PROTODRIVE: AN EXPERIMENTAL PLATFORM FOR ELECTRIC VEHICLE ENERGY SCHEDULING AND CONTROL

DoT UTC Final Report

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Contents

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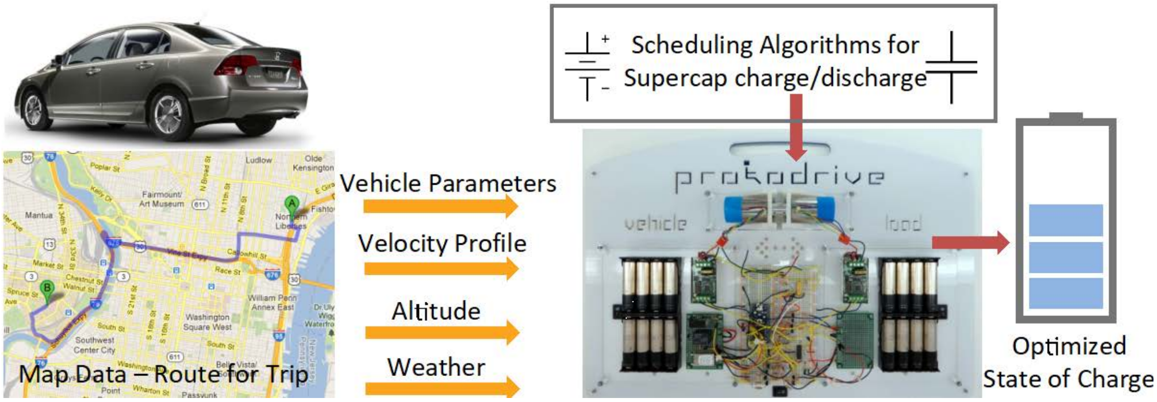
Abstract

Electric vehicles are a promising alternative to vehicles powered by fossil fuels due to their cleaner energy emission, but current limitations in battery technology are preventing electric vehicles from burgeoning in the mass consumer market. Therefore, simulating and prototyping various power trains become paramount for finding different energy efficient models. A portable power train platform, known as Protodrive, is here to provide a stage in between pure software simulation and full-scale hardware simulation. This platform allows energy to transfer between the vehicle power train and the load power train through the use of regenerative braking. Protodrive is also able to accept a plethora of drive cycles and trajectories to help determine the forces acting on the vehicle. Through the use of mathematical models of these forces, the platform is capable of applying the proper load on the vehicle power train to determine the power consumption. Additionally, introduction of a super capacitor to the vehicle power train model allows for the analysis of various control schemes to better manage the power consumption. The resulting simulated drive data can be viewed in real time through an intuitive web application that will allow users to enter drive cycles and define trajectories using Google Maps. The platform data can then be validated by comparing it with actual vehicle drive data.



ProtoDrive Overview showing the inputs of real vehicle parameters, an actual trip from Google Maps with altitude and traffic data, and weather data. The ProtoDrive platform runs a scaled version of the actual drive cycle with various battery/super capacitor charging/discharging schedules to maximize the battery's state of charge and minimize the peak current demand.

List of Figures

Chapter 1

Introduction

On July 29, 2011, the Obama Administration announced a plan aimed to increase fuel economy, decrease oil dependence, and reduce pollution. Model year 2016 vehicles are to have an average fuel efficiency of 35.5 mpg, and model year 2025 vehicles are to have an average of 54.5 mpg, cutting greenhouse gas emissions by more than 6 billion metric tons [1]. To help fulfill the administration's goals, thirteen major automakers have agreed to actively pursue the research and development of electric vehicles [1].

Electric vehicles provide an alternative to vehicles powered by fossil fuels, leading to a dramatic decrease in dependence on gasoline. However, limitations such as low energy density, high costs, and long battery recharging time prevent mass consumer acceptance [2]. There are various ways to optimize the efficiency of electric vehicles. For example, the powertrain system and energy control could be managed to reach an optimal range. The implementation and control of such systems has necessitated the need for widespread use of embedded systems in electric (and conventional) vehicles for applications ranging from traction control, stability control, and powertrain control to cabin temperature control.

Vehicles involved in urban commutes are subjected to highly variable loads as they traverse varying gradients and stop-and-go traffic. Electric vehicles can potentially achieve a high efficiency under these conditions due to their ability to recover energy during braking. However, the high current loads during both charging and discharging cause battery energy losses, making them less efficient and degrading their useful lifetime. This has led to the exploration of various Hybrid Energy Storage Systems (**HESS**) for use in electric vehicles. An example is the battery-super capacitor energy storage system. Super capacitors work well under high power charge and discharge cycles, however, their high cost and low energy density prevent them from being a viable replacement for batteries. A hybrid system consisting of a battery and a super capacitor has the potential to offer the benefits of both devices, which may increase vehicle range and battery lifetime.

Development and testing of such HESSs along with their integration into an electric vehicle requires a significant amount of time and money. Evaluating the performance of such systems is in itself a costly and time-consuming process which involves testing the vehicles on-road or on a dynamometer. The cost of damaging a component and the work involved in replacing it is also a constraint on how rigorous the testing can be. Finally, for every different vehicle model, the process has to be repeated all over again from scratch.

In order to speed up the development and testing process and reduce the cost of testing electric vehicle powertrains, we have developed a small-scale electric vehicle prototyping platform known as Protodrive [2]. The Protodrive platform provides a step in between software simulation and full-scale prototyping. The powertrain is modeled at the small-scale in hardware, making it low-cost and compact enough to fit on a desk. It consists of a physical model of an electric vehicle powertrain coupled to an active dynamometer, making it possible to run the powertrain through its full speed and torque range. The fact that this system has been constructed in hardware allows it to capture intricacies in vehicle operation that may be missed by simulation in software alone.

Protodrive runs a scaled version of an actual commute drive cycle with various battery/super capacitor charging/discharging schedules with the goal of maximizing the battery’s life time and the vehicle’s range. Protodrive has a number of interesting applications that will further EV development. These include:

- Enabling rapid prototyping and evaluation of novel powertrain architectures
- Simulating federal drive cycles to determine a vehicle’s fuel consumption and MPGe rating (Miles Per Gallon equivalent)
- Predicting range, when coupled with elevation data from Google maps and a driver control strategy

Chapter 2

Background

2.1 Electric vehicles today

Electric vehicles use batteries to power the motor, auxiliary devices, or both. Manufacturers have developed several different types of electric vehicles that are either purely battery powered or some sort of combination of battery power and gasoline power. There are several ways to charge these electric vehicles, through either charging stations or regenerative braking. They do, however, have a major disadvantage in that current battery technology has its own limitations.

2.1.1 Types of Electric Vehicles

There are three main types of vehicles using electric vehicle technology (battery power) as a power source: electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEV) [3]. Electric vehicles use an electric motor powered by batteries to run both the motor and auxiliary devices. Hybrid electric vehicles implement both a gasoline engine and an electric motor. There are control schemes to maintain the proper use of the motor and engine so as to create a more efficient system. The plug-in hybrid electric vehicles also have a gasoline engine and electric motor; however, the main difference is the PHEVs having higher energy storage capabilities, i.e. more battery power [3]. These electric vehicles are paving the way to the reduction of fossil fuel emissions.

2.1.2 Consumer acceptance

The main challenge electric vehicle manufacturers are facing is the energy storage requirements. High capacity battery packs are expensive; therefore, manufacturers are forced to use lower capacity batteries to make the vehicles more affordable. By limiting the capacity, manufacturers also limit the vehicle range, i.e. how far the vehicle can drive in one charge. For electric vehicles, batteries need to be designed to improve energy storage capacity. Batteries still need to be improved in many ways, such as durability, life-expectancy, energy density, power density, temperature sensitivity, reductions in charge time, and cost [3]. Without solutions to these problems, mass consumer acceptance is unrealistic.

2.1.3 Charging and regenerative braking

There are two ways to charge batteries within an electric vehicle. First, vehicles can visit charge stations to either swap battery packs, or stations to plug the vehicle in for charging. Second, the discovery of regenerative breaking has allowed for the recuperation of some of the energy lost during a drive. The regenerative braking process occurs when the vehicle is decelerating. A portion of the kinetic energy stored in the vehicle’s translating mass is regained and can be stored in a battery or capacitor. This is generally done by allowing the traction motor to act as a generator, giving the proper braking torque to the wheels and recharging the traction batteries [4]. This recovered energy can then be used for either the motor or auxiliary devices.

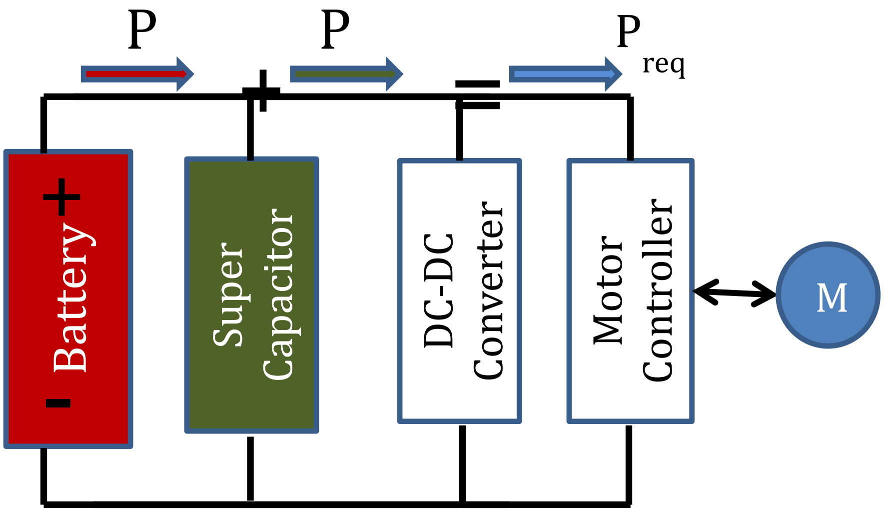


Figure 2.1: *Electric vehicle powertrain battery-super capacitor energy systems*

2.2 Super capacitors in Electric Vehicles

A driving cycle can place different types of strains on the vehicle. These strains include traffic, especially stop-and-go traffic, sudden acceleration due to driver behavior, and varying terrains. The Figure 2.2 shows an example of the Urban Dynamometer Driving Schedule (UDDS) drive cycle. This illustrates the rapidly changing velocity profile attained in city driving. Due to the high dynamic range of these electric loads on the vehicle, the current surges traveling in and out of the battery tend to generate extensive heat inside the battery. This leads to increase in battery's internal resistance, which results in lower efficiency and eventually premature failure. This peak current draw poses a problem when regenerative braking occurs because the process produces a sudden increase in the amount of current entering the batteries. These current spikes can lead to the degradation of the batteries [5]-[7]. A super capacitor, however, has a high power density, meaning it can rapidly charge and discharge. Therefore, it is effective as a buffer for the batteries [8].

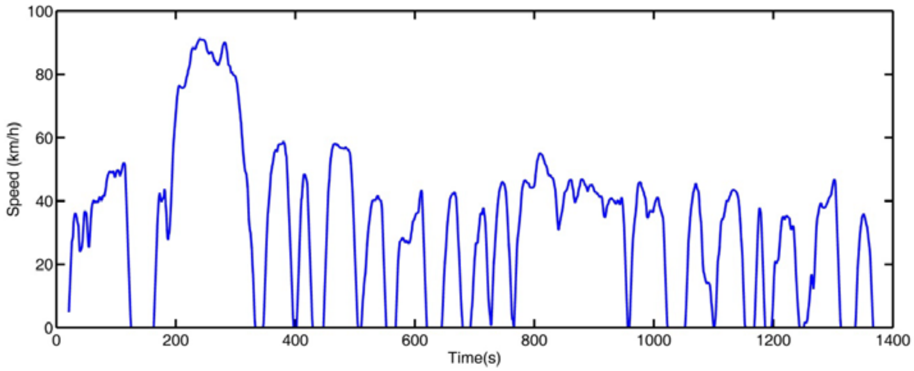


Figure 2.2: *The Federal EPA Urban Dynamometer Driving Schedule (UDDS) drive cycle*

Most powertrain simulations are currently done strictly on software and then created on a full-scale prototype vehicle [2]. This process can be quite costly and very time consuming since it requires putting together so many components. However, Protodrive is a small, portable, and easily modifiable platform. The platform consists of two models: the vehicle model, and load model, which are controlled by an ARM™ based 32-bit microcontroller. The vehicle model is comprised of a brushed DC motor, motor controller with regenerative braking capabilities, lithium ion cells used in the Tesla Roadster, and a super capacitor. There is currently a relay to switch between the super capacitor and battery pack, giving the user control over when to charge and discharge the super capacitor. This model represents a vehicle’s energy consumption [2].

The load model is also comprised of the same Lithium ion cells, a brushed DC motor, and a motor controller with regenerative braking. The two motors (vehicle and load) are rigidly coupled together. This way, the load motor can act against the vehicle motor to simulate the proper load in a real-world situation [2]. There will be a more detailed explanation of how these loads are modeled and simulated in Chapter 3.

2.3 Overview of Protodrive

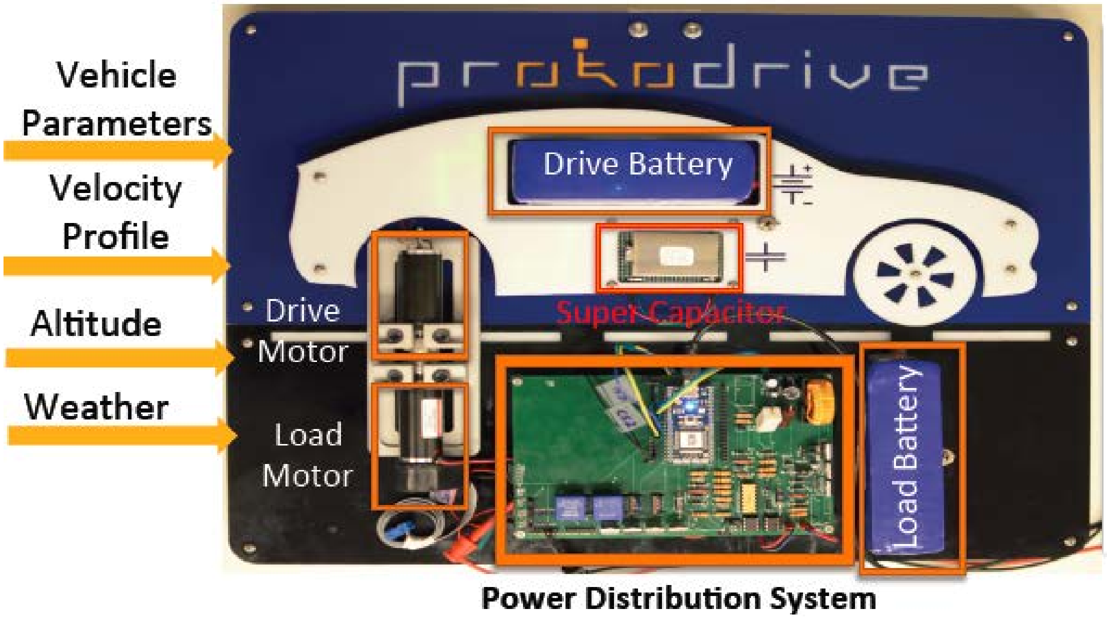


Figure 2.3: *The Protodrive embedded hardware platform*

2.4 Challenges and goals

The challenges involved in a reduced-scale simulation of electric-vehicle powertrains are many. Some of the pressing challenges encountered were:

- Accurately representing the forces acting on a vehicle and their effect on power consumption.

- Modeling the effect of different vehicle parameters on power consumption in the electric vehicle.
- Mapping different vehicle models to the same hardware platform while maintaining the accuracy of the simulation.
- Developing schemes to effectively use the battery-super capacitor hybrid energy storage system to reduce the load on the battery (and increase battery lifetime).

With the Protodrive platform, we aim to have the capability to

- Simulate the behavior of electric vehicle powertrains with accuracy by modeling the forces on the vehicle and interaction of electrical and mechanical components.
- Rapidly evaluate different hardware specifications and energy storage systems for the drivetrain.
- Simulate the EV drivetrain for different scenarios and vehicle models without any additional cost or safety concern.
- Develop and evaluate schemes for energy management in EVs.

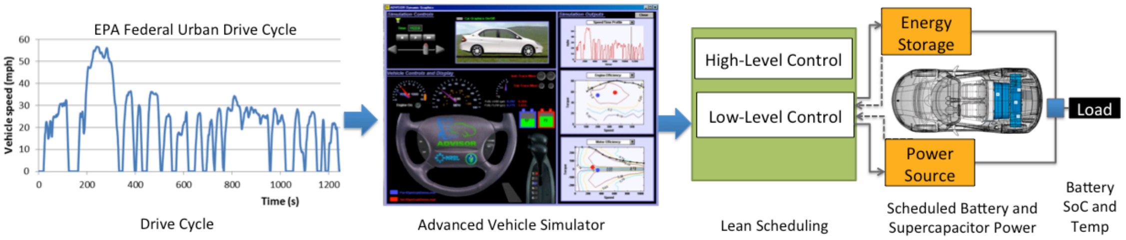


Figure 2.4: *The Protodrive battery-super capacitor energy management system*

Chapter 3

System Modeling

In order to simulate the behavior of an electric vehicle's powertrain, we need to develop a dynamic model of the forces acting on a vehicle. The Figure 3.1 shows the forces acting on a vehicle.

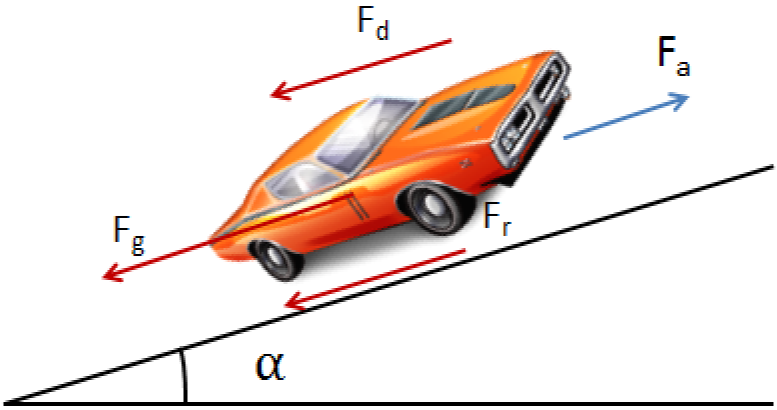


Figure 3.1: *Forces acting on a moving vehicle*

Force balancing gives us,

$$\mathrm{F_t = F_a + F_g + F_d + F_r}$$

Where,

$\mathrm{F_t}$	Total tractive force at the wheels
$\mathrm{F_a}$	Force due to acceleration
$\mathrm{F_g}$	Force due to gravity
$\mathrm{F_d}$	Force due to aerodynamic drag
$\mathrm{F_r}$	Force due to rolling resistance of the tires

These individual forces can be calculated by using vehicle specific parameters:

$$\mathrm{F_a = ma}$$

$$\mathrm{F_g = m_v g sin(\theta)}$$

$$\mathrm{F_d = \frac{1}{2} A_f C_d v^2}$$

$$\mathrm{F_r = C_r m_v g cos(\theta)}$$

Where,

m	Total mass acting on the wheels
a	Acceleration of the vehicle
$\mathrm{m_v}$	Mass of the vehicle
g	Gravity

θ	Angle of inclination of the vehicle
A_f	Frontal area of the vehicle
C_d	Coefficient of drag
v	Velocity of the vehicle
C_r	Coefficient of rolling resistance

The total mass of the vehicle m represents the combination of the vehicle's mass and the mass added due to the inertia of all the rotating components. In general, the moment of inertia can be related to mass using:

$$T = J\acute{\omega} = rF$$

$$F = \frac{J\acute{\omega}}{r} = ma = mr\acute{\omega}$$

$$m = \frac{J}{r^2}$$

Where,

T	Torque
J	Moment of inertia
$\acute{\omega}$	Angular acceleration
r	Wheel radius
F	Force
m	Mass
a	Acceleration

Using this equation it is possible to find the mass due to the moment of inertia:

$$m_j = m_{jw} + m_{jg} = \frac{1}{r^2} J_w + \frac{\gamma^2}{r^2} J_g$$

Where,

m_j	Mass due to moment of inertia
m_{jw}	Mass due to moment of inertia of wheels
m_{jg}	Mass due to moment of inertia of gearbox and motors
r	Radius of wheels
J_w	Moment of inertia of wheels
γ	Gearbox ratio
J_g	Moment of inertia of gearbox and motors

The total mass of the vehicle can now be written as:

$$m = m_j + m_v$$

3.1 Electro-mechanical equivalent model of Protodrive

The Protodrive platform is intended to function as a desktop dynamometer. For this, the forces acting on a vehicle (including those opposing its motion) need to be simulated. Our design to achieve this involves two rigidly coupled motors, one acting as the driving motor, and the other simulating the opposing forces (the load motor). To convert the mechanical model outlined above into an electrical model, which can be controlled, we use the equivalent electrical circuit model for two motors, which are rigidly coupled (see Figure. 3.2).

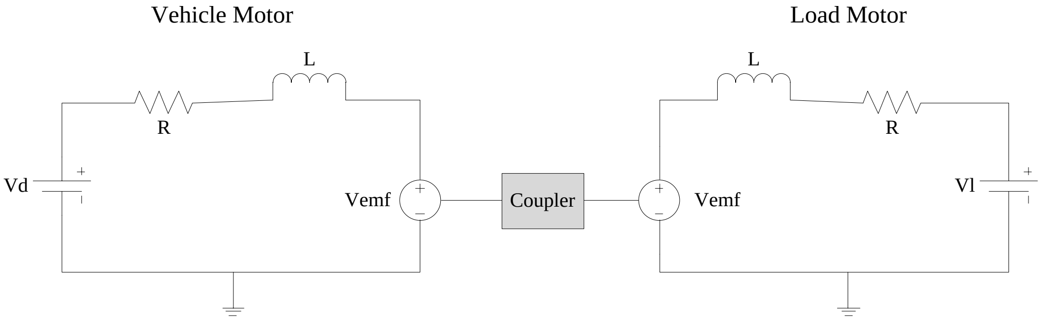


Figure 3.2: *Equivalent circuit of two rigidly coupled motors*

Through this model, the vehicle motor voltage and load motor voltage are described by:

$$V_D = RI_D + L\frac{dI_D}{dt} + V_{emf}$$

$$V_L = RI_L + L\frac{dI_L}{dt} + V_{emf}$$

$$V_{emf} = k_e\omega$$

$$T = k_t I$$

Where,

V_D	Vehicle motor voltage
R	Resistance
I_D	Vehicle motor current
L	Inductance
V_{emf}	Back EMF

k_e	Speed constant
V_L	Load motor voltage
I_L	Load motor current
ω	Angular velocity
T	Torque
I	Current
k_t	Torque constant

Note, the back EMF is the same for both motors as rigid coupling enforces the same angular velocity on both of them (and Vemf=ktI).

Using the mechanical coupling equation, the torque is:

$$J\dot{\omega} = T_D + T_L + T_f \text{ where } T_f < 0$$

Where,

J	Moment of inertia of both motors and a coupler
T_D	Vehicle motor torque
T_L	Load motor torque
T_f	Torque to overcome friction

The electrical and mechanical equations can be combined to calculate the proper motor voltages (the inductance has been set to zero to make it simpler):

$$V_D = \frac{RT_{ref}}{k_t} + k_e\omega_{ref}$$

$$V_L = \frac{R(J\dot{\omega}_{ref} - T_{ref} - T_f)}{k_t} + k_e \omega_{ref}$$

$$T_{ref} = \frac{F_t r}{\gamma T_{scaling}}$$

$$\omega_{ref} = \frac{\gamma v}{r}$$

$$\dot{\omega}_{ref} = \frac{\gamma a}{r}$$

Where,

$T_{scaling}$	Torque scaling between actual vehicle and Protodrive
T_{ref}	Necessary torque
ω_{ref}	Necessary angular velocity
$\dot{\omega}_{ref}$	Necessary angular acceleration

3.2 Controlling the battery-super capacitor system

For the system modeled above, the power to the drive motor is supplied by the battery-super capacitor system. If PD(t) represents the power demanded by the drive motor at time t, the following balance equation has to be met at all times,

$$PD(t) = PB(t) + PC(t)$$

Where,

PB(t) is the power supplied to the drive motor from the battery at time t

PC(t) is the power supplied to the drive motor from the super capacitor at time t

This equation simply means that the motor must receive enough power to attain the desired acceleration at all times, and that the power can be supplied by a combination of battery and super capacitor.

While the battery's high energy density allows us to neglect the effect of power drawn on energy in the battery, the super capacitor has a low energy density and we need to model the energy dynamics of the super capacitor to ensure that we are not asking for energy from an empty super capacitor (or charging a fully charged super capacitor).

The simple (no loss) dynamics to represent the power-energy relation in a super capacitor can be represented (as a discrete-time systems) as

$$\mathrm{EC}(\mathrm{t}+\mathrm{h}) = \mathrm{EC}(\mathrm{t}) - \mathrm{hPC}(\mathrm{t})$$

Here,

EC(t) is the energy in the super capacitor at time t

PC(t) is the power drawn from capacitor at time t. We follow the convention that power drawn is positive and power supplied to the capacitor (for charging) is negative.

h is the sampling time (in seconds).

Power flows to and from the super capacitor need to ensure that we do not violate

$$\mathrm{EC}(\mathrm{t}+\mathrm{h}) \leq \mathrm{Emax}$$

$$\mathrm{EC}(\mathrm{t}+\mathrm{h}) \geq \mathrm{Emin}$$

Where Emax and Emin are the upper and lower limits on the super capacitor’s energy storage.

3.3 Battery thermal model and lifetime

Batteries have a high energy density but low power density, which means that roughly speaking, high magnitudes of power to/from the battery have an adverse effect on it. Battery lifetime is known to degrade with an increase in temperature [10], and battery temperature itself is dependent on the power flow to/from the battery as

$$K\frac{dT}{dt} = Q + H$$

$$Q \propto I^2R$$

Here,

T is temperature of the battery, and dT/dt represents the time rate of change of temperature

K is a constant that depends on mass of battery

H is the heat transfer due to convection

Q is the heat generated due to power flow, and depends on current from battery (I) and the internal resistance of the battery (R).

Being one of the most expensive components of a electric vehicle, it is important for the battery to last as long as (or as close as possible to) its design lifetime. In order to achieve this, it is necessary to minimize the heat generation in the battery, or equivalently reduce the current squared from the battery (or minimize power flow through the battery).

Schemes to control the battery-super capacitor system are designed to minimize the power flow (or peak power flow) from the battery while meeting the power demand from the motor (and ensuring the super capacitor does not violate its energy limits).

3.4 Schemes to use the battery-super capacitor system

The use of a super capacitor in EVs was initially explored to provide three benefits over a battery-only vehicle

- **Increased range of the electric vehicle**. Being an additional energy storage system with more power density than EV batteries, the super capacitor can potentially increase the range of an EV.
- **Increased battery lifetime**. If the super capacitor can reduce the load on the battery (in form of peak power drawn or current squared reduction), the battery should last longer than it would if there were no super capacitor.
- **Reduce battery size**. Super capacitors could potentially allow battery designers to reduce the battery size while maintaining similar guarantees as a battery only system.

The range of an EV on a full charge is highly dependent on the drive cycle, and significantly increasing the range of an EV has proven to be a significant challenge. Since super capacitors do not have a high energy density (and range is proportional to how much energy the system stores), they cannot add significantly to the range. With this limitation, the reduction in battery size is also not a practical possibility for vehicle manufacturers. Increasing the battery lifetime by reducing peak power drawn from the batteries is an application where the capacitor shows significant promise. Even rule based scheme have shown to give good results.

A few of the common schemes that have been researched are

- **The super capacitor as a buffer**. The capacitor is used as a buffer (subject to its energy limitations) in this scheme. If there is charge in the capacitor, is it used to power the motor (until it runs out of energy) [8]. If there is regenerative power available, the capacitor is charged (up to its upper limit on energy). This scheme by default does not ask for any power from the battery to charge the capacitor, so it does not place any additional load on the battery and guarantees an increase in range. The increase may be insignificant though as the super capacitor possess very little energy compared to the battery. Since this scheme simply switches between the battery and the super capacitor, it also has the benefit of not needing any additional circuitry (dc/dc converters) and minimizes losses in energy conversions. The simplicity of this scheme also implies that it does not need any predictions on future load demands, and can be implemented easily.
- **Threshold or reference State of Charge (SoC) based**. In these schemes, the super capacitor is driven towards a reference SoC (energy level) based on some pre-determined rules and is used to provide power when the demand power exceeds some threshold. These schemes, while simple, need additional dc/dc converters and incur losses in energy conversions. These schemes also require the battery to charge the super capacitor when needed, and for most drive cycles reduce the range of the vehicle. The benefits of increased lifetime (by reduced power peaks) are negated by the decrease in range.

- **Optimal control based schemes**. Trying to combine the best characteristics of the two schemes above, the next step is to formulate the current squared minimization as an optimization problem [11]. Smart use of the battery to charge the super capacitor can help increase the battery lifetime and also increase the vehicle range. The drawback with these schemes is that they need some form of prediction of the future load demand in order to formulate the problem as a finite horizon optimization. Obtaining the future demand of power is not a trivial task for a system as dynamic as a electric vehicle. While the subject of much research, the implementation of these schemes is still not a possibility unless the vehicle's trajectory is known a priori.

Chapter 4

System Development

The Protodrive system bridges the gap between software simulation and full-scale prototyping of electric vehicle powertrain. The hardware models the powertrain on a small-scale, making it low-cost and compact enough to fit on a desk. The hardware of the system tries to capture the intricacies in vehicle operation that may be missed by simulation in software alone thus providing better and more accurate results than simulation.

4.1 System Hardware

The hardware for this system can be functionally divided into three main groups:

1. Powertrain representing the vehicle.
2. Powertrain representing the load on the vehicle.
3. Control System.

4.1.1 Vehicle powertrain

The Vehicle Powertrain comprises of

1. Brushed DC motor (Drive Motor)
2. Custom made motor controller which is a part of the power distribution system (fig)
3. A Hybrid Energy Storage System (HESS)

The hybrid energy storage system is a combination of a battery and a super capacitor connected in parallel. A battery has relatively high energy density but low power density, whereas a super capacitor has relatively high power density but low energy density. The HESS is connected to the motor controller, which is then connected to the drive motor (Figure 4.1).

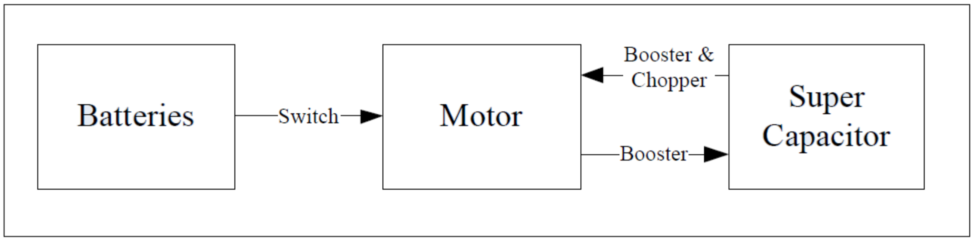


Figure 4.1: *Powertrain of Vehicle showing Hybrid Energy Storage System*

The vehicle motor also acts as a generator in case of regenerative braking and recharges the super capacitor. Since the terminal voltage during regeneration is not high enough to recharge the super capacitor, a boost circuit is used in between the motor terminals and the capacitor-charging path as shown in Figure 4.2.

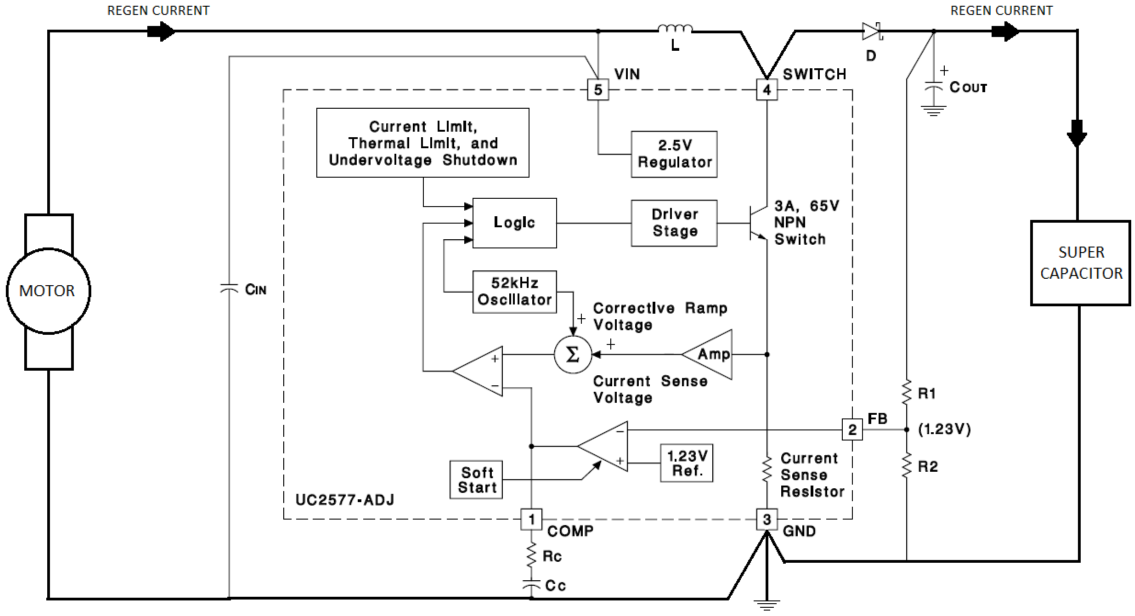


Figure 4.2. *The Boost Circuit*

4.1.2 Load Powertrain

The Load System is a slightly simpler version of the drive system. The energy storage system is simply batteries, which is connected to the brushed DC motor (Load Motor) through the motor controller (see Figure 4.3).

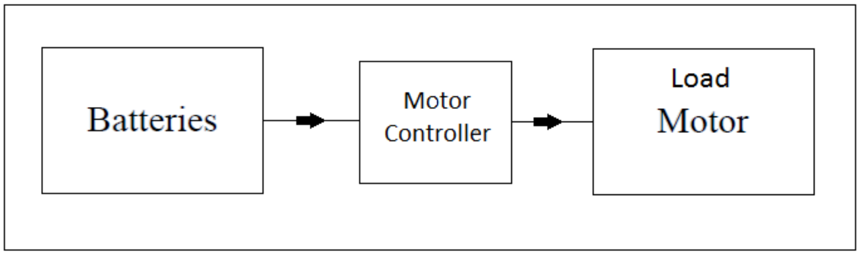


Figure 4.3: *Load motor control*

The load motor and the drive motor are then mechanically coupled, which acts as an active Dynamometer (see Figure 4.4), so that they will spin with the same angular velocity.

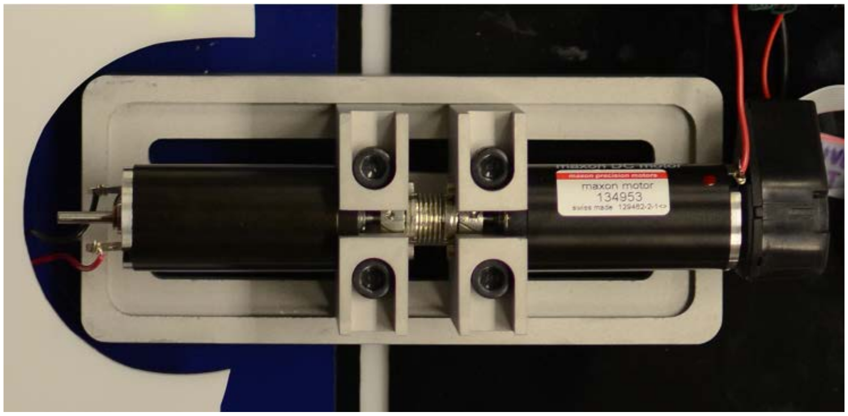


Figure 4.4: *Actively coupled dynamometer*

4.1.3 Control System

The control system consists of a 32-bit ARM (add symbol) based cortex-m3 microcontroller interfaced with a Linux based host system using serial communication. The host system runs MATLAB code, which does the computation and sends the required data to the microcontroller. The microcontroller is interfaced with sensors on the power distribution board (Figure 4.8) for measuring different parameters, which are used as decision variables for the scheduling algorithm. The different interfaces are:

- The battery and super capacitor voltages are monitored using the analog input pins on the microcontroller.
- The output voltages of the current sensors are also measured using analog pins on microcontroller.

- The speeds of the motors are measured using the output (square waves) from the encoder and then measuring the frequency of this signal using counter and timer interrupts.

The microcontroller also controls the motor-controller using PWM (pulse-width modulated) signals. In order to represent the flow of power between the Hybrid Energy Storage System and the drive motor, LED matrix is used and controlled using SPI interface.

4.2 Design challenges

There were many design challenges that we had to face due to interaction of different hardware components and high current.

4.2.1 Motors and Power Supply

Initial design used battery packs with a supply voltage of 7.4V, which limited the motor speed to 3000 RPM. Due to this limitation, high velocity drive-cycles could not be simulated without velocity scaling. However, the motors are capable of reaching 10200 RPM. The power supply was then increased to 16V to attain higher speeds and better simulation.

4.2.2 Current Flow

The platform must be able to use the batteries and super capacitor efficiently. Therefore, a method of controlling the current flow had to be incorporated. Presently the setup involves a MOSFET switching between the battery pack motor and super capacitor motor. However, this did not provide full control over the direction of current. Several ideas were taken into consideration. The first idea was having two relays switching between the battery and super capacitor (see Figure 4.5):

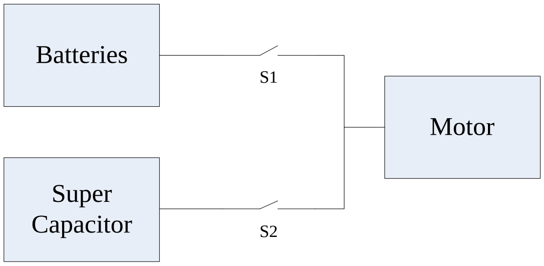


Figure 4.5: *Switching only HESS*

Although the configuration in Figure 4.5 does not allow users to have control over every direction of current, it does allow the super capacitor to be charged by the batteries. Another issue is that all three components must be rated at the same voltage. A solution to this problem would be using buck-boost converters (see Figure 4.6) to apply proper voltages to each component; however, this converter does limit the current. The final configuration should involve a dc-dc converter and a buck-boost circuit.

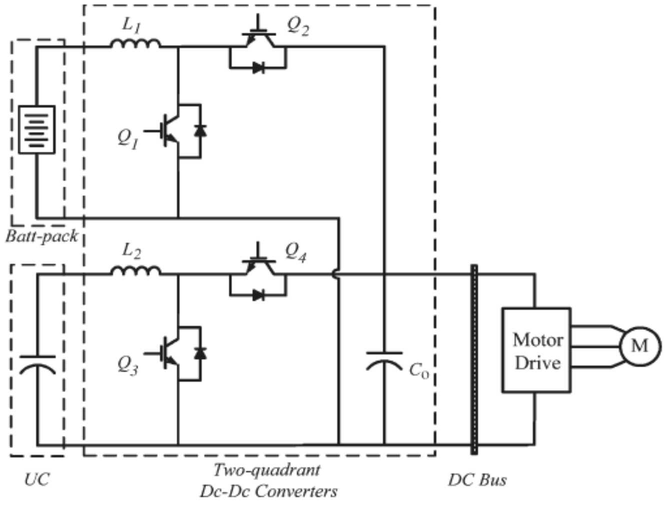


Figure 4.6: *Example of a circuit for the future (figure from [12])*

4.3 System architecture

Figure 4.7 shows the interconnection of the various components on board the Protodrive System.

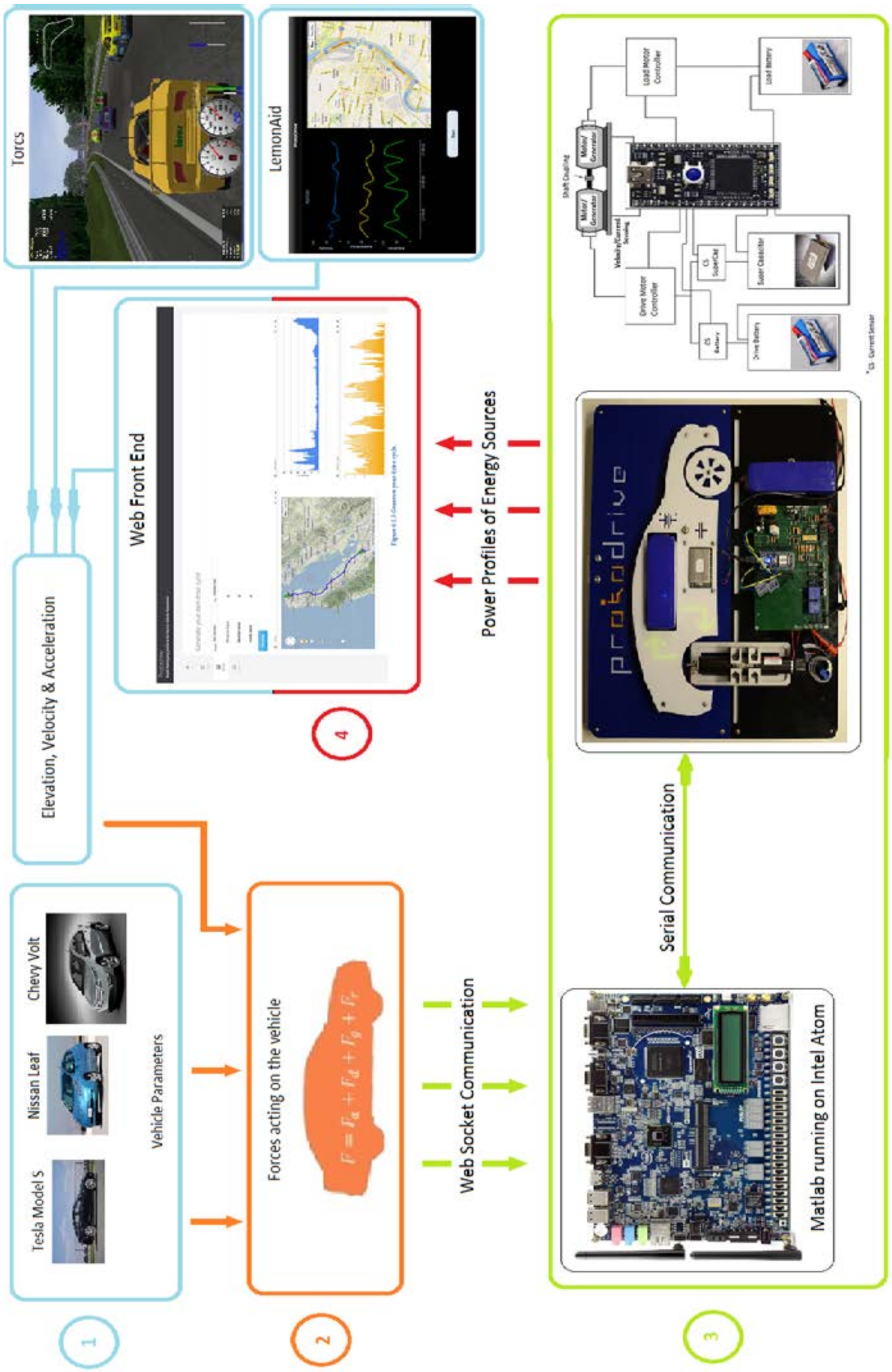


Figure 4.7: *An overview of the Protodrive architecture with all interfaces*

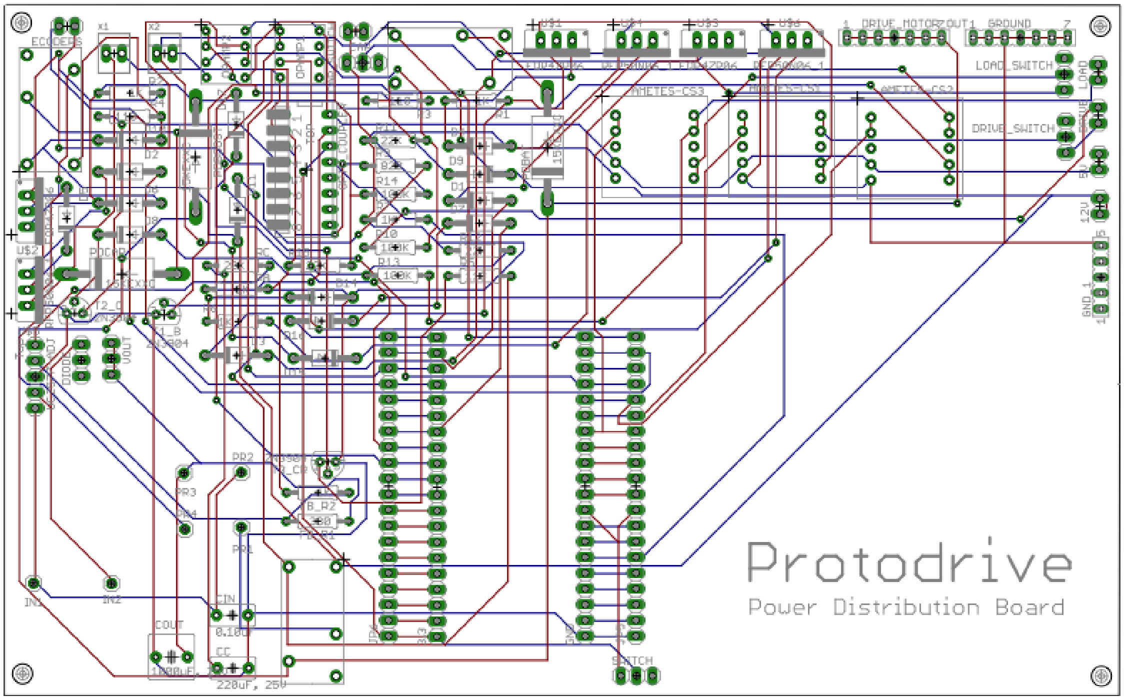


Figure 4.8: *Power Distribution board*

Chapter 5

User Interface

User interaction is an important aspect of the Protodrive system. User can interact with Protodrive using three different interfaces.

1. HTML5 web application.
2. iPad application.
3. Game simulator (TORCS).

5.1 HTML5 web application

With an aim to provide the user with accessibility to the system from a remote location and also provide a more enriching and intuitive user interface, we have developed a HTML5 web application. With this interface, users have complete control over the simulation. Users have access to the simulation results in real-time and can choose paths for simulations, as well as enter drive cycle parameters.

The front end of the web application is created using HTML5 and JavaScript in conjunction with the Google Maps API. The front end enables the user to:

1. Select from pre-existing drive cycles to simulate on the platform.

2. Select a mode to configure the hybrid power distribution system, options are
    a. Battery only.
    b. Battery and super-capacitor.
3. Select a source and destination to generate a custom drive cycle.
4. Choose a combination of parameters that user would like to simulate in addition to standard drive cycle input, options are
    a. Elevation information.
    b. Weather information.
    c. Traffic Information.
5. Simulation results, which include the following information, are plotted in real-time:
    a. Demand Voltage profile.
    b. Battery State of Charge (SoC).
    c. Capacitor SoC.
    d. Motor speed.
    e. Battery Current.
    f. Super-capacitor current.
    g. Super-capacitor voltage.

The back-end of the application uses node.js and socket.io application programming interface (API). Node.js and socket.io uses event-driven, non-blocking I/O model, which is perfect for data-intensive real-time application like Protodrive. This allows the user to interact with Protodrive in real-time and exchange information using web-socket communication.

5.2 iPad application: Mapping with real-world parameters

We developed an iPad application to connect to vehicle’s information bus (On-board diagnostic port) and collect vital parameters like velocity, acceleration and elevation.

To establish connection with the automobile we connect PCAN USB cable to car’s OBD port (see Figure 5.1) and other end is connected to gateway. A program running on the gateway sniffs the CAN (Controller Area Network) bus for particular CAN ids corresponding to velocity. Using the GPS module interfaced with gateway, we collect elevation and acceleration information and store it in gateway in a database.

Figure 5.1: *PCAN USB connected to the OBD port*

Our iPad application (see Figure 5.2) connects to the gateway using web-sockets through ad hoc Wi-Fi network hosted by gateway. The server running on the gateway serves the application with parameters from the vehicle.

This information is then available on the iPad and is displayed in playback mode. Furthermore, we interfaced this application with Protodrive so that we can use these parameters for simulation purposes and validate our scheduling schemes on real-world drive cycles.

Figure 5.2: *iPad data capture tool for real vehicle drive cycles*

5.3 Game simulator: Generating drive cycles

TORCS (The Open Race Car Simulator, see Figure 5.3) is an open source 3D car-racing simulator capable of running on various platforms. TORCS provides configuration setting to define customizable tracks. In order to simulate a real-time drive environment, we tweaked the source code and added hooks that provide velocity with timestamp at an interval of 2 milliseconds. These values acts as an input to the MATLAB program in order to simulate a Protodrive drive cycle. We run TORCS on a Linux machine, which runs the MATLAB code and also hosts the server for the web application.

Figure 5.3: *A screenshot from TORCS*

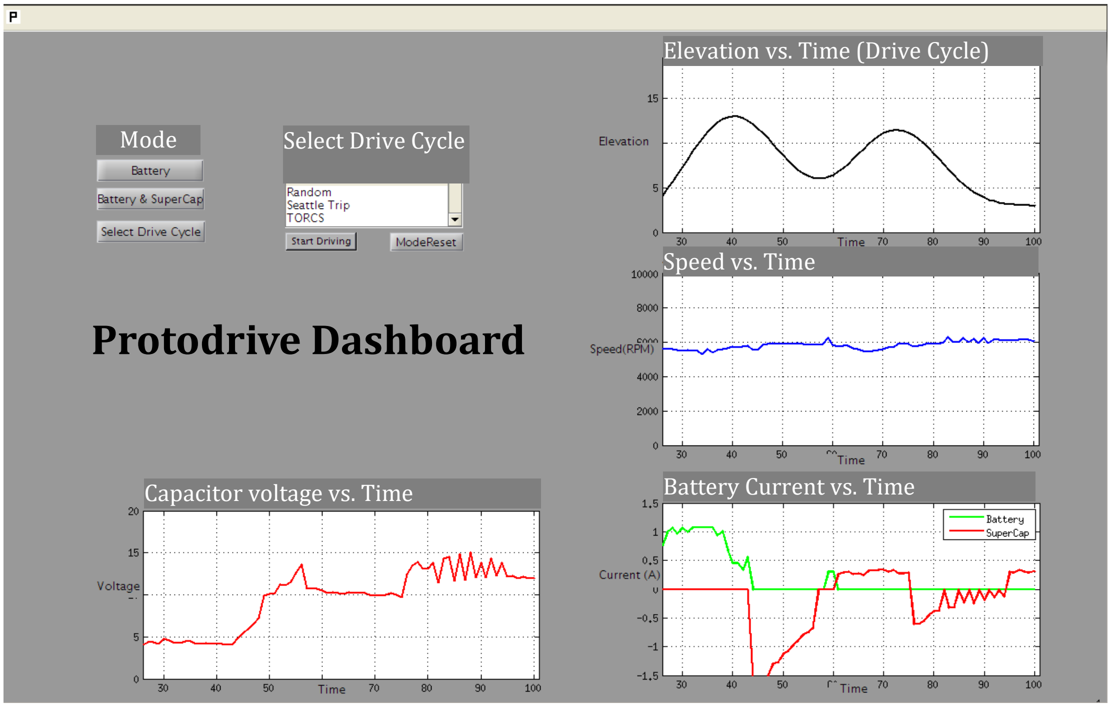


Figure 5.4: *Protodrive dashboard showing runtime performance*

To summarize, Figure 4.7 shows the interconnection of the various components driving Protodrive. The inputs from various sources to Protodrive are as follows:

Web application – Gives us predefined drive cycles and predefined modes (Battery only or Battery-Super capacitor). It also has the capability to generate drive cycle/elevation information using Google maps.

iPad application – Using this we can get the data such as elevation, velocity and acceleration of a real vehicle when it travels from point 'A' to point 'B'.

Game simulator (TORCS) – We can get real time velocity and acceleration profile using this gaming simulator and provide the input to Protodrive.

The inputs are provided to the host system running the computation code using web sockets. The host system, which has MATLAB running on it then sends the data over serial to Protodrive which in turn runs the selected scheduling algorithm and computes and sends the power profiles and the state of charge of the various energy sources (Battery & Super capacitor) to the web front-end in real time.

Chapter 6

Results

Platform evaluation and testing its efficiency for simulating the powertrain and the hybrid energy storage system was done by running multiple simulations on the Protodrive system. The hardware performance was evaluated by considering the following factors.

- **Response to multiple drive cycles**: Protodrive allows us to evaluate different drive cycles with varying velocity and elevation profiles. This allows us to get one step closer to real world scenarios, but with the accuracy of a software simulation.
- **Ability to mimic real world driving trends**: In a real EV, acceleration or going uphill put an additional load demand on the motor (and the battery). Impact of elevation on a static platform like Protodrive needs the motor control of both the drive and load motor to be precise. With Protodrive, we can mimic real world loads on the motor and energy system with reasonable accuracy.
- **Quirks of an actual system and component level sensitivity**: Computer modeling and simulation can rarely account for the real world behavior of a system, e.g. the noticeably non-linear behavior of a super capacitor when it is

charged from a 0 initial State of Charge leads to a current spike. With Protodrive, we can, not only evaluate different architectures, but also the effect of individual components.

- **Ability to map different vehicles onto the same platform**: The MATLAB code which converts drive cycles to power demands is flexible enough to allow us to change vehicle parameters corresponding to different vehicle models, e.g. a truck will have more mass and more maximum torque than a Chevy Volt. The test-bed allows us to model these different vehicle models and simulate them using the same hardware, but with different parameters driving the MATLAB control code.

Software is another key component of the system. Code was written in C and embedded C for low-level control of drive-load motor system. MATLAB code provided the high-level control for the drive cycle selection and the calculations for voltage demands based on the force balance equation are also performed in MATLAB. The web application front end was developed in Java and HTML. All these different software components interact in to provide an accurate and real-time response to a drive cycle. In addition, we also modified The Open Racing Car Simulator (TORCS) to interface with MATLAB and allow us to generate our own drive cycles on the fly. This Hardware-in-loop simulation gives us another degree of flexibility in our testing. With this system in place, we can go to the next level of evaluating control schemes for the hybrid energy storage system. Considering the following factors can do the evaluation of a scheme:

- **Information required**: Drive cycle information is in the form of real-time knowledge of velocity of the vehicle, acceleration and path elevation. This is the minimum amount of information that is available. Some schemes require knowledge of the power demand (dependent on the three parameters above) for either the entire drive cycle or a time window in the future. Evaluation of such schemes is left for future work because of the unrealistic nature of this knowledge being available (that too perfectly).

- **Current squared demand (on the battery)**: As explained earlier, battery heating is proportional to the current squared demand. Schemes should ideally reduce this quantity (on the battery) by using the super capacitor.
- **Computational tractability**: Schemes must be computationally light enough to be implemented on embedded controllers and provide real-time control to the rapidly changing power demand of the motor. Schemes like Model Predictive Control, which finds popular use in industrial control, are ill suited to the fast dynamics of an EV.
- **Battery final SoC**: Any scheme, which uses the battery to charge the capacitor must ensure that the battery's final SoC is not lower than it, would have been for a battery only system (for the same trip). The capacitor as buffer scheme is one, which can possibly attain this without much formal proof (as the battery never supplies power to the capacitor).

By running a simulation on the platform using the battery-super capacitor HESS (configuring the super capacitor as a buffer), we get a current profile as shown in Figure 6.1.

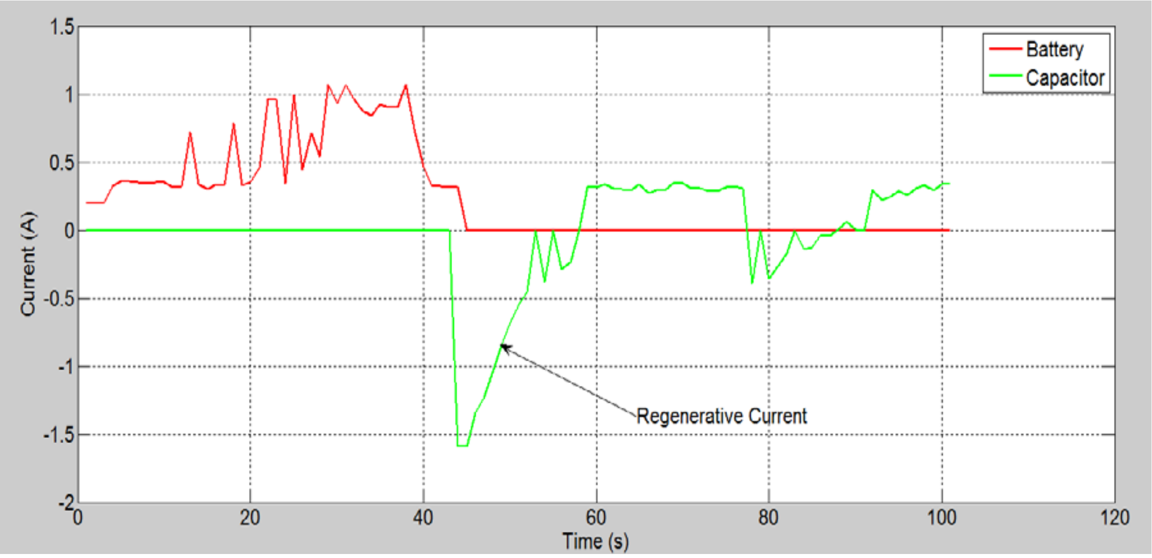


Figure 6.1: *Current profiles from Protodrive*

Note how the capacitor charges with regenerative current and then supplies power to the load. The Table 6.1 shows the effect of super capacitor in the system:

Table 6.1: *Percent reduction in current square*

Scheme	**Current squared (battery)**	**Reduction (%)**
Battery only	32.0203	-
Battery-super capacitor (buffer)	24.5808	23.23

The significant improvement obtained (the reduced current squared demand in the battery) by using the super capacitor shows the potential benefits of this HESS.

Another focus of the Protodrive project has been on development of schemes for control of HESS to maximize battery lifetime. The focus on development of schemes has been independent of platform limitations as well as limitations on knowledge available.

The Figure 6.2 shows the normalized current demand for the first 3 minutes of the Urban Dynamometer Driving Schedule (UDDS) drive cycle (sampling rate of 10Hz).

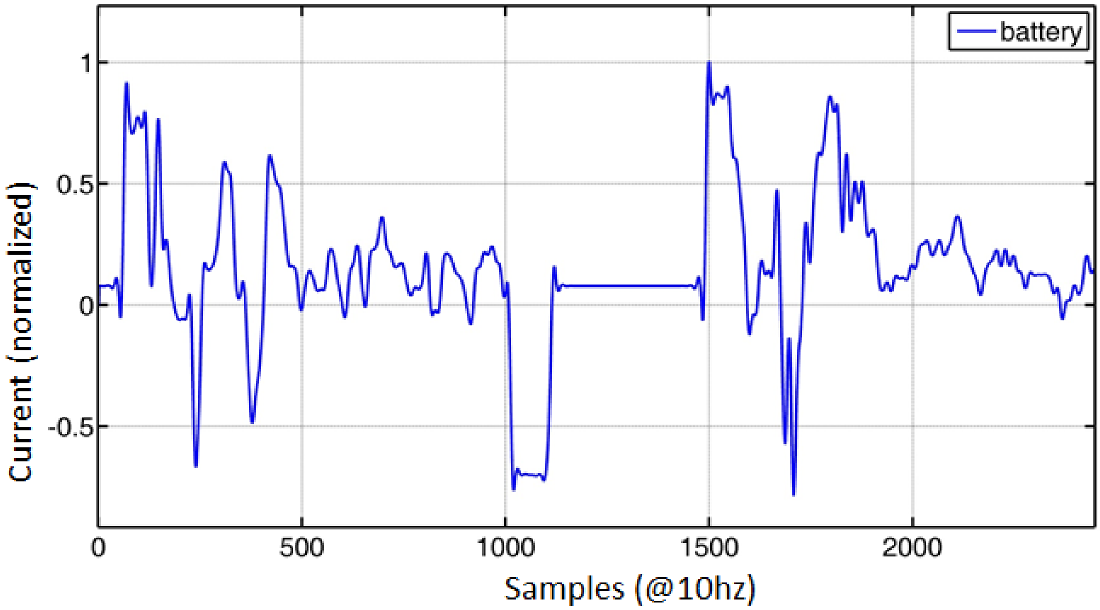


Figure 6.2: *The current demand for the first 3 minutes of the UDDS drive cycle*

Using the capacitor as a buffer shows that the capacitor does reduce load demand on the battery, but not necessarily reduce the peaks (see Figure 6.3).

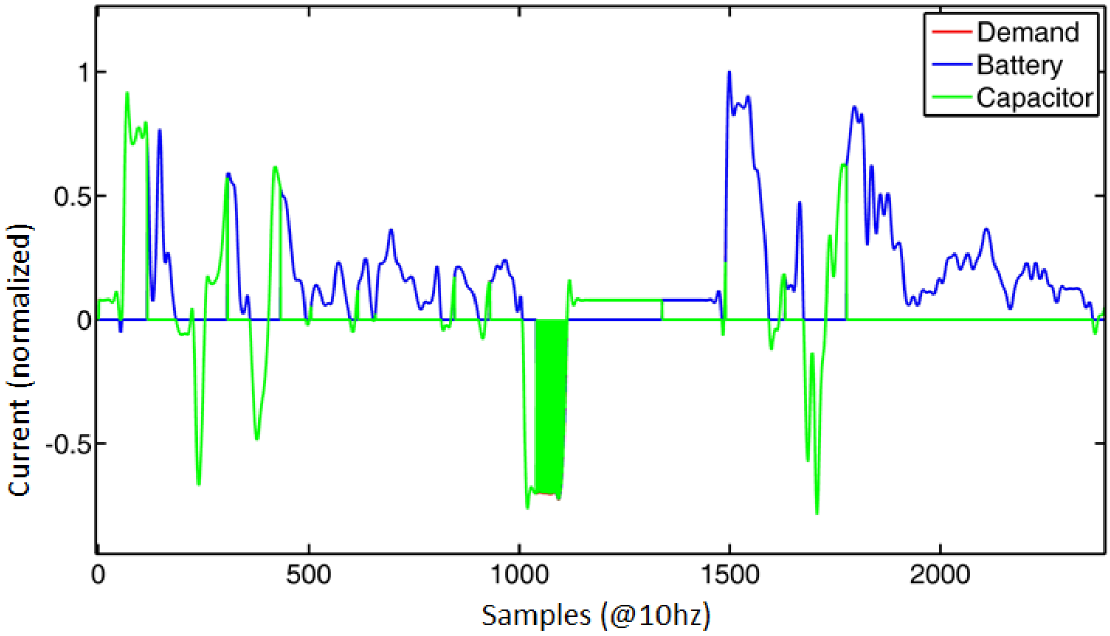


Figure 6.3: *First 3 minutes of the UDDS drive cycle, with the super capacitor as buffer*

Optimal control (with perfect knowledge of future load demands) shows the best possible use of the battery-super capacitor system (see Figure 6.4).

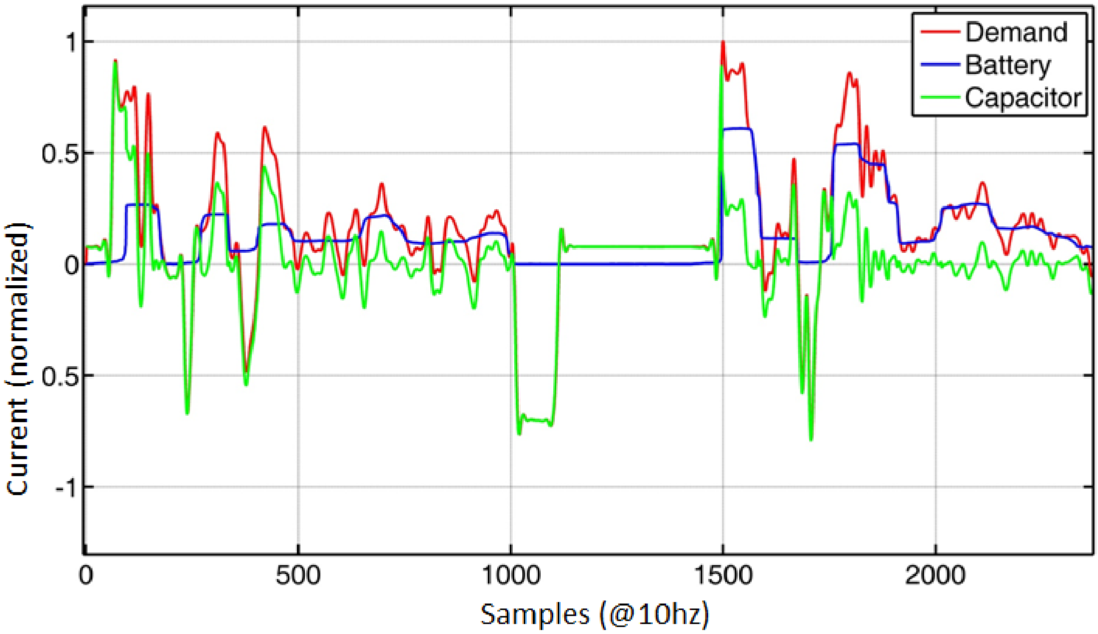


Figure 6.4: *Finite horizon control of the battery-super capacitor system (first 3 minutes of the UDDS drive cycle)*

It is worth noting that the battery profile is much smoother than the previous cases, and peak demands are also reduced. This shows there is much scope of improving battery lifetime by using smart schemes, which can judiciously use the super capacitor.

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