspect of many of their jobs. The concept of how an approximate solution to a differential equation can be generated numerically is discussed. The primary emphasis of this discussion is to demonstrate to the students that simulation is indeed a numerical approximation of a true closed-form solution. This lesson is further emphasized through some simple simulation exercises where a known analytical solution can be compared to results produced by a simulation. Students are also taught how to structure a simulation of a more complicated system, such as an automobile. In particular, students are taught about a *backward-looking* approach where a drive-cycle input (desired velocity) is assumed to be achieved by the automobile and the resulting tractive effort required to achieve this profile is calculated and passed "backwards" to the individual component models. Often a backward-looking simulation relies on steady-state maps of efficiency to estimate quantities like fuel usage or battery state of charge. Conversely, students are also taught about a *forward-looking* approach to simulation where the drive cycle profile serves as the input to a driver model which in turn generates the brake and throttle commands that are passed "forward" to the individual subsystem models [9].

C. Controller Design and Implementation

The final area covered in the course is controller design and implementation. The control strategy that is most emphasized in the course is proportional-integral-derivative (PID) control due to its prevalence in the automotive industry. Students are taught some general intuition for the effects of each of the three terms a PID controller. However, it is also emphasized that in some cases the actual performance of the controller may be counter to this intuition. Students are also taught some practical drawbacks of the PID approach to control and some heuristic techniques for mitigating these drawbacks. Specifically, the tendency of the derivative term to "kick" and amplify noise and the problem of integrator "wind-up" are discussed.

In addition to a conceptual understanding of the PID controller and heuristic ways for designing such a controller, students are also taught more formal techniques for designing controllers, including structures other than PID control. Specifically, a pole-placement approach to control is introduced; first students are taught an algebraic approach to choosing controller parameters and then students are introduced to the root locus as a tool for designing controllers. In general, students are fairly comfortable with these techniques because it is the first design technique introduced and because it relies on concepts regarding the relationship between pole locations and time response that have been emphasized throughout the semester. In keeping with the goal of emphasizing concepts in place of in-depth calculation, students are taught only to draw a rough approximation of a system's root locus. Specifically, students are taught to draw a "back-of-the-envelope" version of the root locus that does not require any calculation.

Students are also taught to employ the Bode plot to design controllers based on frequency response data. Students are taught to employ control to reshape the open-loop Bode plot to achieve a qualitative change in the closed-loop time response. Minimal calculation is again required of the students, and rather, students make design decisions based on general trends. For example, if they want to speed up the time response of their system they know to push the gain crossover frequency higher, but they do not calculate a specific value for the new crossover frequency.

Since the students are taught to design controllers in a primarily qualitative manner, a greater emphasis is placed on software design tools. Specifically, students are taught how to plot the roots locus and Bode plot in MATLAB. Furthermore, students are taught to use the SISO Design Tool within MATLAB to guide the tuning of their controllers. The SISO Design Tool allows the students to apply their understanding of the theory without getting bogged down in detailed calculations. The SISO Design Tool also helps the students design systems that include zeros and higher-order dynamics, and assists the students in assessing other measures like robustness to exogenous inputs and the "cost" of their controller in terms of the required control effort.

Students are also introduced to different control architectures besides the standard, controller in the forward path with unity feedback structure. Specifically, students are taught conceptually about employing feed-forward control, precompensation and moving some control to the feedback path. Students are also taught to design a cascade control structure for higher-order systems that decouples the dynamics based on speed of response. A classical example of this is the speed (or position) control of a motor where a "fast" inner-loop controller is designed for motor torque control, followed by the design of a slower outer-loop for controlling motor speed [8]. Students are also introduced to a heuristic technique for motor control that applies armature control and field control together to achieve a typically desired torque-speed profile for the motor.

At the end of the course some more advanced topics are introduced at a high level, without actually being assigned in homework. One example is the introduction of a vector control (field-orientation control) approach to controlling AC motors. Furthermore, while the majority of the course has been focused on subsystem-level control, the students are also introduced at a conceptual level to the challenges of designing control at the vehicle system level. Specifically, students are introduced to the type of discrete-event control that characterizes the vehicle system level. For example, the vehicle-level controller decides what mode the vehicle is in (which power sources are active, how the required braking is being proportioned, etc.) and attempts to balance a range of competing goals from drivability and fuel efficiency, to emissions and component health. Students are introduced to some optimal control techniques for balancing such goals.

As was the case with subsystem modeling, several other courses in the graduated certificate program address the problem of control from a more practical standpoint. The individual subsystem courses may identify specific architectures or controllers that have found acceptance in practice. Some of the theory learned in AEV 5020, such as the Laplace transform and Bode plots, is also leveraged by these courses.

The topic of controller implementation is also briefly mentioned at the end the course. Specifically, how control logic can be implemented in passive and active circuits, or in software, is mentioned. Along these lines, the concept of a digital implementation of a controller is introduced. Some of these concepts were also introduced as part of the laboratory exercises performed in the course.

III. Laboratory Activities

Within the AEV 5020 course two laboratory activities focused on motor modeling and control are performed. Each lab activity is performed in groups and takes approximately two hours to complete. There is also a homework assignment performed in groups associated with each activity that involves interpreting and evaluating the data taken in the lab.

The blueprint for the laboratory hardware and software set-up came from the Center for Reforming Education in Electric Energy Systems at the University of Minnesota. This institute has graciously developed and disseminated (with support from various granting agencies) a list of materials from which other universities can develop their own instructional laboratories on power electronics, electric drives and power systems [10].

Fig. 5 illustrates the experimental set-up used in AEV 5020 which is specifically the electric drives laboratory from the University of Minnesota. The hardware includes a motor coupling system consisting of two electrical machines. In this course, the motor-under-test, that is, the plant, is a DC motor equipped with an encoder for measuring speed. In the electric drives course (AEV 5050), the students may replace this motor with a Three-Phase Permanent Magnet AC (PMAC) machine. The motor under test is coupled to a second motor that can be controlled to generate different load profiles, though this motor is not used in AEV 5020. These motors are controlled by a pulse-width modulated (PWM) voltage generated by a custom, but commercially available, power electronics board. The power electronics board has two independent channels for generating the PWM signal from a single DC power source. Additionally, this board provides access to the motor currents and voltages. The signals that control the PWM output originate from a DS1104 R&D controller Board and CP 1104 I/O board from dSPACE Inc. The controller board runs the C code that commands the motors, while the I/O board handles the data acquisition from, and signal generation to, the physical hardware. The code running on the controller board is automatically generated based on a Simulink model that the user creates. Additionally, the user may interact with the physical hardware in realtime through the dSPACE ControlDesk software.

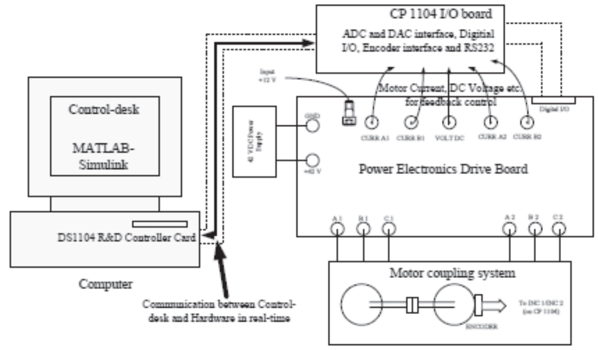

Fig. 5. Laboratory experimental apparatus [10]

The tasks performed within the laboratory activities are not fundamentally new to the students. Each task has been encountered in some respect through lecture and homework problems. However, the labs reinforce concepts from the classroom and demonstrate to students some of the complicating aspects that arise when dealing with real systems.

In the first laboratory activity the students generate two types of models of the DC motor plant. In the first approach to modeling, the students employ models derived from first principles to identify unknown physical parameters of the motor through a series of experiments. In the second approach, the students generate blackbox models of the motor based on recorded data from different step inputs. The students then build simulations of the models they have derived and compare the simulation results to the data from the physical system. The students then must discuss the tradeoffs between the different types of modeling approaches and formalisms.

This process helps to illustrate concepts from class regarding predicting time response and modeling systems in a very tangible way. Furthermore, the students see firsthand some of the real-world complications that had been mentioned in class. For example, students observe that the friction in the motor is a nonlinear function of motor speed. Another example is that students observe that some motor parameters vary with time. One prime example of this is the motor's armature resistance. Also, student's observe the noise present in real signals and the quantization that arises in a digital signal. Even something as simple as reinforcing the fact that the motor transfer function has units, or making the students think about how to handle the fact that their system has non-zero initial conditions, is valuable.

The second laboratory activity involves the students tuning a PI controller for motor speed. The purpose of this activity is to give students experience tuning a controller for a closed-loop system that is not a canonical first- or second-order system and where their model is inherently uncertain. Furthermore, the students observe and attempt to account for the amount of control effort required of their controller and its ability to reject load disturbances. None of these activities are fundamentally different from those the students performed in their homework, but the lessons stick with them better when experienced firsthand. Additionally, the lab serves to illustrate the tradeoffs between different design techniques and gives confidence to the students that the tools they are learning are applicable to real systems.

The final lesson provided by the laboratory activities is that the students get to see how a control system is implemented in the real world. The students get to witness firsthand the concept of automatic code generation and get to see the hardware needed for interfacing the physical world with the control software. The students also can observe how filters are employed to attenuate noise, but at the expense of adding time lag and possibly filtering aspects of the motor's actual response. While the digital implementation of the controllers is not emphasized, the students do get to see how a low-pass "averaging" filter is implemented digitally.

IV. CONCLUSION AND FUTURE WORK

In this paper the development and implementation of a new course on the modeling and control of advanced electric vehicles (AEV 5020) has been described. The underlying theory taught and employed within the course is not fundamentally different from most standard introductory systems dynamics and controls courses, however, this course does differentiate itself in its emphasis on applications related to advanced electric vehicles (AEVs) and its audience being practicing engineers who have a wide range of backgrounds.

These unique circumstances have shaped the way the course has been designed and can provide lessons for the introductory system dynamics and control curriculum in general. Specifically, the fact that the course is focused on a particular type of application which is revisited from different perspectives in a larger certificate program has proven to be beneficial. This is advantageous for one because the application is directly relevant to the students and helps to motivate for them the necessity of learning the material. Perhaps more importantly though, the fact that the students become so intimately familiar with the specific subsystems being addressed (power electronics, motors, batteries, etc.) means that the students have some intuition from which to interpret the mathematics. Furthermore, the theory is discussed repeatedly in different courses from different perspectives thereby allowing students time to assimilate the information. While most undergraduate degree programs are broader than a single specific application, there are common systems that can be investigated across multiple courses with a little coordination amongst faculty members. This kind of approach has been applied at the University of Detroit Mercy in a spiral curriculum employed within the Department of Electrical Engineering. This department specifically employs mobile robotics as the focus application and has found success with the approach [11].

The diverse backgrounds of the students enrolled in AEV 5020 and the limited amount of time available to cover the additional material relevant to AEVs has also shaped the course to make it more conceptual and to rely more heavily on software tools. A similar refocusing of the general introductory controls curriculum could be beneficial. It is often the case that students will be able to more readily absorb and apply information for which they are able to build meaning for themselves. Furthermore, a focus on concepts allows students to understand more complex systems and a greater array of characteristics, than simply how to design a controller that achieves minimal error for a perfectly-known, linear, time-invariant system. A greater emphasis on software design tools and simulation will also likely be of benefit to students entering a workplace that more than ever relies on the use of such tools.

Going forward it is the goal to continue to improve the content and delivery of this course. Specifically, faculty that teach courses within the graduate certificate program are attempting to better coordinate the content of the their courses to reduce overlap and to leverage knowledge students have gained from prior courses. Within the modeling and controls course it is the goal to put more emphasis on the system level. For example, it is the goal to better demonstrate heuristic techniques for designing and analyzing multiple interacting subsystems. It is anticipated this will be achieved through more system-level simulation.

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