MOBILITY OF THE FUTURE: HYBRID AND ELECTRIC VEHICLES

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McMaster Automotive Resource Center (MARC), ON Canada
SPEAKER BACKGROUND

Education

• Masters of Business Administration (MBA) Candidate (2015-2017)
  DeGroote School of Business, ON Canada

• Ph.D. in Mechanical/Mechatronics Engineering (2014)
  McMaster University, ON Canada – Battery Management and Control

• M.A.Sc. in Mechanical Engineering (2011)
  McMaster University, ON Canada – Engine Management and Fault Detection

• B.Sc. in Mechatronics Engineering (2007)
  Ain Shams University – Mechatronics Engineering

Work Experience

• Adjunct Professor, McMaster University, ON Canada (2016 – present)

• Senior Systems Engineering Lead, Samsung SDI America, USA (2015 – 2016)

• Senior Technical Specialist, Fiat Chrysler Automobiles (FCA), ON Canada (2014 – 2015)

• R&D engineer, Ford Powertrain R&D Center, ON Canada (2011 – 2014)

• Teacher Assistant, Ain Shams University (2007 – 2009)
AGENDA

• Why Electric Vehicles?
• Paradigm shift in transportation
• Hybrid Vehicles Configurations
• Mechatronics Engineering in the Automotive Industry
• Case Study: Battery Management Systems (BMS)
  o Battery Modeling
  o Battery Aging
  o State of Charge Estimation
  o State of Health Estimation
• Alternative Technologies
WHY ELECTRIC VEHICLES?

HYBRID ELECTRIC VEHICLES ~ 50-60%

Well-to-Tank

~ 30%
~ 80%
~ 83%
~ 20%
~ 17%

Tank to Wheel

~ 24%

Sustainability

Well-to-Wheel Efficiency

Energy Recovering

Environmental Impact


Ain Shams - 24/12/2016

Research Seminar: Mobility of the Future
Not sustainable – Transportation 1.0

- ICE
  - Not efficient – Efficiency of approximately 20%

- More Electric Vehicles
  - Electrification less than 20% – Non-propulsion Electric components
  - Electrically assisted power steering, electrically driven air-conditioning, electromechanical valve control

- Hybrid Electric Vehicles
  - Micro hybrids, mild hybrids, power (full) hybrids, and energy hybrids
  - Hybridization factor is ratio between its peak electrical power and peak total electrical and mechanical power

Sustainable – Transportation 2.0

- More Efficient, cleaner, greener

- Plug-In Electric Vehicles
  - Dual fuel vehicles – Most Promising

- All Electric Vehicles
  - Electrification level 100% – Ultimate form
PARADIGM SHIFT IN TRANSPORTATION

- HEVs market will form 8% of the global passenger vehicle segment by **2020**
- PHEVs will become one of the main forms of transportation in Canada and across the globe by **2030**
- In five years, advanced electric-drive vehicles will exceed 15% of the global new vehicle market
- This means production of at least **7.5 million units per year**
HEVs POWERTRAIN CONFIGURATIONS: SERIES HYBRID EV

- Engine is **mechanically decoupled** from the wheels
- Power is delivered by the electric motor while the engine drives an electric generator
- Generator charges the batteries which drives the electric motor
HEVs POWERTRAIN CONFIGURATIONS: PARALLEL HYBRID EV

- The engine and electric motor are coupled to drive the vehicle

**PLUG-IN HYBRID – PARALLEL CONFIGURATION**
HEVs POWERTRAIN CONFIGURATIONS: BATTERY ELECTRIC VEHICLES (BEV)

- No engine exists, pure electrified vehicles
MECHATRONICS ENGINEERING: AUTOMOTIVE INDUSTRY

- Electrical Engineer
- Chemical Engineer
- Mechanical Engineer
- Software Engineer
- Validation Engineer
- Hardware Engineer
MECHATRONICS ENGINEERING: JOB MARKET IN U.S.

Salary Range: 65K-110K USD

# Openings: 168,984
MECHATRONICS ENGINEERING: INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE)

http://www.incose.org/
V PROCESS MODEL:

- Represents a structured process for guiding project development from its conception through design, implementation, operations.
- This approach increases the probability of producing a successful outcome and minimizes the project budget and schedule.
CASE STUDY: BATTERY MANAGEMENT SYSTEM
Battery cell:
• Smallest packaged form of a battery
• Voltage ranges from 1 - 6V

Module
• Modules are formed by connecting cells in series and parallel configurations
• Cells are contained in metal case to protect them

Pack
• Assembled by connecting a group of battery modules together in series or parallel

http://blog.cafefoundation.org/less-expensive-batteries-may-lead-to-more-homebuilt-electric-airplanes/
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE
NISSAN LEAF BATTERY PACK

Cell

- Cells should provide **long life span, strong heat dissipation** and **high energy density**
- Lithium Manganese Oxide cells

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Laminate Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Active Material</td>
<td>LMO with LNO</td>
</tr>
<tr>
<td>Anode Active Material</td>
<td>Graphite</td>
</tr>
<tr>
<td>Rated Capacity (0.3C)</td>
<td>32.5 Ah</td>
</tr>
</tbody>
</table>

- Example of discharge profiles (25°C, BOL)

Module

- The EV modules adopted in the Nissan Leaf and other vehicles feature a **2-series, 2-parallel** formation.
- The case functions are used to **protect the cells from vibration**.
- It improves the **pack design flexibility** because of its **simple and compact** shape.

<table>
<thead>
<tr>
<th>Number of Cells</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>2 parallel, 2 series</td>
</tr>
<tr>
<td>Exterior Dimensions</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>303 mm</td>
</tr>
<tr>
<td>Width</td>
<td>223 mm</td>
</tr>
<tr>
<td>Height</td>
<td>35 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>3.8 kg</td>
</tr>
</tbody>
</table>

Pack

• The pack is formed by installing a battery management system, sensors, and housing
• For Nissan Leaf, battery pack is formed by connecting 48 modules in series with 360V, capacity of 24kWh
• The pack can be designed with a shape suitable to be installed under the vehicle floor

<table>
<thead>
<tr>
<th>Number of Modules</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>360V</td>
</tr>
<tr>
<td>Capacity</td>
<td>24kWh</td>
</tr>
</tbody>
</table>
- **Voltage, current** and **temperature** are monitored by sensors from each module.
- Data is sent from the battery controller (**BMS**) to the **vehicle control unit** via **CAN**.
- During maintenance, the circuit is interrupted by operating the **SDSW (Service Disconnect Switch)**.
A Battery Management System (BMS) is employed to actively monitor and protect the cells in real-time.

The BMS accurately monitor cell voltage, current, temperatures, impedance and other variables of the cells.

The BMS performs several functions:
- Cell Monitoring
- Supervising Battery Pack Behavior
- Cell Balancing
- Fuel Gauging (SOC Estimation)

CASE STUDY/BATTERY MANAGEMENT SYSTEM: CELL SUPERVISORY CIRCUIT (CSC)

- The BMS consists of the ECU (micro-controller) or the brain along with the CSC (Cell Supervisory circuit) (Cell Module)
- The CSC is attached to each module to measure individual cell voltages.
- The CSC has balancing resistors used to dissipate current into them to maintain all cells at the same state of charge.
- The CSC measurements are sent to the ECU (brain) for decision making.

http://ams.com/eng/Products/Battery-Management/Cell-Supervision-Circuits
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS

- Prevent over/undercharge
- Short circuits
- Temp. limits

- Communication
- Data recording/reporting

- State of health
- Remaining useful life

- SOC estimation
- Power limits
- Cell balancing

Safety/ Protection

Interfacing

Diagnostics

Performance Monitoring/ Management

V,I,T monitoring
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS:
BATTERY STATE OF CHARGE (%) ESTIMATION

• Equivalent to fuel gauge in conventional vehicles
• Represents battery current capacity as a percentage of maximum capacity
• SOC is calculated using coulomb counting/current integration

“However, while there exist sensors to accurately measure a gasoline level in a tank, there is no sensor available to measure SOC. Instead, SOC must be estimated from physical measurements by some algorithm.”
Battery Life Time

Fresh Battery
Life Fraction (LF) = 0
Model 1
Capacity = 100%

Midlife Battery
LF = 0.5
Model 2
Capacity = 90%

Aged Battery
LF = 1
Model 3
Capacity = 80%

• Battery SOC and SOH?

• EVs are Relatively new, some time is required to assess the estimators in real-world operating conditions
After many charging/discharging cycles, cells may become *out of balance*

Cells vary due to **manufacturing differences**, **columbic efficiencies**, and **capacities**

Cells may limit the **discharge ability** of the pack if their SOC is much lower than remaining cells
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY STATE OF CHARGE (%) ESTIMATION

High Fidelity Model + Estimation Strategy = SOC SOH

Input Current

Output Voltage

State of Charge

Input Current

Output Voltage

SOC/SOH

Error ~ 0

SOC [%]

Voltage [V]

Time [s]

Current [A]

Time [min]


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Research Seminar: Mobility of the Future

SLIDE 26
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING

**Battery Models Overview**

- **Lumped-parameters models**
  - Empirical models
  - Account for hysteresis, polarization $T_s$, ohmic loss
  - No/minimal physical significance/SOH

- **Equivalent circuit models**
  - Simple, less parameters to tune
  - Easy implementation/Computationally efficient
  - No/minimal physical significance/SOH

- **Electrochemical models**
  - Model lithium diffusion
  - Physical insight of battery SOH
  - Large number of parameters
  - Hard to obtain these parameters
  - Computationally expensive (reduced form)
CASE STUDY/BATTERY MANAGEMENT SYSTEM: EXPERIMENTAL SETUP

- Mount temperature sensors on each cell
- Chambers: thermally stress cells (-20 to 70°C)
- Independent parallel channels (Ex: 400 A, 20V)
- Software
- Test Procedure

CASE STUDY/BATTERY MANAGEMENT SYSTEM: VELOCITY PROFILE TO CYCLER

- Generate Velocity Profile to Cycler?
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- Aging Model Development: Aging Study

- Real-World Driving Scenario (Aging Test)
- Static Capacity Test
- SOC-OCV C/25
- Pulse Charge/Discharge
- Repeat Every 5% Capacity Degradation
- Resistance Test
- Driving Cycles: UDDS, HWFET, US06
- Hybrid Pulse Power (HPPC) Test

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- Aging Model Development: Real-World Driving Aging Test

Velocity Profile for One Week Day With Errands
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- Aging Model Development: Experimental Data Sample

Experiments Running on 24/7 basis for ~ 13 months
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING

ELECTROCHEMICAL BATTERY MODEL

• Solid and electrolyte potentials
\[
\frac{\partial}{\partial x} k^{\text{eff}} \frac{\partial}{\partial x} \varphi_e + \frac{\partial}{\partial x} k^{\text{eff}} \frac{\partial}{\partial x} \ln c_e = -j_{Li} \]
\[
\frac{\partial}{\partial x} \sigma^{\text{eff}} \frac{\partial}{\partial x} \varphi_e = j_{Li}
\]

• Linear lithium diffusion in electrolyte:
\[
\frac{\partial}{\partial t} \varepsilon_e c_e = \frac{\partial}{\partial x} \left( D_e^{\text{eff}} \frac{\partial c_e}{\partial x} \right) + \frac{1 - t^0}{F} j_{Li}
\]

• Spherical solid diffusion:
\[
\frac{\partial}{\partial t} \frac{\partial c_s}{\partial r} = \frac{\partial}{\partial r} \left( D_s \frac{\partial c_s}{\partial r} \right)
\]

• Terminal Voltage Calculation
\[
J_{Li} = a_{s} j_0 \left[ \exp \left( \frac{\alpha_{a}}{R T} \eta \right) - \exp \left( \frac{\alpha_{c}}{R T} \eta \right) \right]
\]
\[
\eta = \phi_s - \phi_e - U(c_{se})
\]
\[
V = \phi_s(x = L) - \phi_s(x = 0) - R_f l
\]

Model Assumptions:
• No aging or capacity fade has been accounted for
• Model parameters assumed to be held constant
• Significant errors at high C-rates (rate capacity/recovery effect)
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING
ELECTROCHEMICAL BATTERY MODEL

• SOC Module: Reduced-Order Electrochemical Model

\[
c_{s,pugen} = \frac{c_r}{V} = \frac{\text{total lithium concentration}}{\text{particle volume}} = \frac{\sum_{i=1}^{M_t-1} r_i^2 4\pi \Delta r c_i}{4 \pi (R_s - \Delta r)^3}
\]

\[
SOC = 100 \left( \frac{c_{s,pugen}}{c_{s,max,p} - \theta_{p0\%}} \right)
\]

• Terminal Voltage Module

\[
\bar{c}_{se,n} = c_{s,max,n} \left( \theta_{n0\%} + \left( \bar{c}_{se,p} - \theta_{p0\%} c_{s,max,p} (\theta_{n100\%} - \theta_{n0\%}) \right) \right)
\]

\[
\eta_p = \phi_{s,p} - \phi_{e,p} - U_p(c_{se,p})
\]

\[
\eta_n = \phi_{s,n} - \phi_{e,n} - U_n(c_{se,n})
\]

\[
V(t) = (\bar{\eta}_p - \bar{\eta}_n) + (\bar{\phi}_{e,p} - \bar{\phi}_{e,n}) + (U_p(c_{se,p}) - U_n(c_{se,n})) - R_f I
\]

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING
ELECTROCHEMICAL BATTERY MODEL

- Model Parameters Fitting
  - Actual SOC (Arbin Cycler) vs. Model SOC for UDDS Cycle
  - Model Terminal voltage vs. Measured voltage

\[ V_T \text{ RMSE (UDDS)} = 0.22 \text{ mV} \]

\[ \text{SOC RMSE (UDDS)} = 0.0547 \% \]
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SOC ESTIMATION

\[ \eta_j = a_{ij} \left[ \exp \left( \frac{\alpha_a F}{RT} \right) - \exp \left( \frac{\alpha_c F}{RT} \eta \right) \right] \]

Model States Update

\[ K_{k+1} = \text{diag} \left( \left[ \frac{e_{z_{k+1} | k}}{\sqrt{\Psi}} \right] \left( e_{z_{k+1} | k} \right)^{-1} \right) \]

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SOC ESTIMATION

```matlab
for k = 1 : 1 : ik
	%% Plotting Data
	SOCEstimated = [SOCEstimated; X(k)];
	hold on
	plot(Time, SOCEstimated);
	hold off
	hold on
	plot(Time, SOC);
	hold off
	hold on
	plot(Time, SOCEstimated);
	hold off
	hold on
	plot(Time, SOCActual);
	hold off
	hold on
	plot(Time, TerminalVoltage);
	hold off
	hold on
	plot(Time, TerminalVoltageEstimated);
	hold off
end

%% Calculate Required Parameters.
SOC = X(1);
T = [R_plus; R_minus; K0; K1; K2; K3; K4];
CoffB3 = -(eta * DeltaT / Cn);

%% Linearize Model For Kalman Use.
[C_x] = CombineBModel_ComplexDiff(X, T, Current(k), 1);

%% Run Updated Model
U = Current(k);
if Current(k) >= 0
	TerminalVoltage = K0
	- (R_plus * Current(k))
	- R1/SOC
	- R2*SOC
	+ K3*log(SOC)
	+ K4*log(1-SOC);
else
	TerminalVoltage = K0
	- (R_plus * Current(k))
	- R1/SOC
	- R2*SOC
	+ K3*log(SOC)
	+ K4*log(1-SOC);
end

%% Calculate Error in States.
Error_X = TerminalVoltageActual(k) - TerminalVoltage;

%% Time Update for the state filter.
A = 1; B = CoffB3;
X = (A * X) + (B * U);
P_X = (A * P_X * A') + Q_X;

%% Measurement Update for the state filter.
KalmanGain_X = (P_X) * (C_X') * inv((C_X * P_X * C_X') + (R_X));
X = X + (KalmanGain_X * Error_X);
P_X = (eye(n_X, n_X) - (KalmanGain_X * C_X)) * P_X;

%% Plotting Data
TerminalVoltageEstimated = [TerminalVoltageEstimated; TerminalVoltage];
```
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY STATE OF HEALT LH ESTIMATION

- Battery models change over the vehicle lifetime
- Estimators are used to predict the battery state of health

Battery Model

High Fidelity Model + Estimation Strategy = SOC SOH

Healthy Vs. Aged SOC - Driving Schedule A1

Battery SOC - Fresh [Capacity = 100%]
Battery SOC - Aged [Capacity = 80%]

Healthy Vs. Aged Terminal Voltage - Driving Schedule A1

Terminal Voltage - Fresh [Capacity = 100%]
Terminal Voltage - Aged [Capacity = 80%]

Input Current

Output Voltage

Error ~ 0

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- **Aging Model Development: Do we need model update?**
  - Actual SOC from Aged Battery vs. Model SOC
  - RMSE variations for healthy and aged batteries
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

• Aging Model Development
  • Model increase in the electrode resistance to accept $Li^+$
  • Track changes in $R_{SEI}$, $D_s$, $OCV - SOC$
  • Introducing: electrode aging factor ($\tau$), electrode effective volume
OTHER TECHNOLOGIES: RAGONE PLOT

- The Ragone plot compares the performance of various electrochemical devices.
- **Ultra capacitors provide a high power density** but their storage capacity is very limited, thus making them suitable for capturing **regenerative braking energy** in EV applications.
- **Fuel Cells have very high energy density but low power** density, limiting their application in EV applications.
- Lithium batteries are in between, therefore providing a compromise between the two.
- A combination of more than one device can be beneficial.
OTHER TECHNOLOGIES: ULTRA CAPACITORS

- A supercapacitor (ultracapacitor) is a high-capacity electrochemical capacitor with capacitance values much higher than other capacitors.

- Supercapacitors bridge the gap between electrolytic capacitors and rechargeable batteries.

- They are capable of storing 10 - 100 times more energy per unit volume or mass than electrolytic capacitors.

- They have very high power capability, i.e.: can accept and deliver charge much faster than batteries.

- They have a high cycle life, can withstand a greater number of charge and discharge cycles than rechargeable batteries.

- However, they have low energy density, they require 10 times more space than conventional batteries for a given charge.

- Supercapacitors are used in regenerative braking, i.e.: applications with many rapid charge/discharge cycles.

“Supercaps can charge in seconds, without capacity degradation like rechargeable batteries. They can endure virtually unlimited charge cycles”

http://www.mouser.com/applications/supercapacitors-hero-automotive/

https://en.wikipedia.org/wiki/Supercapacitor
OTHER TECHNOLOGIES: FUEL CELLS

• A fuel cell converts chemical energy from a fuel into electricity on the fly.

• Fuel cells are different from batteries in requiring a continuous source of fuel and oxygen (or air) to sustain the chemical reaction.

• Check this out: https://www.youtube.com/watch?v=08ZH7vwzzEg


CASE STUDY/BATTERY MANAGEMENT SYSTEM: RESEARCH AREAS

- **Smart embedded controllers**
  - Artificial Neural Networks
  - Optimal HEV controls

- **Energy storage systems**
  - Management and control
  - Thermal management/packaging
  - Modeling, SOC, SOH estimation, and aging

- **Hybrid battery/Supercap.**
  - Modeling
  - State prediction
  - Packaging and integration

- **Fault detection**
  - State estimation
  - Fault prediction and RUL prediction
THANKS, QUESTIONS?

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