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Development and Implementation of a Control Strategy for a Hybrid Power Train System in a Classroom Setting

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Abstract

The project, a bench-scale hybrid electric powertrain system, is designed, analyzed and fabricated by students in six modules, starting in their sophomore year and culminating in their final semester as seniors. This complex project has been selected in order to integrate the core mechanical engineering courses: Mechanical Design, Thermodynamics, System Dynamics and Control, and Fluid Mechanics. A bench-scale hybrid-electric vehicle powertrain has sufficient complexity to involve all Mechanical Engineering disciplines and the simplicity to be built by students over the course of five semesters. The work is designed to test two hypotheses:

1. A long-term design project that integrates knowledge from multiple courses strengthens student knowledge retention.
2. A large-scale design project requiring tools from many courses improves student problem-solving and design skills.

By integrating five semesters of the mechanical engineering curriculum into a cohesive whole, this project has the potential to transform the way undergraduate education is delivered. Before and after testing is being conducted to assess: a) Change in retention between courses and b) Change in student problem-solving and design skills.

Students at Rowan University have built almost all of the "hardware" for the HPT (air engine, planetary gearset, tachometer, etc.) in earlier semesters. The control system is the "capstone" for the five-semester design project, which has been described in an earlier publication [1]. This paper describes the development of the "faculty prototype" of the control system, and gives preliminary results of implementing the control system design project in the classroom.

Introduction

Toyota has been recognized for developing cutting-edge hybrid systems. Specifically, they have developed and implemented the Toyota Hybrid System (THS) which combines a gasoline engine and an electric motor, with the advantage of not requiring external charging. According to the Toyota [2] the THS II system achieves nearly twice the fuel efficiency of conventional gasoline engines. This system was included in the Toyota Prius. The THS uses a gasoline engine, electric motor, and electric generator to achieve better fuel efficiency which results in reducing exhaust emissions of carbon dioxide (CO_2). A simplified diagram of the Toyota Hybrid System (THS) is shown in Figure 1.

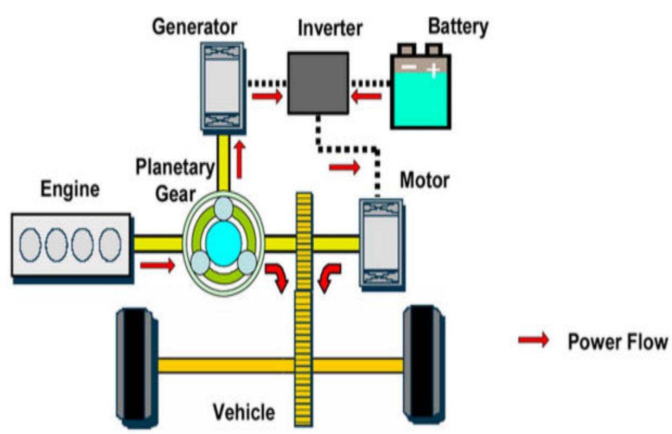

Figure 1: Diagram of the Toyota Hybrid System (THS) [3]

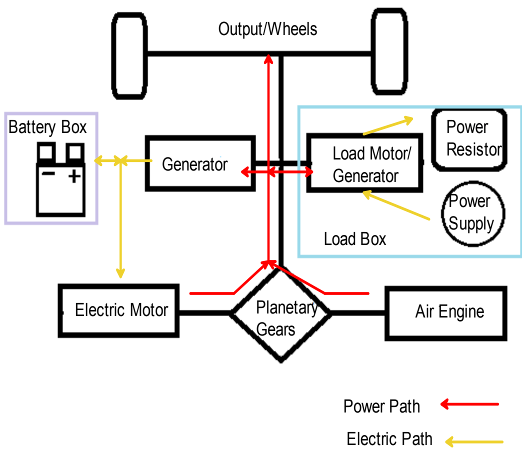

Figure 2: Diagram of the Hybrid Power Train (HPT)

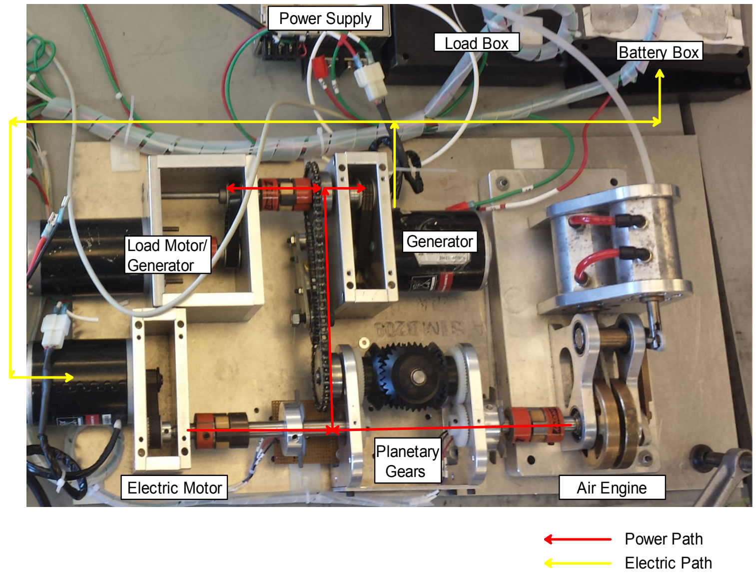

Figure 3: Bench-scale Hybrid Power Train (HPT) prototype developed at Rowan University

For educational purposes, a simplified version of the THS has been developed at Rowan University. The bench-scale Hybrid Powertrain (HPT) prototype is very similar to the one used in the first generation Toyota Prius, and the differences between the two systems can be seen in Table 1. Figure 2 depicts the HPT diagram and Figure 3 the HPT prototype. The main difference is that instead of using a gasoline engine, it has an air engine powered by shop air at 120psi (8.3bar). The flow of air is controlled by six solenoid valves which are not shown; these will be described below. Also, the prototype has a DC electric motor and DC generator so there is no need for an inverter. The system also includes a planetary gearset. In this case, a differential gearset was used since it was cheaper and more reliable to build this type of geartrain in an educational environment. The result is that the inputs and the output of the planetary gears are linked to different shafts than in the THS.

Table 1: Differences between Toyota Hybrid System (THS) and Bench-Scale Hybrid Powertrain (HPT)

	THS	HPT
Main Power Source	Gasoline Engine	Air Engine
Electric Motor	AC	DC
Generator	AC	DC
Planetary Gears	Sun/ring/planet	Differential
Sun	Linked to generator	Linked to motor
Ring	Linked to motor/wheels	Linked to engine
Carrier	Linked to engine	Linked to gen/wheels
Inverter	Needed	Not needed
Load Box	Not needed	Needed

Table 2: Planetary gearset connections to inputs and output

Input/Output	Gear	Linked to Shaft
Input 1	Sun 1	Electric motor
Input 2	Sun 2	Air engine
Output	Carrier	Wheels / Generator

The THS system is electronically controlled in order to achieve a variable transmission. It changes to adapt itself to different driving conditions with the aim of working at its most efficient range of operation. The THS vehicle achieves smooth acceleration and deceleration, as well as excellent driving response [3]. Likewise, a control algorithm has been developed for the HPT in order to implement the same concept. The system has two tachometers (based on Hall-effect sensors) which measure the speed of the air engine and electric motor. Overall control of the system is achieved using a microcontroller, in this case an Arduino UNO. Finally, the system has a “load box” with the aim of simulating the up and down grades of a road.

Laboratory Implementation

Providing the students with a Station
In order for the students to implement the required control scheme, three laboratory stations have been fabricated. The first cohort of students that has undertaken the project have already built all of the components within the HPT, with the exception of the battery pack, load box, electric motor, generator and solenoid valves. Each station is shared by 4 groups and includes:

Battery Pack: two 12V batteries (Power Sonic, Model: PS-1212, 12V-1.4Ah) that power the 24V electric motor (AmpFlow M27-150). The Battery Pack also includes temperature (Analog Devices, Model:TMP36), current (Polulu, ACS711EX -15.5A to +15.5A) and voltage (voltage divider) sensors to monitor the state of charge of the battery. The students are required to write code to interpret the sensor readings and respond appropriately.
Load Box: the load box is used to simulate uphills and downhills on a road. It has a motor/generator (AmpFlow M27-150) and up to five 5Ω power resistors in parallel. When simulating down grades the motor/generator acts as a motor in order to drive the output shaft. It is powered by a benchtop power supply. When simulating uphill grades the motor/generator acts as a generator connected to the resistors in order to apply an electrical load to the output of the HPT. The intensity of both situations is varied using Pulse Width Modulation (PWM).
Electric Motor and Generator: both are provided to students. In the case of the electric motor, a motor controller (Polulu, Motor Driver 15A IRF7862PBF) is also provided in order to control the speed and direction of the motor using the Arduino.
Solenoid Valves: six solenoid valves (AutomationDirect AVS-5313-24D) are used to regulate the flow of air with the aim of controlling the speed of the air motor. The students will design and fabricate an orifice block to regulate the amount of air flowing through each solenoid.

Each group of students is required to purchase their own Arduino UNO microcontroller. They are familiar with this microcontroller since they have already used it for previous modules: the Arduino-based tachometer, air valve selection and implementation, and air motor speed control module. For the last module: System Control of the Hybrid Powertrain, the students are required to design and implement a control strategy using this microcontroller in order to achieve constant speed under variable load.

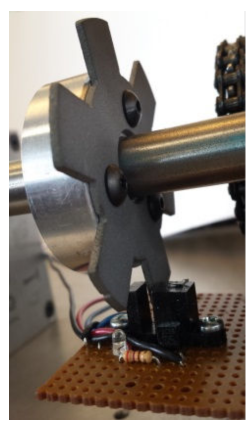

Figure 4: Hall-Effect Tachometer

Hardware Design for Control of the Hybrid Power-Train System
Sensing the speed of the motors
The speed of the air engine and the electric motor are measured using a student-built tachometer. Figure 4 depicts one of the

tachometers used for the HPT, comprised of a Hall-effect sensor and a slotted disk commonly known as a "daisy wheel''. The two tachometers are installed on the shaft of the air engine and the electric motor, respectively.

Air Flow Control Module

The air engine is powered by shop air at 120psi (8.3bar). This air is supplied to an aluminum block with six appropriately-sized orifices. These orifices limit the flow of air based on their cross sectional areas. The exhaust of each orifice is directed into a solenoid valve. Finally, the air from the valves is combined and sent to the air engine. By opening and closing each solenoid valve, the speed of the air engine can be regulated. A schematic diagram of the system is shown in Figure 6.

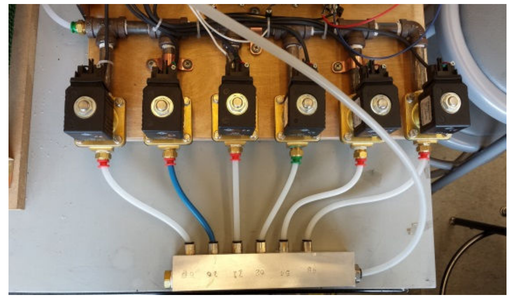

Figure 5: Air flow control system for HPT prototype

The design of the aluminum block is determined by the cross-sectional area of each orifice such that the six valves can work together in a "binary" pattern. That is, opening the smallest orifice gives the lowest speed (speed "000001"), opening the second smallest gives the second lowest speed (speed "000010"), opening the two smallest simultaneously gives the third speed (speed "000011") and so on, for a total of 63 different "steps". Figure 5 depicts the solenoid valves and aluminum orifice block used for the prototype.

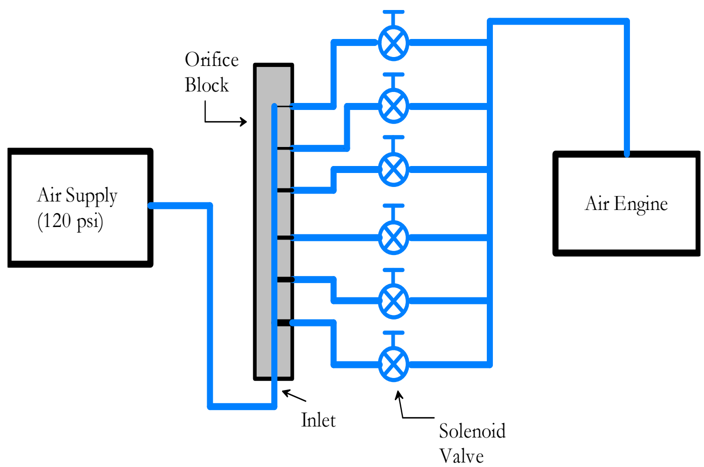

Figure 6: Air flow control hardware consisting of solenoid valves and orifice block

Electric Motor Speed Control

The electric motor is powered by a 24V lead acid battery. A DC motor controller (Motor Driver 15A IRF7862PBF) regulates the speed of the motor depending on the signal it receives from the microcontroller. The motor controller is basically an "H-Bridge", that allows the motor to move forward or backward at different speeds. It receives two signals from the Arduino. The first one is a digital signal which regulates the direction of the electric motor. The second signal is an analog signal PWM (Pulse Width Modulation), which governs the motor's speed. The PWM signal ranges from 0 to 255, with 0 being the minimum speed and 255 the maximum. Taking both signals into consideration the range of the action for the code is between -255 and 255, with -255 being maximum backward speed and 255 being maximum forward speed.

Overall Control of the Hybrid Power-train System

The combination of microcontroller, sensors and actuators results in a continuously variable transmission. Due to variable transmission the system has excellent response time and keeps the air engine at its most efficient operating range. The microcontroller determines the desired operating condition and the existing operating condition, and then it controls the motors, generator, battery, and other components in real time to achieve the desired output.
A flowchart of the HPT control scheme can be seen in Figure 7. The Arduino has control over the speed of both the air engine and electric motor. Also, it monitors the battery state of charge (SOC) and it can connect/disconnect the generator to the system. A second (faculty-operated) Arduino controls the load applied to the system in order to simulate hills or slopes as a common road. Additionally, for safety the system has sensors to monitor the temperature and voltage of the battery to detect malfunctions. In that case the Arduino sends a signal and turns the electric motor off.

Finally, to achieve "cruise control", two independent proportional-integral-derivative (PID) controllers are integrated into the code: one for the air engine and the other for the electric motor, since they are the power sources engaged to the driving wheels of the car.

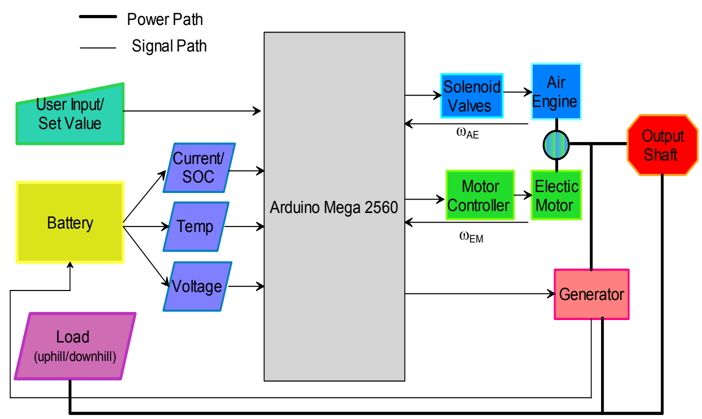

Figure 7: Overall control diagram for the bench-scale HPT

Decision-Making Algorithm

The decision-making of the HPT is fairly similar to the THS with the aim of achieving maximum instantaneous fuel economy. For the prototype, the three variables that influence the decision making are the setpoint (desired wheel speed), the state of charge (SOC) of the battery and the actual wheel speed. Based upon these values the microcontroller decides between three cases:

- **Case 1:** Air engine works by itself and not necessarily at its most efficient speed. This occurs when the battery charge is low. The generator is connected to the system in order to charge the battery.
- **Case 2:** Electric motor works by itself. This occurs when the set point is set to a slow speed (less than 300rpm for the HPT prototype). The generator is disconnected from the system.
- **Case 3:** Both power sources work simultaneously. This occurs when the battery's SOC is greater than 20% and the set point of the wheel speed is greater than 300rpm. For this case the air engine operates at its most efficient speed and the electric motor compensates to reach the desired setpoint. The generator is connected to the system. For this system the optimal speed of the air engine is 1000 rpm, although the students must choose the most efficient operating point for their own air engines (determined in a previous semester's project).

After the microcontroller decides which of the operating source(s) to activate, the "cruise control" system is effected by using a PID controller for each motor.

Setpoint: Air Engine and Electric Motor

The *Setpoint* of the HPT is the speed that the user wants to reach and maintain with the *Cruise Control System*. The equation governing the speed relations in a differential gearset was used to develop the relationship between individual setpoints:

$$S_C = \frac{S_{AE} + S_{EM}}{2} \tag{1}$$

where S_C is the desired wheel speed (user input), S_{AE} is the setpoint of the air engine and S_{EM} is the setpoint of the electric motor. Depending upon which of the three states the system is operating in, the controller uses Equation (1) to determine the setpoints of the electric motor and air engine. If the air engine is operating alone (Case 1), then the electric motor setpoint is zero, and vice versa for Case 2. When both operate simultaneously then the setpoint of the air engine is 1000 rpm.

$$S_{AE} = 2S_C - S_{EM} \tag{2}$$

$$S_{EM} = 2S_C - S_{AE} \tag{3}$$

PID controller: Air Engine and Electric Motor

A PID (proportional, integral and derivative) controller is used to regulate the speed of the motors under varying loads. The PID controller equations programmed in the microcontroller code are:

$$U_{AE} = U_{0AE} + K_{pAE}e + K_{iAE}\int_0^t e_{AE}\,dt + K_{dAE}\frac{de_{AE}}{dt} \tag{4}$$

$$U_{EM} = U_{0EM} + K_{pEM}e + K_{iEM}\int_0^t e_{EM}\,dt + K_{dEM}\frac{de_{EM}}{dt} \tag{5}$$

where U_{AM} is the control action for the air engine, which ranges from 0 to 63. Similarly U_{EM} ranges from -255 to 255 for the electric motor, U_0 is the previous control action, and K_p, K_i and K_d are the proportional, integral and derivative gain respectively for the air engine and the air engine respectively. Furthermore, e is the error and is calculated by the difference between the engine or motor's set value and the actual speed sensed by the tachometers.

$$e = (setpoint) - (measured\ speed) \tag{6}$$

The controller gains were found experimentally by manually tuning the parameters. These values are shown in Table 3.

Table 3: Gain Values for HPT Controller

	K_p	K_i	K_d
AE	0.02	0.008	0
EM	0.02	0.1	0

First Estimation of the Required Velocity

A more rapid stabilization period can be achieved for each of the motors every time that the setpoint changes. This is done by giving a first estimate of the step that has to be taken (AE [0 to 63] or EM [-255 to 255]) in order to reach the desired speed. The no-load speed was measured at each setting for the air engine and electric motor. The approximation of the first step [-255 to 255] which the electric motor should operate is:

$$U_{0EM} = 0.1038(S_{EM}) + 3.5965 \tag{7}$$

The same procedure was done with the air engine:

$$U_{0AE} = 1.7468 * 2.71828^{0.0011 S_{AE}} \tag{8}$$

The equation found for the air engine was not linear since its maximum speed is limited by the pressure of shop air.

This procedure is used to give a first estimate in the control algorithm. Since the load is not taken into account it will only be accurate when there is no load applied to the system, however, after this step the PID controller is used for fine-tuning the speed.

Battery

For programming purposes the state of charge (SOC) of the battery is calculated as:

$$SOC = \frac{Q}{C_{bat}} + SOC_0 \tag{9}$$

where Q is the amount of charge that has entered the battery, C_{bat} is the capacity of the battery (1.4Ah) and SOC_0 is the previous state of charge. The amount of charge that has entered the battery is:

$$Q = \int i_{bat}\, dt \tag{10}$$

where i_{bat} is the current flowing in or out of the battery, which is measured using a bidirectional current sensor (ACS711EX -15.5A to +15.5A). After *SOC* has been calculated, it is stored as SOC_0 for the next time step. Note that SOC_0 must be stored in a "permanent" way which is not reset when the system is powered down – a battery retains its charge even if the system is turned off. Otherwise, the program will reset the state of charge and the next calculation of the *SOC* will not be correct. In order to achieve this, an Electrically Erasable Programmable Read-Only Memory (EEPROM) is used. This is a type of non-volatile memory used in computers and other electronic devices to store small amounts of data that must be saved when power is removed, e.g., calibration tables or device configurations. The Arduino UNO includes this memory.

To keep the battery in its safe operating range, a temperature sensor (TMP36) has been added. The sensor is connected to an analog input on the Arduino and it is programmed to give the temperature in Celsius and Fahrenheit. If the system senses high temperature in the battery, the electric motor will be automatically turned off and a red LED will turn on to alert the user. This way the user can detect that something is wrong with the system.

Conclusions

This paper describes a control system used to regulate a bench-scale hybrid power train (HPT) used in a classroom setting. A variable transmission and a cruise control system have been implemented; achieving excellent response time and an efficient operating range. Students have designed and fabricated most of the components of the HPT in earlier semesters, and the overall control system is the “capstone” for the project. A PID control system for the air engine was implemented successfully by students in the Fall semester of 2013, and sample videos can be seen at benchtophybrid.com. For this last module the students will have two PID controllers for the cruise control system and are free to design their own control algorithm. Possible student competitions will include tests to see how “far” each team’s powertrain can travel through a variable drive cycle with a fixed amount of compressed air available. The main learning outcome for this module is the design and implementation of a digital controller. This outcome will be assessed through observing the effectiveness of the student controller designs and also the efficiency of their overall hybrid powertrain systems. The overall control system is being implemented in the Spring semester of 2014; results and sample videos will be provided at the conference.

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