Hybrid Control Systems

1. Introduction

The EcoCAR Challenge is a three year competition, in its first year, that includes 17 colleges in the US, including Howard University. The main objective of the project is to challenge students to improve on a specified GM model car to improve fuel economy and reduce emission, while meeting the competition car performance requirements. General Motor (GM) was the first among several companies that developed a hybrid electric vehicle (HEV) in an attempt to create the cleanest, most fuel efficient vehicle possible. Because people can see the positive impacts of driving a hybrid car, more consumers have been demanding a comprehensive vehicle that embodies good performance, aesthetic beauty, safety, and environment friendliness. Consumers demand such a package because it helps reduce costs with the ever-rising price of gas, and it reduces global warming.

The main problem to be tackled by the Howard University, team Intelligent Controls Engineers (I.C.E), is to design a two-mode hybrid control strategy by developing an efficiently managed controller area network that will minimize unnecessary work from the internal combustion engine; while ensuring maximum output based on the external driving conditions. During the first year, which is the only time team I.C.E has to work on the project, the team will deliver a software based hybrid control strategy, where most of the work will be done using Simulink, a software program based in MATLAB. Furthermore, the team will benefit from this by having hands on experience with research, product knowledge, and systems engineering.

The design of Hybrid Vehicles has changed over time. Current approaches include supervisory control, optimal control, predictive control, digital control, Variable structure control, and switching control. Hybrid control systems can be considered as computer control systems with advanced control algorithms because of its networking ability throughout the vehicle. So, based on the details of our proposal, it will be shown that it is important to focus on the control systems of a car, since that is its brain; if it's not at its best, the car will not function to its maximum potential.

Throughout this proposal the team will show how the team plans to build this control system and how our strategy will allow the EcoCAR to meet the specified performance requirement. The proposal is organized such that the definition of the problem is followed by present status of engine control systems, then our way of solving the problem, the solution approach chosen, and the timeline for the project. With the knowledge the team have received thus far, and what the team are going to acquire, team I.C.E will definitely deliver.

2. Problem Definition

To design a two-mode hybrid control strategy by developing an efficiently managed controller area network that will minimize unnecessary work from the internal combustion engine; while ensuring maximum output based on the external driving conditions. The team will simulate the functions of the control strategy and observe how it performs in different driving conditions, for example, different terrains and speeds. This is to ensure the best performance for the car while adhering to the standards of the government and environmental agencies. This strategy will be used to control the two-mode hybrid architecture being used by the Howard University EcoCAR team. This control strategy is used to ensure that the EcoCAR Hybrid vehicle operates within the general constraints specified by the EcoCAR competition officials. Therefore, the requirements of the control system are as follows:

Performance & Function

- Emissions mitigation and fuel consumption rate of at least 30 miles per gallon
- The ability to monitor and control battery power level
- Manage the motor heat control system in the vehicle
- Facilitate acceleration 0-60mph in less than 14s
- Facilitate acceleration 50-70mph in less than 10s
- Facilitate a car start time of less than 15s
- Facilitate a smooth transition from ICE to motor and vice versa
- Ensure efficient communication between the different control units in the controller area network, such as
    - Engine control unit
    - Transmission control unit
    - Exhaust control system
    - Battery control unit
    - Vehicle/Hybrid supervisory Electric Control Unit (ECU)

Regulations

The control system strategy when implemented should ensure that the vehicle meets performance requirements in accordance with the SAE Standard J1711. The weighting of the testing results from the J1711 method is obtained from the NHTSA (2005) data that has quantified the average driving distance by the population in the US.

3. Current Status of Art

Architecture operation:

The GM two-mode system quite possibly is the most significant gasoline-electric propulsion advancement since the original Toyota Prius. The hybrid two-mode system has four basic parts, that are, the Electric Control Unit (ECU), internal combustion engine (ICE), two motors/generator and battery (storage device). Besides those four basic parts, there are connecting wires, gears and shafts. All the three parts are connected to ECU with conducting wires. The ECU plays a vital role here, it is like a sensor that switches the operation based on the situations such as low speed and light load or high speed and heavy load. The hybrid system has two modes. The first mode is operated at low speed and light load, and the second mode is operated at high speed and heavy load.

When the hybrid system is operated on the first mode, the energy is generated to drive the shaft either by motor/generator, by engine, or by the combination of motor/generator and engine. In low load or moderate speed situations, the car is running with the help of motor/generator, and the engine is turned off at this mode of operation. In order to get continuous power from the motor/generator, as said there are two motors/generators, while one of the motor/generator supplies energy to planetary gears the other one can act as a generator to regenerate charge to restore the storage device and vice versa. During this operation, the engine is ready any time to give function when the ECU sense acceleration or heavy load.

When the hybrid is operated in the second mode, again the mode is sensed by the ECU. At this period the engine gives its 100% efficiency in addition to the energy supply from the two motors/generators. At their maximum efficiency, the two motors/generators play back and forth as a motor and a generator that keeps any one of the motor/generator to supply power and to recharge the storage device.

**Note: planetary gear is a connection point for power coming from either motor and the ICE.*

Two-mode Control Strategy:

Our control strategy will depend on these important characteristics of the two-mode system architecture:

a. The parallel configuration of the two-55KW electric motors and the Internal combustion engine (ICE)
b. A system configuration that allows the motor when not in electric mode or during breaking to act as a generator that charges the batteries
c. Variation of the output torque from the internal combustion engine (ICE), and intelligent switching between the motors and ICE

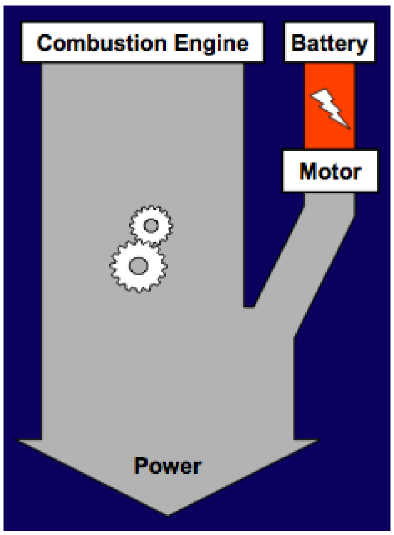

Fig. 0

Figure 0 shows the flow of power from the motor(s)/generator(s) through the planetary gearing system. The current two-mode control system regulates power/energy flow between:

- Energy storage devices and the motor/generators
- The first and second motor/generators
- Level of emissions from vehicle

In addition, the two-mode control system regulates power flow to the planetary gears, as such:

- Motor 1 and/or 2 power only
- Motor(s) and ICE power
- ICE power only

The current status of art in two mode control strategies provides a solution to our problem. However, the complexity of the current state of art surpasses the functional requirements for the EcoCAR project control system and the knowledge base of the students involved. Therefore, while Team I.C.E may use a very similar method of controlling the two-mode environment, our algorithms will be less complex than those of the GM two-mode control system algorithms.

4. Engineering Solutions

Initial solution ideas

Solution 1

Fig.1

The main approach to this project is to set up models and simulate the environment for our control system (see Fig.1). Firstly, this involves the modeling of the control units. This top level modeling well be done using simulink. Around the algorithms for the individual control unit will be an algorithm that determines how the control units in the Controller Area Network (CAN) communicate with each other. (see Fig.2)

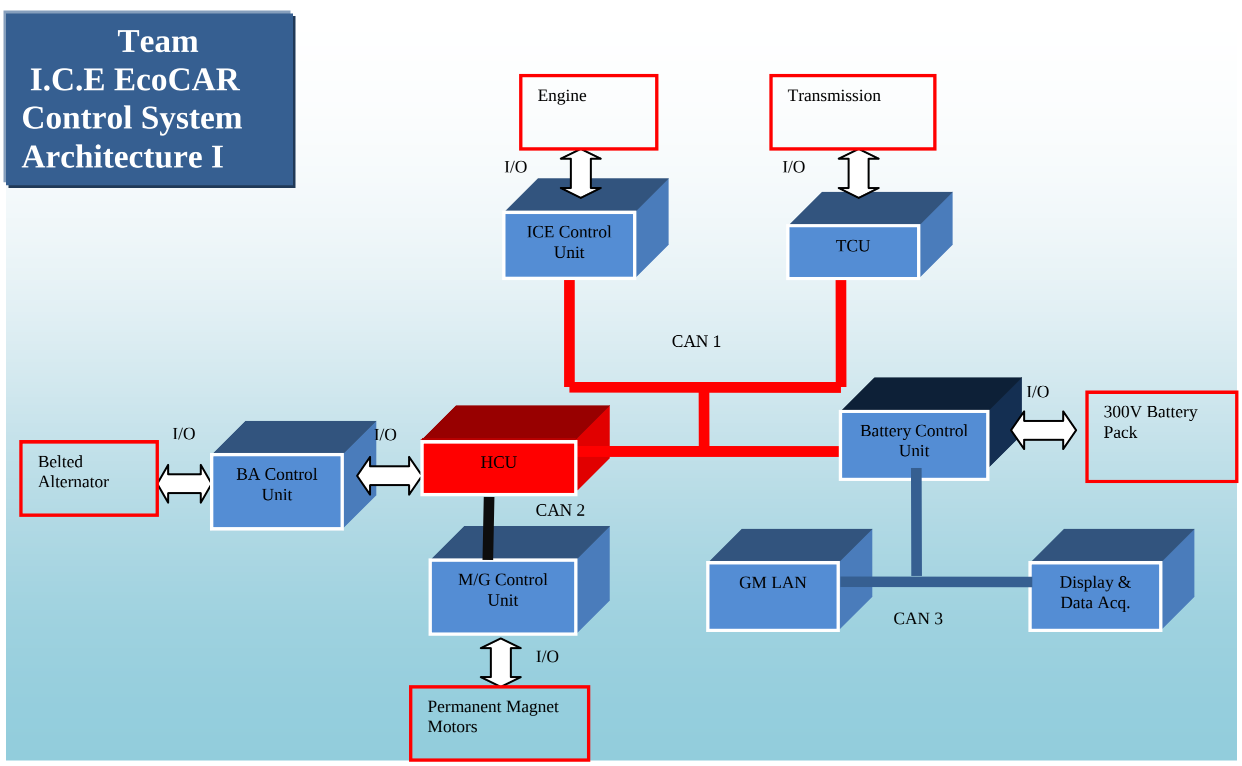

Fig.2 Architecture I of real time communication using CANs

The use of linear control systems is the crux of the control strategy for the controller area network. Each hybrid control unit has to respond to current condition stimulus from power sources, like the engine, motor(s)/generator(s), battery, and figure out if it meets required conditions coming from the sensors throughout the vehicle. This is done using a feedback loop so that the hybrid control unit is able to juxtapose current and required situations and make needed adjustments.

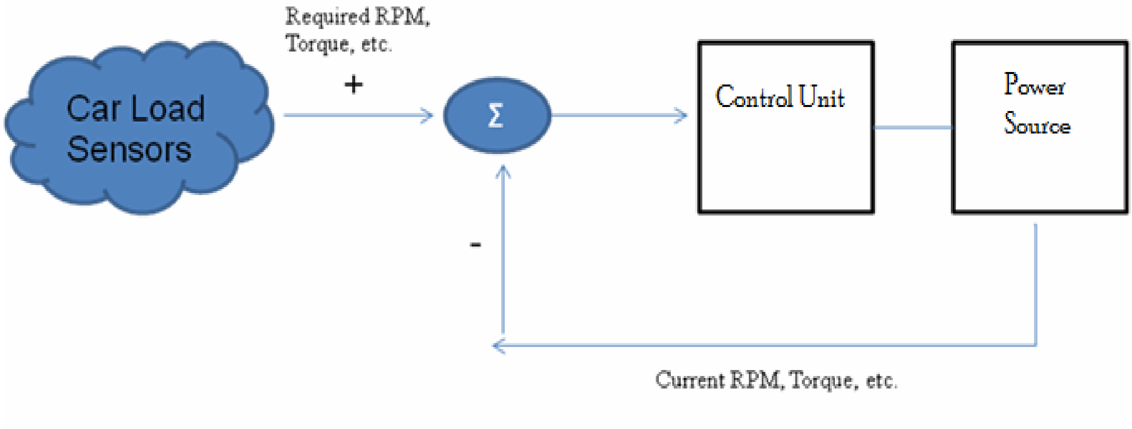

Fig. 3 Feedback loop for Hybrid Control Unit

The control units for the power train will all communicate with the Hybrid control unit as illustrated in Figure 3, but will each require different stimulus.

- **Battery:** Team I.C.E proposes to control the battery charge by consistently monitoring charge levels. Our control system will act to ensure that battery charge is not depleted below some specific minimum charge level. The team also intends to control the battery heat levels by monitoring battery temperature and enacting the battery fan when needed. The BCU will also be used to pass on current hybrid function messages to the interface. Furthermore, the team proposes to control the on/off status of the battery, to maintain high safety levels, depending on the following conditions:
  - Airbag deployed status
  - Isolation fault detection
  - High voltage interlock loop
- **Internal Combustion Engine:** Team I.C.E proposes to control the engine performance level by monitoring current torque and RPM output conditions from the ICE then sending a torque and RPM request from the Hybrid supervisory unit based on required conditions. Furthermore, the Hybrid supervisory unit will need to receive the engine temperature and turn the cooling fans on and off. It is our understanding that the transmission on the 2-mode system will actually start the engine so the transmission control unit will control the engine on/off status. The engine will be turned over initially and warmed up using a belted starter alternator.
- **Electric motor (inverter):** Team I.C.E proposes to control motor performance level by monitoring current torque and RPM output conditions from the motor

and comparing these readings to required conditions. In addition, the team intends to control the mode of operation of the inverter, that is, based on the current battery charge levels or during regenerative braking a motor will be used to generate charge to be stored in the battery. The temperature of the motor/generators will be controlled by monitoring current operating temperature at all times and enacting the motor/generator cooling system when the temperature surpasses satisfactory operating level.

- **Transmission/planetary gearing system:** The team proposes to control the dynamics of the planetary gearing system in an effort to control the flow of power from the ICE and/or motors to the wheels.

Note that the Electric motors (M/G), the battery, and the ICE all come with stock control units equipped with failsafe modes of operation, and will be used by our team. For example, the engine control unit (ECU) has a mode that tells the engine to run at a default RPM if a gas pedal signal from the CAN is not detected. There are many other failsafe responses for both the ECU and M/G control unit, such as predefined responses to motor code created when the M/G is too hot or when the fuel pressure to the injectors is too low in the ICE. The ECU and M/G control units also have default modes of operation when no stimulus is coming from the vehicle, for example, the case where the Hybrid control unit is not functioning or the CAN wiring fails at some point. GM will provide the different failsafe scenarios and corresponding default responses to us in the coming weeks.

Furthermore, the complete control strategy developed for the hybrid control unit must be thoroughly tested. It will be tested using software like PSAT, which simulates real time driving conditions, and hardware controllers, such as the dSpace or National instruments controllers, and other system diagnostic tools.

Solution 2

Solution 2 will be the same as solution 1 in every respect except for implantation of failsafe system and a custom exhaust control unit. In solution 2, the team proposes to develop an electrical emergency control system. This system will include a manual power system shut down button placed on the body of the vehicle, in case of electrical shock while the vehicle is at a standstill and being worked on by a mechanic. The main constraint of this system, as it pertains to the control systems team, is that it falls outside the realm of our responsibilities, and into that of the Electrical systems design group on the Howard EcoCAR competition team.

The exhaust control unit must be designed to monitor the emissions of the vehicle, and send messages to the HCU if emission levels need to be mitigated. The emissions of the vehicle at any point in time must adhere to the regulations set forth in the SAE Standard J1711, which is the recommended practice for measuring the exhaust emissions and fuel economy of Hybrid-Electric vehicles. This unit well be developed if need be at a later stage of the competition.

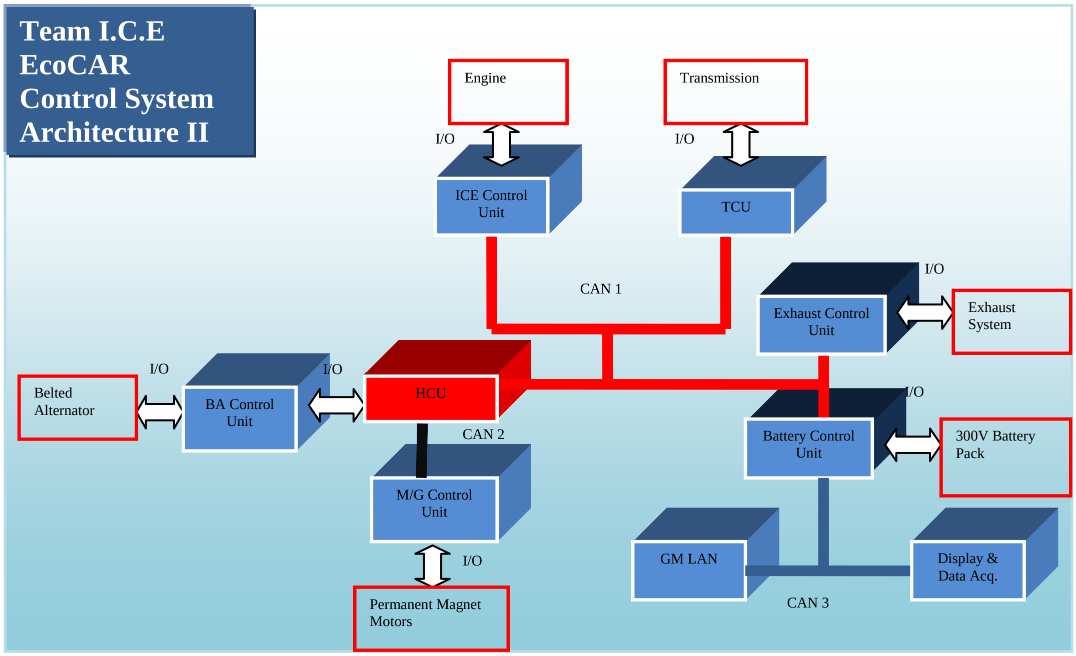

Fig.4 Architecture II of real time communication using CANs

Resources required for solution

- Linear Control (EECE 414) lecture and Lab is the main requirement for the understanding of control systems in general.
- Access to Matlab with Simulink on some workstations in the EE lab

Knowledge Required for the Solution

- An understanding of control system modeling in Simulink, and how to integrate and test the control system with PSAT.
- A thorough understanding of the different types of control units that will be developed and the GM Control Area Network (CAN) system is needed.
- Comprehension of the function of the products being offered by Dspace and National Instruments.
- Knowledge of components for the selected system architecture and the Saturn VUE. These components include an Internal Combustion Engine, Electric Motor(s).

5. Tasks and Deliverables

Tasks	Deadline
Report 2B: Architecture Selection Report sent to GM	11/20/08
Control system strategy	01/31/09
Subsystem design report sent to GM	02/02/09
SIL testing completion and results accumulated by the team and analyzed	03/01/09
HIL testing completion and results accumulated by the team and analyzed by System development and integration report delivered to GM report	04/15/09

As with any project development lifecycle, there are major steps the team will confront. These are project initiation, preliminary engineering, planning, construction, and deliverance of a production line product. The EcoCar project has a structured cycle of three years. As part of the design group of the EcoCAR team, Team I.C.E. will be managing the systems and controls modules. Year one will focus its energies on research and virtual design. First year deliverables for the team include its vehicle's control strategy. Team I.C.E's responsibilities comprise of the controls architecture, hardware in the loop utilization, and the handling of the high power electrical system of its hybrid vehicle. The controls architecture will require control system definition and strategy development for its implementation. Experimental HIL validation and testing will be addressed only after thorough software in the loop for controls prototyping realizations are exhausted. This will be accomplished in the vein of General Motor's Global Vehicle Development Process. Thus, the endeavor will have particular emphasis on subsystem design using math-based design tools.

Heavy reliance on MathWorks' Simulink and Stateflow, which both run on the Matlab platform, will assure well-tested control systems. These modeling programs, compiled by a tandem compiler, achieve auto-code generation that is deployable. In fact, entire simulation will take place within the development computer. The group will need to get up to speed on using these programs to model the chosen vehicle architecture before it receives production vehicle SIL models by the end of December. Competition donated component models will be made available to Team I.C.E by the end of January. At this time, thorough research of the component parts will be necessary to set the parameters of their control algorithms. All initial controller programming will be handled in a Simulink, model-based, environment, which will refine the group's control systems algorithm. The group's concentration for the rest of 2008 and the first month of the New Year will be its vehicle's supervisory control unit. Team I.C.E.'s year-end goal is to have a preliminary supervisory hybrid control unit (HCU) able to run through a limited scope of the 1 Hz urban dynamometer driving schedule (UDDS), as outlined by the U.S. Environmental Protection Agency. These drive cycle events will include an initial crank of vehicle, an engagement of gear shifts to accelerate the vehicle forward from rest, a time allowance of a few minutes of coasting at 30 mph, a downward gear shifting and braking event, a 60 second idling, a resumption of forward acceleration and gear shifting to attain a top-speed of 60 mph, followed by another down-shifting and break event, and finally turning off the vehicle. These exercises are in preparation for a 2 February 2009 submission of Report 3: Subsystem Design.

Deliverables include the submission of a vehicle architecture report, and a forthcoming control strategy presentation. The Howard University EcoCAR team's Report 2A: Architecture Selection Proposal was refined in the November 20th submission of Report 2B: Architecture Selection. The report will contained the selection of controller and the proposal for the team's HIL system. Due at the end of January 2009, Report 3: Subsystem Design, will outline their finalized control system architecture design. The group's presentation, to be delivered early next year, will evaluate how its SIL and HIL architecture meet the objectives of the powertrain the vehicle utilizes. Due mid-April 2009, Report 4: System Development and Integration, will highlight the complete HIL setup design. Due the first week of May 2009, Report 5: Final Design, will detail the HIL testing results and resulting control strategy, vehicle design, and component selection adjustments. This submission will be a technical SAE-styled report.

6. Project Management

Timelines and milestones

Timeline for the first year of the EcoCAR competition:

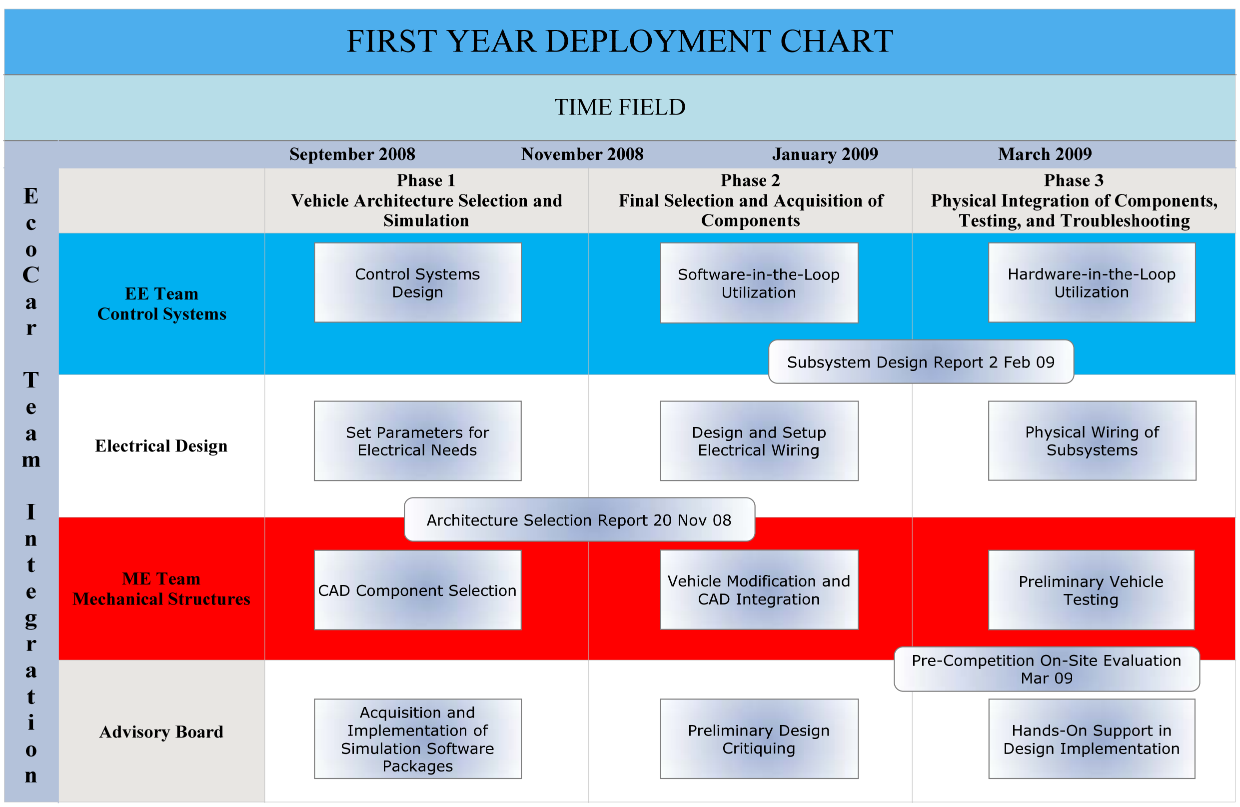

Fig. 5

The above diagram shows the interdisciplinary cooperation needed for the success of the EcoCar project. The level of communication between the four entities and their integration of each part's deliverables will be evidenced in each scheduled report submission.

Verification and development process

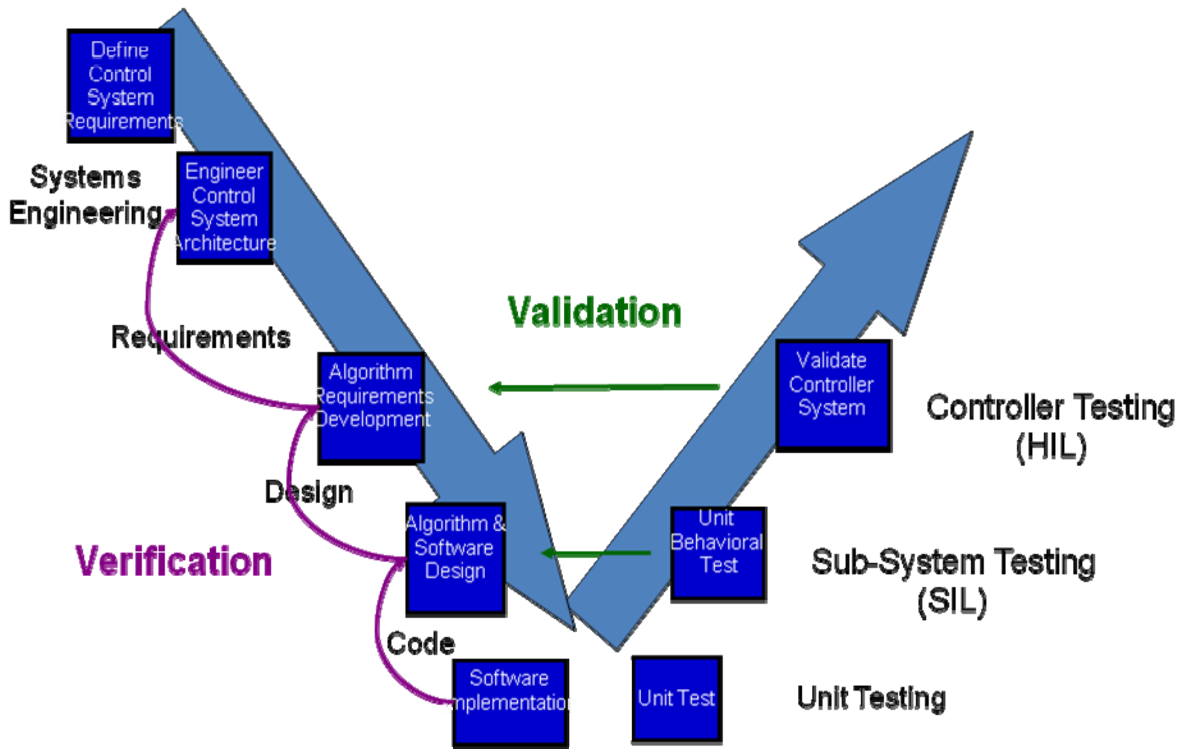

Fig.6

Conceptualization, modeling, and implementation are but half of the overall design process on which Team I.C.E. has embarked. Component integration, testing, and verification are what lie ahead in the first half of 2009. Testing and verification of the controls systems will ultimately bring the need for validation as we seek to fix bugs and hone in on loftier performance goals. An on-going report of their design process will be facilitated by means of the structured approach of a V-diagram. In so doing, they will be following a modification of General Motor's Global Vehicle Development Process (GVDP). This structure will not only track their progress, but affords them a map of where to look for solutions when problems arise. They will be incorporating Process Potential Failure Modes and Effects Analysis (PFMEA) in GM's GVDP.

The above V-diagram shows the progressive steps that the team will take towards developing a tested control system. Each step of the software development stage will require constant back checking and verification to ensure the next step is successful. In addition, each team member will work together on achieving one-step at a time on the first leg of the V-diagram, in an effort to meet the previously outlined timeline. Detailed following of the verification process is important because any errors due to faulty software control systems will result in bugs in the testing stage. Bugs at this stage will result in the retaking of several steps in the software controls development stage and excessive loss of time in the project. In the testing stage, the group will be split into two small teams of two. One team will work on testing and recording of results while the other team will work on analysis and reporting on results. A rather optimistic estimate of the launch of the team's testing time period would be Mid-April of 2009.

Resources and Budget

Training

GM and DOE have and will continue to provide training for the students involved in the EcoCAR project.

- Firstly, with a workshop in September 2008, students received training in several aspects of the project ranging from PSAT tutorials to the presentation of the Hybrid car components to be used and an explanation of how they work
- Access to a SharePoint website, which serves as an access point for helpful documents and a point of communication with several team mentors and experts
- In January 2009, there will be another first year workshop that will elaborate on the CAN communications Plan
- A Mathworks sponsored Model Based Design (Matlab/Simulink) session in November

Equipment and Parts

The following equipment and parts were provided for the different aspects of the project:

1. Software in the loop (SIL)
    - Matlab 7.5 and Simulink 7.7 – Control strategy development
    - PSAT 6.2 – Control strategy testing in simulated driving environment
2. Hardware in the loop (HIL)
    - Hardware for testing the control strategy and performance of the Hybrid system, for example, a choice of Dspace or Nation Instruments controllers and diagnostic components

Engineering ethics issues

- Quality – An overwhelming effort towards ensuring that our work meets or surpasses industry standards, such as the miles per gallon standard set at 30mpg for Sedans.
- Treatment of confidential or proprietary information – Appropriate treatment of important and confidential information that comes from our corporate sponsors
- Consideration of the employer’s assets – Appropriate treatment and use of equipment and training offered by corporate sponsors
- Plagiarism – All ideas and work should that comes from a source should not be passed off as one’s own but should be credited to that source

7. Conclusion

This project stems from the Challenge X EcoCAR project created by GM and the department of energy (DOE). College students from all over the country are involved in the competition are vying for the prize for the most fuel economic and low level emission hybrid vehicle created. This competition educates and encourages students to get involved in the hybrid vehicle revolution, which will assuage the problem of consumption of high priced fuel and global warming. The hybrid control strategy team, which is composed of Electrical Engineering students, will work towards developing a control system that allows the vehicle to meet its competition performance requirements. This project will allow our team to indulge in the development of an industry standard control system for an electric hybrid vehicle. The team will use the attached design requirements and other resources available to first develop a control system architecture followed by the algorithm and completed simulink model. This model will be tested in a virtual driving environment using PSAT and will then be tested using a hardware controller and diagnostic units provided by our sponsors. Students involved will gain valuable industry insight, and get experience working with industry standard tools. This year-long project will be archived and passed on to those involved in the remaining two years of the EcoCAR project, which includes Rapid Control Prototyping, and control system testing in the vehicle. Just to recap our team will complete the control system and software testing by February 2009 and Hardware testing by march 2009.

8. References

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