A Hardware In the Loop Simulation System for Fuel Cell Vehicle Control

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Erik J. Wilhelm
Dr. M. Fowler
Alternative Fuels Team

- UWAFT formed in 1996
  - Propane Vehicle Challenge
  - Ethanol Vehicle Challenge
  - Tour de Sol
  - Challenge X

- ~140 members
  - Primarily engineering students
  - ~30 core members
  - 6 graduate students
# Fuel Cell Hybrid Powertrain

<table>
<thead>
<tr>
<th>Device</th>
<th>Make/Model</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Stack</td>
<td>Hydrogenics/HYP</td>
<td>Max Power: 65kW</td>
</tr>
<tr>
<td></td>
<td>M 65kW</td>
<td>Voltage Range: 190-300V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current Range: 0-300A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass: 415kg</td>
</tr>
<tr>
<td>Hydrogen Storage</td>
<td>Dynetek/ZM180*</td>
<td>Max Pressure: 5000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tank Capacity: 4.31kg H2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tank Weight: 92kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tank Volume: 178L</td>
</tr>
<tr>
<td>DC/DC Converter Design and</td>
<td>Custom UWAFT</td>
<td>Input Voltage Range: 190-310V</td>
</tr>
<tr>
<td>Construction</td>
<td>Converter Type:</td>
<td>Output Voltage Range: 300-385V</td>
</tr>
<tr>
<td></td>
<td>Mass: 30 kg</td>
<td>Boost</td>
</tr>
<tr>
<td>Motors (2 units)</td>
<td>Ballard/312V67</td>
<td>Peak Power: 67kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous Power: 32kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max Torque: 190Nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass: 84kg</td>
</tr>
<tr>
<td>Motor Controller (2 units)</td>
<td>Ballard/312V67</td>
<td>Continuous Power: 67kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Input Voltage: 260-385V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Output Current: 280A RMS</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>Cobasys/NiMHax2</td>
<td>Voltage Range: 220-360V</td>
</tr>
<tr>
<td></td>
<td>88-60</td>
<td>Capacity: 8.5Ah</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Energy: 2.4kWh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass: 88kg</td>
</tr>
</tbody>
</table>
Integration Overview
Control Development V-cycle

- Off-line Controller Modeling (SIL)
- Rapid Controller Prototyping
- Controls Designers (OEM)
- Code Generation (3rd party)
- Target Controller Development
- Vehicle Testing
- HIL Testing
- CIL Testing

Target Controller Development

5
Mototron Control Development

- Off-line Controller Modeling (SIL)
- Rapid Controller Prototyping
- HIL Testing
- Vehicle Testing
- CIL Testing

Controls Designers (OEM)

MotoHawk™ Auto Code Generation
Software In the Loop

- SIL implementation:

Vehicle model → Virtual → Vehicle control algorithms
Hardware In the Loop

- HIL implementation:

  - Vehicle model on real-time processor
  - Actual vehicle wiring harness
  - Actual vehicle controller

  Virtual  →  Real-world
Vehicle Testing

The InuksH₂uk
SIL Model
Validation of model predicted bus voltages versus vehicle acceleration data
SIL Regen Fault

Regenerative braking control strategy not functioning as intended
Regenerative braking control strategy functioning as intended
HIL Methodology

Vehicle Controllers
- Supervisory Controller MPC-565 128
- Secondary Controller MPC-555 80

Real-time Controller PXI-8187
- Plant Model
  - Vehicle
  - FCPM
  - Battery
  - Motors

Machine-time Controller Toshiba Satellite A40
- User interface
- Data logging

Connections:
- Analog/Digital Out signals
- Analog/Digital In signals
- CAN 1, CAN 2
- Visual Data Stream
- Data
HIL Test Stand
HIL Goals

Communication Bus Testing
- I/O Lag
- CAN performance
- Signal Robustness

Hybrid Control Development
- Power module control optimization
- Hybrid control strategy tuning

Safety System Validation
- Failure memory
- Failure insertion
- OBD
- Emergency simulation
- Implausibility recognition
- Redundancy

Dynamic Control Development
- Anti-lock braking development
- Torque control strategy development

Non-Powertrain Control Development
- GUI development
- Start-time optimization
- Drive quality tuning
- Bluetooth interface
- DC/DC control

Phase 1
Phase 2a
Phase 2b
Phase 3
Phase 4
I/O Lag Test Block

Vehicle Controllers

- Supervisory Controller MPC-565 128
- Secondary Controller MPC-555 80
- AD
- LSD

Real-time Hardware PXI Chassis

- PXI-8187 RT Controller
- PXI-6289 AO
- PXI-6229 AI

Machine-time Controller

- Toshiba Satellite A40

Connections:
- 13.8V
- 5.0V

Test Block 23
Rising: 15ms
Falling: 17ms

Lag causes:
- Line inductance from oversized pulldown
- Relay actuation time
- Code execution (Processor overhead and signal discretization)
HIL Results - Charge Depleting Strategy

![Graph showing battery state of charge over time](image-url)
Voltage Spikes Revealed in HIL
Vehicle Testing

The InuksH₂uk
Acknowledgments

Supervisors
Dr. M.W. Fowler, Dr. R.A. Fraser

UWAFT

Michael Whalstrom, Alain Boutros, Matthew Stevens, Christopher Lawrence, Sam Arsenault, Christopher Haliburton, Marty Long, Daniel Sellan, Vishal Singh, Thomas Geraghty, Joshua Bruce, James Goh, Will Williams, Greg Dong, Ryan Huizing, Adrian Kwan, Ramandeep Virk, Ian Tam, Brian Vandenboomen, Kuo-Feng Tong, Jennifer Bauman, Christopher Mendes, Josh Aziz, Curtis Knischewsky, Hinkel Yeung, Zarrar Ali, Devin Cass, Christin Strong, Charles Hua, Tim Horton, and many more...

Platinum Sponsors
Thank you

Questions?
Safety System: OBD

### Information From FCPM

<table>
<thead>
<tr>
<th>Message ID</th>
<th>Data Length</th>
<th>Data0 (8bit)</th>
<th>Data1 (56bit)</th>
<th>Period</th>
<th>Date Upon Entering Fault State</th>
</tr>
</thead>
<tbody>
<tr>
<td>647</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

#### State

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>BCU Bootup</td>
</tr>
<tr>
<td>1</td>
<td>Start</td>
</tr>
<tr>
<td>2</td>
<td>Standby</td>
</tr>
<tr>
<td>3</td>
<td>Wait OLV</td>
</tr>
<tr>
<td>4</td>
<td>Wait Output Precharge</td>
</tr>
<tr>
<td>5</td>
<td>Run Mode - Closed Loop</td>
</tr>
<tr>
<td>6</td>
<td>Run Mode - Hard Recovery</td>
</tr>
<tr>
<td>7</td>
<td>Cool Down</td>
</tr>
<tr>
<td>8</td>
<td>Fault State</td>
</tr>
<tr>
<td>9</td>
<td>Blower Startup</td>
</tr>
<tr>
<td>10</td>
<td>FCPM cathode purge</td>
</tr>
<tr>
<td>11</td>
<td>Run Mode - Open Loop</td>
</tr>
<tr>
<td>12</td>
<td>Run Mode - Soft Recovery</td>
</tr>
<tr>
<td>13</td>
<td>Anode Purge</td>
</tr>
</tbody>
</table>

#### Faults

<table>
<thead>
<tr>
<th>Fault</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Stack Undervoltage</td>
</tr>
<tr>
<td>1</td>
<td>Coolant Overtemp</td>
</tr>
<tr>
<td>2</td>
<td>OLV overpressure</td>
</tr>
<tr>
<td>3</td>
<td>(N/A) Stack Isolation fault</td>
</tr>
<tr>
<td>4</td>
<td>(N/A) Output precharge fail</td>
</tr>
<tr>
<td>5</td>
<td>(N/A) Hydrogen leak</td>
</tr>
<tr>
<td>6</td>
<td>Cathode Saturation low speed fault</td>
</tr>
<tr>
<td>7</td>
<td>External System E-stop</td>
</tr>
<tr>
<td>8</td>
<td>FIT Sensor Out of range</td>
</tr>
<tr>
<td>9</td>
<td>Current Sensor Out of range</td>
</tr>
<tr>
<td>10</td>
<td>Coolant Temp Sensor Out of range</td>
</tr>
<tr>
<td>11</td>
<td>(N/A) Coolant Pump relay fault</td>
</tr>
<tr>
<td>12</td>
<td>Reeve Pump relay fault</td>
</tr>
<tr>
<td>13</td>
<td>Blower Fault</td>
</tr>
<tr>
<td>14</td>
<td>OLV ShutOff Valve fault</td>
</tr>
<tr>
<td>15</td>
<td>OLV Purge Valve fault</td>
</tr>
<tr>
<td>16</td>
<td>Cathode Saturation motor fault</td>
</tr>
<tr>
<td>17</td>
<td>Water Separator Drain Valve fault</td>
</tr>
<tr>
<td>18</td>
<td>Pilot enable fault</td>
</tr>
<tr>
<td>19</td>
<td>(N/A) Coolant Pump relay over current</td>
</tr>
<tr>
<td>20</td>
<td>Reeve Pump relay over current</td>
</tr>
<tr>
<td>21</td>
<td>Blower Control signal short circuit</td>
</tr>
<tr>
<td>22</td>
<td>OLV ShutOff Valve over current</td>
</tr>
<tr>
<td>23</td>
<td>OLV Purge Valve over current</td>
</tr>
<tr>
<td>24</td>
<td>Cathode Saturation over current</td>
</tr>
<tr>
<td>25</td>
<td>Water Separator Drain valve over current</td>
</tr>
<tr>
<td>26</td>
<td>(N/A) Fuel Enable over current</td>
</tr>
<tr>
<td>27</td>
<td>(N/A) Ass Back relay fault</td>
</tr>
<tr>
<td>28</td>
<td>(N/A) Ass Rose relay short</td>
</tr>
<tr>
<td>29</td>
<td>OLV Low Supply Pressure</td>
</tr>
<tr>
<td>30</td>
<td>Blower Boost Enable Short</td>
</tr>
<tr>
<td>31</td>
<td>12V Buck Enable Short</td>
</tr>
<tr>
<td>32</td>
<td>Stack Over Current</td>
</tr>
<tr>
<td>33</td>
<td>Stack Coolant Flow Low</td>
</tr>
<tr>
<td>34</td>
<td>Hydrogen level switch Fault</td>
</tr>
</tbody>
</table>
ChallengeX-Factor

• Changes to the team structure:
  – Six 2006 Graduates, Two “Retirees”, and Eleven fresh recruits

• Coverage Areas:

<table>
<thead>
<tr>
<th>Summary</th>
<th>Business</th>
<th>Electrical</th>
<th>Mechanical</th>
<th>Controls</th>
<th>Fuel Cell</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max 1 year competency</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>=5</td>
</tr>
<tr>
<td>Max 2 year competency</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>=5</td>
</tr>
<tr>
<td>Max 3 year competency</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>=5</td>
</tr>
<tr>
<td>Max 4+ year competency</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>=5</td>
</tr>
<tr>
<td>Average 1 year competency</td>
<td>3.4</td>
<td>3.5</td>
<td>3.5</td>
<td>3.3</td>
<td>3.5</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Average 2 year competency</td>
<td>3.3</td>
<td>3.3</td>
<td>3.5</td>
<td>3.3</td>
<td>3.5</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Average 3 year competency</td>
<td>4.3</td>
<td>2.7</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
<td>&gt;3</td>
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<tr>
<td>Average 4+ year competency</td>
<td>3.9</td>
<td>2.1</td>
<td>3.7</td>
<td>3.3</td>
<td>2.5</td>
<td>&gt;3</td>
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</tbody>
</table>
Hybrid Control SIL Results

Load Following

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Mileage (mpge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Efficiency</td>
<td>47.0%</td>
<td></td>
</tr>
<tr>
<td>DC/DC Efficiency</td>
<td>90.4%</td>
<td></td>
</tr>
<tr>
<td>Battery Efficiency</td>
<td>97.0%</td>
<td></td>
</tr>
<tr>
<td>Mileage (mpge)</td>
<td>41.0</td>
<td></td>
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</tbody>
</table>

Cost Function

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Mileage (mpge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Efficiency</td>
<td>54.1%</td>
<td></td>
</tr>
<tr>
<td>DC/DC Efficiency</td>
<td>90.4%</td>
<td></td>
</tr>
<tr>
<td>Battery Efficiency</td>
<td>94.8%</td>
<td></td>
</tr>
<tr>
<td>Mileage (mpge)</td>
<td>47.0</td>
<td></td>
</tr>
</tbody>
</table>
Torque Control Strategy

- Efficient torque splitting algorithm
- Allows for traction control strategy between motors
- Optimized for performance and efficiency
Torque Control Strategy

Motor Efficiency map and Maximum Motor Efficiency wrt Speed

Motor Torque

Motor Speed
Cost Based Parasitic Control

1. CALCULATE $\alpha$ RANGE
2. CALCULATE COST OVER THIS RANGE
3. STORE EACH VALUE IN COST TABLE

IF $P_{\text{ACC}} = P_{\text{ACC-Max}}$

NO

YES

1. FIND LOWEST COST IN COST TABLE
2. OUTPUT CORRESPONDING $P_{\text{ACC}}$ – (DESIRED)
3. RESTRICT SEARCH TO ALLOWABLE $P_{\text{ACC}}$ RANGE AND FIND LOWEST COST
4. OUTPUT CORRESPONDING $P_{\text{fuel-cell}}$ – (COMMAND)

ACCESSORY CONTROLLER
1. READ AND IMPLEMENT $P_{\text{ACC}}$ COMMAND
2. OUTPUT $P_{\text{ACC}}$ FEASIBLE RANGE

VEHICLE DATA
(SOC, TEMPERATURE, ETC...)

$P_{\text{ACC}} = 0 \rightarrow P_{\text{ACC-Max}}$
99% Buy-off Features

**Tactile**
- Electronic gear selector
- Touch screen GUI
- Custom upholstery
- Trim and finish
- Emergency lighting solution
- On-board inverter
- Air conditioning
- Cabin heating

**Visual**
- Polycarbonate tinted windows
- Custom Paint
- Custom fiber engine cover
- Custom rockers
- Fuel storage cover
- Manifolded exhaust
- Fuel port interface cover
- PAX™ Tires

**Auditory**
- Air delivery muffling
- Recirculation pump isolation
- Entertainment center
- On-star
- Start sequence audio cue
- Emergency state warning

**Unperceivable**
- Drive quality tuning
- Hard acceleration anticipation
- WATsafe system
- Intelligent fuel use optimization
- Anti-lock braking system
- Traction control

**ZERO TAILPIPE EMISSIONS**

≡ Can I drive?
ChallengeX

2004  Year 1: rapid prototyping of green technology using advanced software simulations

2005  Year 2: implementation of design into 2005 Equinox

2006  Year 3: optimization of design meeting original stock performance

2007  Year 4: Competition Finale
# ChallengeX Goals

<table>
<thead>
<tr>
<th>Metric</th>
<th>Base Vehicle</th>
<th>Waterloo Y2 VTS</th>
<th>Waterloo Y3 VTS</th>
<th>Vehicle Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy - combined EPA [l/100km]</td>
<td>≤10.1</td>
<td>≤6.96</td>
<td>≤7.35</td>
<td>6.29-12.37</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>≤1818</td>
<td>≤2227</td>
<td>≤2000</td>
<td>2095</td>
</tr>
<tr>
<td>Acceleration: 0-100kph [s]</td>
<td>≤8.9</td>
<td>≤9.9</td>
<td>≤9.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Acceleration: 80-110kph [s]</td>
<td>≤6.8</td>
<td>≤9.4</td>
<td>≤6.8</td>
<td>N/A</td>
</tr>
<tr>
<td>Range – highway [km]</td>
<td>≥512</td>
<td>≥224</td>
<td>≥220</td>
<td>270</td>
</tr>
<tr>
<td>Start Time [s]</td>
<td>&lt;2.0</td>
<td>≤5.0</td>
<td>≤5.0</td>
<td>4.03</td>
</tr>
<tr>
<td>Passenger Capacity</td>
<td>3.5</td>
<td>2.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Emissions [Tier, bin]</td>
<td>Tier 2, Bin 5</td>
<td>Tier 2, Bin 1</td>
<td>Tier 2, Bin 1</td>
<td>Tier 2, Bin 1</td>
</tr>
<tr>
<td>Trailering Grade-ability 7% gr. – 90kph – 0.4km [kg]</td>
<td>1591</td>
<td>1136</td>
<td>1136</td>
<td>N/A</td>
</tr>
<tr>
<td>Trailering Grade-ability 4% gr. – 90kph – 10km [kg]</td>
<td>1591</td>
<td>1136</td>
<td>1136</td>
<td>N/A</td>
</tr>
</tbody>
</table>
• Simulate drive speed request based on data
• AVL, FU505, Trip-EPA, Consumer Report
Validation Results

- Model rationality and hybrid control strategy validated

- Vehicle Speed/Motor Current (mph/A)
- Battery Current (A)
- Battery SOC (%)
- FCPM current (A)
The impact of differing battery power limits on a 0-100kph acceleration run using the two-stage torque control strategy
Powertrain Control Requirements

- Two vehicle controllers (supervisory and safety)
- Six powertrain component controllers
- Three CAN (controller area network) communication busses

### Powertrain elements

- F/C Module 1
- F/C Module 2
- A/C Inverter
- Distribution Box
- HV Box
- Inverter
- Motor
- Rear Motor
- Controller: 128
- Processor: Motorola MPC565
- Clock Frequency: 56 MHz
- Internal Flash: 1M
- External Flash: NIL
- EEPROM: 8K serial/optional, 64K x 8 (parallel)
- Internal SRAM: 36K
- Supply Voltage: 6-32VDC
- Analog In/Out Used: 24
- Digital In/Out Used: 8
- PWM Used: 8
- CAN Used: 2

### Supervisor controller
- Controller: Mototron ECU565-128
- Processor: Motorola MPC565
- Clock Frequency: 56 MHz
- Internal Flash: 1M
- External Flash: NIL
- EEPROM: 8K serial/optional, 64K x 8 (parallel)
- Internal SRAM: 36K
- Supply Voltage: 6-32VDC
- Analog In/Out Used: 24
- Digital In/Out Used: 8
- PWM Used: 8
- CAN Used: 2

### Safety controller
- Controller: Mototron ECU555-80
- Processor: Motorola MPC555
- Clock Frequency: 40 MHz
- Internal Flash: 448K
- External Flash: 2M (optional)
- EEPROM: 8K serial/optional, 128k (parallel)
- Internal SRAM: 32K
- Supply Voltage: 8-16V
- Analog In/Out Used: 7
- Digital In/Out Used: 6
- PWM Used: 16
- CAN Used: 2