The OSU-GATE program: development of a graduate program in hybrid vehicle drivetrains and control systems at The Ohio State University

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Abstract

This paper describes the development of a Department of Energy DOE) Graduate Automotive Technology Education (GATE) Center focusing on *Hybrid Drivetrains and Control Systems.*

A hybrid electric vehicle (HEV) combines an electric drivetrain with an auxiliary power unit (APU). The APU is usually an internal combustion engine (ICE) or fuel cell. Properly designed HEVs synergistically maximize the advantages of their combined power plants while minimizing the disadvantages. HEVs offer excellent potential for reduced emissions and lower energy usage.

Three major objectives have driven the development of the GATE graduate program: First, is the establishment of a laboratory environment that includes computer workstations for design and analysis, data acquisition and control hardware, a hybrid powertrain dynamometer test cell and a chassis (vehicle) dynamometer. Second, is the development of two new courses (one entitled *HEV Energy Analysis of Hybrid-Electric Vehicles*: and the other entitled *Modeling, Simulation and Control of Hybrid Electric Vehicles*). Third, is the integration of hybrid vehicle education into the MS Graduate Specialization in *Automotive Systems Engineering.*

I. Introduction

OSU researchers have been involved in research related to control system and drivetrain design aspects of electric hybrid-electric vehicles for the past six years[1,2,3,4,5,6]. The graduate education program described in this paper represents the culmination of these activities into a formal program, and builds on previous educational activities in mechatronics design[7,8,9,10]. One of the principal objectives of the OSU GATE program is to incorporate the latest developments in HEV technologies into a novel curriculum emphasizing creative interdisciplinary thinking, mechatronic design techniques, and the latest research in engineering education. Some of the more specific outcomes of the curriculum development proposed here are listed below.

1. *Collaborative learning environment:* In the proposed design courses the students will be assigned to small teams. Each team includes mechanical and electrical engineers. The

projects are structured so each member of the group is responsible for some instruction in the context of the project..

2. *Interaction with industry and other government agencies:* a further objective of this proposal is to serve as a catalyst for interaction among university, industrial and government partners in HEV drive research. This interaction takes place through the already established mechanisms of the interdisciplinary *Center for Automotive Research*, and through co-operative and consortium-based research.

3. *Graduate education:* OSU's role in supplying engineers to the auto industry has been a major one in recent years, with one out of every five MS and Ph.D. graduates being hired by automotive OEMs and suppliers. A final, and major objective of this proposal is to create a steady supply of highly educated graduates at the MS and Ph.D. level with expertise in all of the technologies that are critical to the successful commercial implementation of HEV drives.

II. MS / ASE Graduate Specialization

Overview

The Automotive Systems Engineering (ASE) Program at The Ohio State University has been formulated as a "graduate specialization" (indicated as such on the student's transcript) and is administered by the Center for Automotive Research (CAR) at Ohio State. The primary objective of this program is to provide interdisciplinary graduate education and training in the engineering discipline of primary interest to the student, while focusing on the application area of automotive systems.

Currently, the Departments of Mechanical Engineering and Electrical Engineering participate in the interdisciplinary ASE, with other departments in the College of Engineering to join in the future. Since CAR is not a degree granting entity, students wishing to participate in the ASE program are required to gain admission to the graduate program of one of the participating ("home") departments. Common to both departments, a minimum of 45 credit hours (Ohio State is on the quarter system) is required to earn the Master of Science degree, and two master's degree program plans are available: thesis option and non-thesis option. However, since the departmental requirements vary from one department to another, the student prepares a study plan that satisfies the requirements of the graduate studies committee of the home department as well as the ASE Program. This plan is then submitted to the ASE Program Committee for approval.

Depending on whether the thesis or non-thesis option is chosen, students complete one or two sequences of "core" courses chosen from the core focus areas. A core sequence is defined as any three courses chosen from those indicated in the core focus areas (see next section). The student then completes a variety of interdisciplinary expertise area courses (from the home or other departments in the college of engineering) related to the chosen focus area. Generally speaking, relevant courses on mathematics, statistics and computational methods also qualify as expertise area courses.

Briefly, the ASE requirements (detailed in the next sub-section) are:

- Thesis option students are required to take one core sequence. It is expected that the thesis be on a topic related to automotive systems. Non-thesis option students are required to take two core sequences.
- In addition to the core sequence(s), students fill out the coursework portion of their degree requirements with expertise area courses, some of which should be drawn from the core focus area courses.
- All students are required to regularly attend seminars on topics in automotive systems.

The requirements on the number of core course/sequences and expertise areas serve to increase the breadth of skills that the graduate engineers can apply to complex automotive problems. At the same time, the student gains an understanding of the perspectives, capabilities, and approaches of other engineering disciplines as well as their relevance to automotive systems.

Program Requirements

The ASE requirements are flexible enough to provide adequate depth within engineering disciplines of primary interest to the student. Students typically choose elective courses so that the programs of study have an appropriate focus on an automotive-related discipline in addition to the breadth of scope resulting from the core area courses and expertise area requirements.

In the thesis option, students take one core sequence (three courses) and at least seven expertise area courses, depending on individual departmental requirements. Completion of the MS thesis is equivalent to three-five courses, depending on the departmental degree program. All students participate in a seminar series on automotive topics.

Students opting for the non-thesis option take two core sequences (six courses) and nine expertise area courses. All students participate in a seminar series on automotive topics.

Core sequences consist of basic courses of critical importance to automotive systems in areas matching the research focus areas of CAR. A student completes a core sequence by selecting three courses, offered in either the Mechanical or Electrical Engineering Department, from one of the core focus areas:

1. **Internal Combustion Engines** (courses to choose from consist of: energy conversion, introduction to combustion, engine modeling, and experimental IC engines)
2. **Powertrain Dynamics and Control** (courses to choose from consist of: powertrain dynamics, powertrain control, and projects in powertrain control)
3. **Automotive Noise, Vibration and Harshness** (three courses on the various elements of NVH)
4. **Electromechanical Subsystems** (courses to choose from consist of: introduction to mechatronics, electromechanical motion devices, control of industrial electric machinery, and sliding mode control of electromechanical systems)
5. **Automotive Electronic Subsystems** (courses to choose from consist of: power electronic devices and systems, I and II, autonomy issues in vehicles, and automotive electronics)

6. **Hybrid Electric Vehicles** (courses to choose from consist of: energy analysis of hybrid electric vehicles, modeling, simulation and control of hybrid vehicles, and hybrid vehicle laboratory)

In addition to the core sequence(s), each student is required to take at least seven courses (depending on departmental requirements) of interdisciplinary expertise area course work, at least three hours of which must be drawn from a list of core focus areas.

III. GATE Curriculum

In the present section we describe the curriculum of each of the three new courses developed within the GATE program.

Energy Analysis of Hybrid Electric Vehicles

This course is specifically targeted at engineering students enrolled in a Masters degree and interested or working in the area of energy conversion and utilization at the vehicular level, and more specifically towards hybrid electric vehicles (HEV). This course can also be taken by advanced undergraduate as a technical elective course with permission of the instructor. This course is offered as the first course in the GATE sequence. A relatively strong background (at the undergraduate level or entry-level graduate) in Fluid Mechanics, Heat Transfer, Applied Thermodynamics, Principles of Electrical Engineering and System Dynamics and Control is required for this course.

The material in this course is focused on the overall energy conversion, storage, utilization and optimization of complete road vehicle systems (conventional and hybrid electric vehicles). The educational objectives of this course are several fold:

1. Provide a thorough understanding of the energy storage, conversion and utilization, both on the power consumption side (vehicle) and power generation (powertrain) in road vehicles, and particularly hybrid electric vehicles.

2. Provide an overview of all the components used in conventional and hybrid powertrains (Energy storage: fuels, batteries, etc.; Energy conversion: internal combustion engines, fuel cells, electric motors and generators, etc.; Energy converters: transmissions, power controllers, reformers)

3. Provide a unified description to their characteristics, specifically in terms of input/output power relationships and energy efficiencies, as well as modeling building blocks for complete system energy simulation.

4. Develop conceptual framework for the energy flow modeling in vehicles, with specific considerations to well-to-wheel energy usage.

5. Showcase the latest technologies targeted for use in hybrid vehicles by leading automotive manufacturers.

6. Motivate and provide a specific platform for the application of all the above objectives through the participation of Ohio State University in the Future Truck 2000 competition, aimed at

converting a full-size SUV to an energy-efficient and clean hybrid electric vehicle.

Shown below is the course outline:

The Power Consumption Side of Vehicles: Aerodynamic losses, inertial load (linear and rotational), rolling resistance losses, transmission losses, accessories losses, idling losses, overall energy budget, drive cycles and their modeling, driving cycles and their impact of power consumption, concepts of component energy *vs.* overall cycle vehicle efficiency.

Conventional Power Generation Side: IC Engines Heat engine types: spark-ignited, Diesel, Stirling, etc., basic engine operating parameters and characteristics, control parameters, emissions characteristics, “black box” energy efficiency maps and models of heat engines, Willans line approach.

Energy Analysis of Conventional Vehicles Coupling power generation and power consumption in conventional vehicles, sizing the power source and transmission system for best cycle energy efficiency, energy constraints for driveability, performance, safety and consumer acceptance, the motivation behind hybrid electric vehicles (energy and emission considerations).

Concept of Hybridization Concept of hybrid vehicles for energy optimization, types of hybrid: hybrid electric (HEV), mechanical hybrids, degree of hybridization, hybrid electric vehicle (HEVs) types: series, parallel, mixed, charge sustaining, charge-depleting.

General Model of Energy Forms and Energy Flows Energy domains (chemical, thermal, mechanical, electrical), feasible energy flow between energy domains, a general, scalable representation of all components: modules and interfaces, classes of "modules" and interface definitions.

On-Board Energy Storage Fuels as a form of on-board chemical energy storage, liquid fuels (gasoline, reformulated gasoline, diesel and bio-diesel, M85, E85, etc.) (density, viscosity, energy content, etc.), gaseous fuels (natural gas/methane, propane, hydrogen), pollution issues associated with fuels, well-to-wheel pollutant and energy cost of fuels, batteries as a form of on-board electrical energy storage, battery types (lead-acid, Ni-Cd, Ni-Fe, Ni-Zn, Ni-MH, Li, etc.), battery charge/discharge characteristics (specific energy, energy density, specific power, power density, etc.), “black box” modeling of power inflow/outflow to/from batteries and energy efficiency, ultra-capacitors, efficiency considerations, mechanical on-board energy storage devices (flywheels, hydraulic accumulators), efficiency consideration, on-board energy storage trade-offs.

Overview of Electro-Mechanical Energy Converters Electric to Mechanical Converters (i.e., motors and generators (EM)), overview of motor and generator types, characteristics (mass, efficiency, power and torque, controllability, etc.), “black box” modeling of EM energy efficiency, Willans line approach.

Transmissions Conventional manual transmission (manual and automated), automatic transmission, torque converters and clutches, CVT, EVT, torque splitters/epicycloidal gear trains, “black box” modeling of transmission energy efficiency, Willans line approach.

Fuel cells Fuel cell principles, fuel cell types for automotive applications, fuel reformers, fuel cell characteristics, “black box” modeling of fuel cell, energy efficiency.

Hybrid Electric Vehicle Modeling From components to system: an unified approach to energy/power flow modeling in HEVs, constrains on energy and power flows, kinematic constraints, synthesis of HEV energy/power modeling, overview of current energy simulation tools: promises, limitations and challenges.

Modeling, Optimization and Control of Hybrid Vehicles

The primary aim of this course is the optimization (from a powertrain design point of view) and control of HEVs. This course can also be taken by an advanced undergraduate as a technical elective course with permission of the instructor. A relatively strong background (at the undergraduate level or entry-level graduate) in System Dynamics and Classical Control is required for this course. Heavy use of computer-aided tools such as Matlab™ and Simulink™ is expected. The educational objectives of this course are given by the following:

Optimization

1. Upon the completion of the class, the student should be able to utilize basic optimization techniques to narrow the design space for a HEV given specific performance data on the vehicle's operation.

2. The students will be able to use dynamic programming to narrow choices and the design space for a HEV given specific performance data on the vehicle's operation.

3. The students will develop an understanding of how to employ large scale (> 1 million possible combinations) optimization techniques are utilized for narrowing design spaces for HEVs.

4. The students will be able to utilize degree of hybridization (DOH) based techniques for narrowing designs quickly.

Control

5. The students will be able to determine whether a regulator based control or event based control should be applied to a given class of systems. Once a type of control is chosen, the students should be able to determine what type of controller should be developed.

6. The students will understand the fundamentals of state space controller design, of Programmable Logic Controller (PLC) design, of Intelligent Control (Fuzzy Logic Control/Neural Networks) and will use these techniques with application to the design of controllers for HEVs.

7. The students will become acquainted with a rapid control prototyping system such as dSpace and will learn to implement their controllers in this environment.

Course Outline

***Introduction to Optimization of HEV*:** The process of Optimization. Engineering optimization vs. Engineering Analysis, basic terminology and notation

Fundamental Optimization Concepts: Relative Maxima and Minima, Gradient Vectors, Taylor Series Expansion, Hessian Matrix, Optimality Conditions, Linear Unconstrained Problems,

Optimization Concepts II: Linear Constrained Problems, Equality Constraints, LaGrange Multipliers, Convex Sets, Linear Programming. (Simplex Method, Newton's Method, Conjugate Gradient Method,)

Advanced Optimization Techniques: Nonlinear Programming, Artificial Intelligence in Optimization, Dynamic Programming, and Applications to HEVs

Introduction to Control: Understanding control, Degree of Hybridization of Control Systems, Control systems terminology, for HEVs (disturbance rejection in HEVs, electromagnetic noise, Steady State Error and Sensitivity.), Control system design for efficiency, Control system design for optimum fuel use, Control system design for improved vehicle emissions.

Classical Control System Design: Design of Proportional, Integral, and Derivative controllers for HEVs. Frequency based control system design approaches (Lead, Lag and Lead/Lag control).

State Space Control System Design: Full State Feedback, Estimator Design, Full and Reduced Order Estimators, Compensator Design (combined Estimator and Control Law), Dealing with reference inputs, Advanced Techniques (LQR).

Event Based Control: Event based control versus conventional control, Fuzzy Logic Control of Hybrid Electric Vehicles. Neural Networks in HEV control, Using PLCs in HEVs.

Comments on the organization of the lecture courses

To achieve the educational objectives listed above in two quarters proved to be challenging, owing to the breadth of the material and its interdisciplinary nature. The courses were organized into 20 72-minute lectures (2 per week for a 10 week quarter). As there are no textbooks specifically devoted to the topic, course notes were specially prepared for this course and were made available to the students through the Web[11]. In addition to the course notes, a large numbers of handouts, papers, web links, topical books were made available to the students both through the course web site and as reserved books in the library at the Center for Automotive Research. Furthermore, the students were required to extend the material formally taught in lectures through a number of carefully "crafted" homework assignments and mini-projects throughout the quarter.

The students participated in a class project performed in small groups aimed at analyzing and simulating the energy usage in a specific HEV configuration (for the first course), and at developing an energy management strategy (second course). The project required the application of many of the concepts seen in lectures towards a more realistic, open-ended, HEV design problem. During the 1998-99 academic year, the project involved the conceptual design, powertrain configuration and energy simulation of the Ohio State University FutureTruck 2000. This involved not only minimizing fuel consumption for a full-size Sports Utility Vehicle, but also delivering a very demanding performance envelop for the vehicle (towing capability, gradeability, acceleration, 4-wheel drive off-road mode, etc.). The student designs resulting from these class projects evolved into the current design actually selected by the OSU Future Truck 2000 for the upcoming competition[12,13]. In the course of these projects, the students are required to apply the concepts seen in class, but firmly basing their design and implementation on existing, state-of-the-art hardware (combustion engines, electric machines, batteries, etc.). Throughout the courses, we provide the latest information obtained from our industrial partners in terms of emerging technologies and actual state-of-the-art hardware characteristics.

Hybrid-Electric Vehicle Laboratory

Facilities specially developed for GATE Program

A dedicated laboratory located within the Center for Automotive Research has been developed as part of the GATE project, including the following facilities:

- CAD/CAE tools: Matlab/Simulink, Saber, ASCET, Electronics Workbench.
- Rapid prototyping tools; dSpace, ETAS
- VPSIM HEV simulator (Figure 1)
- CVT control experiments using a scale model CVT.
- Experiment on management of HEV battery modules.
- Measurement of combustion engine fuel economy using a portable small engine dynamometer (Figure 2)

A hybrid powertrain test cell was developed for use by GATE Program students. A layout of the test cell is shown in Figure 3. A chassis (vehicle) dynamometer (Figure 4) is also available through the facilities of the Center for Automotive Research.

Figure 2 Portable small engine dynamometer

Figure 4 Chassis dynamometer test cell

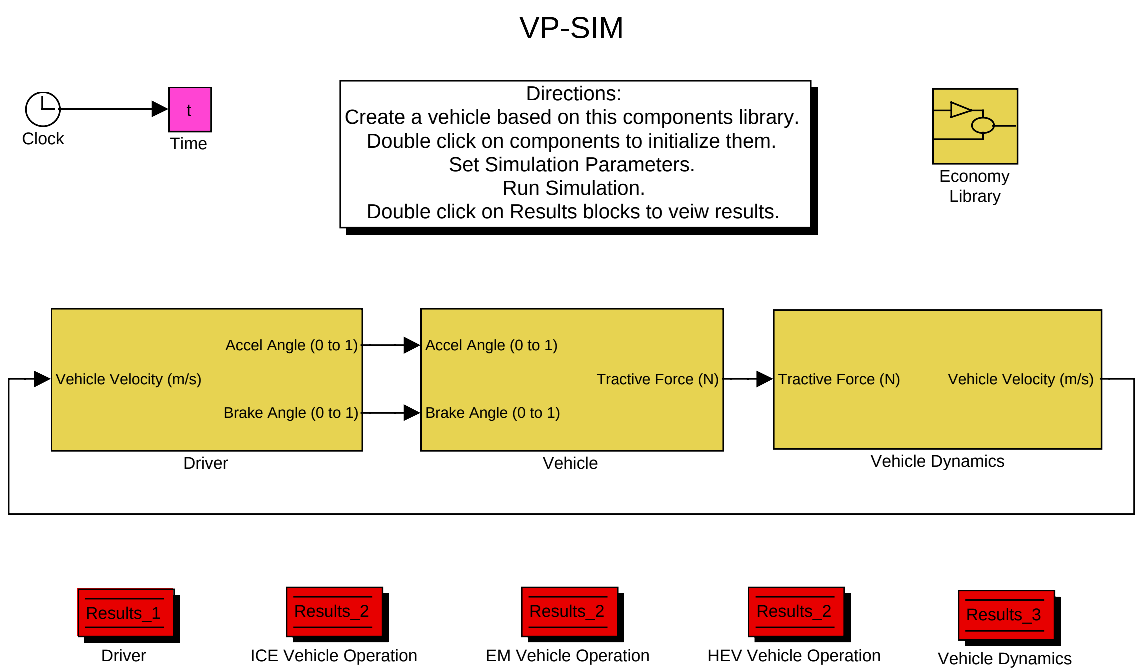

Figure 1 GUI for VPSIM HEV simulator

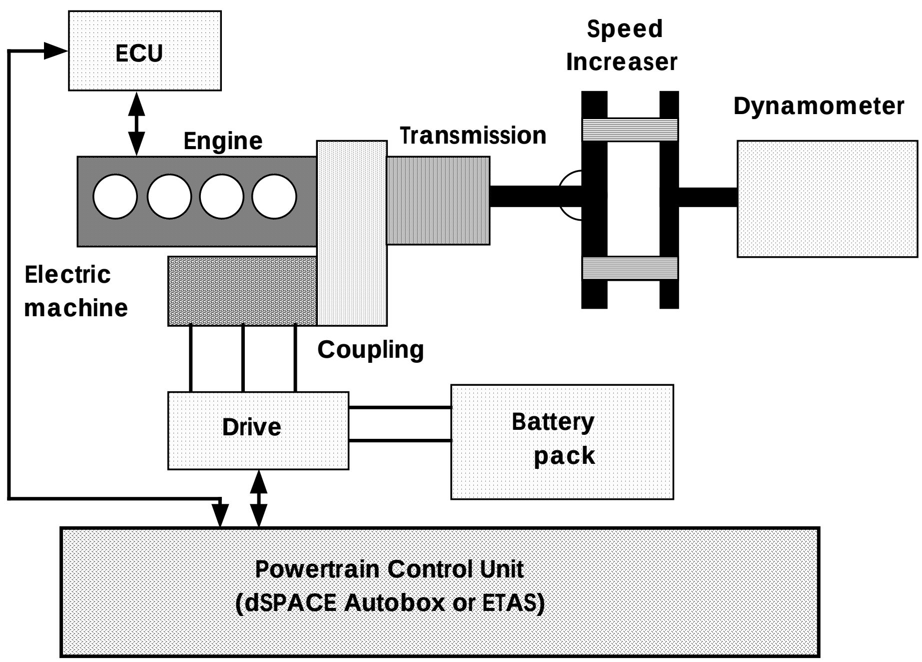

Figure 3 HEV drivetrain test cell

IV. Conclusion

The graduate program described in this paper will continue to evolve thanks to a very active government-industry-university collaboration. The current program includes a number of Fellowships sponsored by the Department of Energy, and an equal (probably greater at the time of printing) number of Fellowships sponsored by industrial partners (Delphi Automotive Systems, Ford and General Motors to date). In addition the sponsors have provided a number of summer internship opportunities for GATE Fellows. Approximately 20 graduate students are currently enrolled in the OSU GATE program through the above mentioned Fellowships and other Graduate Assistantships.

We feel that this program is an excellent example of what can be accomplished when private industry and government join forces in supporting important educational initiatives.

V. Acknowledgments

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