MATLAB EXPO 2016

Hardware-in-the-Loop
Real-Time Simulation

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Sabin Carpiuc
Overview

- Introduction
- Hardware-in-the-Loop Demonstration
- Conclusion
Why Real-Time Simulation?
Why Hardware-in-the-Loop (HIL)?

- **Challenge**
  - Confirm standard operation and fault modes for controllers early in development cycle

- **Solution**
  - Perform Rapid Control Prototyping (RCP) of controller on low-cost hardware or production ECU
  - Use HIL test rig to represent physical equipment

- **Benefits**
  - Reduce risk to real hardware and personnel during commissioning and operation
  - Test fault modes that would damage real hardware
  - Increase confidence that it will work first time
  - Reduce cost associated with testing and with late-development-process system-design changes
The Challenge

Develop and use the latest technology to deliver a more capable product and meet more challenging performance requirements.

Deliver the product in shorter timescales than previous products and be capable of rapidly adapting to changes if required.

Meet cost challenges to deliver a more affordable product.
Detect Integration Issues Early in the Development Process

Control engineers and domain specialists can work together to detect integration issues in simulation

- Convert control models to C, C++, VHDL, Verilog or PLC code
- Convert plant models to C code for HIL tests
Model-Based Design (Including HIL)

- **Requirements Definition**
- **Desktop Modeling and Simulation**
- **Code Generation**
- **Realization**
  - **Control System**
  - **Physical System or Process**
  - **Hardware-in-the-Loop (HIL)**
  - **Validation**
- **Rapid Control Prototyping (RCP)**
Code Generation

- Unit testing
  - Software-in-the-Loop (SIL)
  - Processor-in-the-Loop (PIL)
  - FPGA-in-the-Loop (FIL)

- System testing and production deployment
  - Rapid Control Prototyping (RCP)
  - Hardware-in-the-Loop (HIL)
  - Production Code Generation (PCG)
Overview

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Baseline – Plant and Controller on HIL
Baseline – *Plant* and Controller on HIL
Baseline – Plant and Controller on HIL
Adding I/O to Interfaces

HIL to Controller Signals:
- Analog I/O
  - Phase Currents
  - Rotor Speed
  - DC Voltage
Adding I/O to Interfaces

Controller to HIL Signals: Digital I/O
6*PWM
## I/O connectivity
Over 200 I/O module types are available

<table>
<thead>
<tr>
<th>I/O Type</th>
<th>Functionality</th>
<th>Configurable (FPGA)</th>
<th>Static</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog</td>
<td>A/D, D/A, frame support</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Digital</td>
<td>TTL, LVCMOS, LVDS, RS422, RS485</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pulse train</td>
<td>PWM generation and capture, interrupt, negation</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Encoders</td>
<td>Absolute and incremental encoder measurement and simulation (quadrature and SSI), EnDAT 2.2, SSI2, and BiSS encoder measurement</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Video</td>
<td>USB (Webcams), CameraLink</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>LVDT/RVDT, Synchro/ Resolver</td>
<td>LVDT, RVDT, Synchro, and Resolver measurement and simulation</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Shared memory</td>
<td>Shared and reflective memory</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermocouple, RTD, and NTC measurement and simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain, pressure</td>
<td>Strain gauges and pressure sensor measurement and simulation</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>IEPE/ICP measurement</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Resistors</td>
<td>Resistor, potentiometer, and reed relay (SPDT, DPST, SPST) simulation</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
Protocol interfaces

**Multi-Industry**
- CAN / SAE J1939
- LIN 2.1
- Real-time UDP
- SPI Master and Slave
- I2C Master and Slave
- UART (RS232/RS422/RS485)
- IRIG with GPS
- Precision Time Protocol (PTP)
- Shared/reflective memory

**Aerospace**
- ARINC 429
- ARINC 629
- AFDX (ARINC 664 P2)
- MIL-STD-1553
- SDLC/HDLC

**Industrial**
- EtherCAT
- Profibus
- Profinet
- Modbus/TCP
- Modbus RTU
- EtherNet/IP
- POWERLINK Controlled Node

**Automotive**
- XCP over Ethernet
- XCP over CAN
- LIN 2.1
- SAE J1939
- FlexRay
I/O support specifically for Hardware-in-the-Loop simulation (examples)

- **Analog and digital**
  - Large portfolio of I/O modules available
  - High-density connectors and high channel count
  - Terminal boards and breakout panels

- **Encoder emulation**
  - Absolute / Incremental, hall sensors
  - EnDat, BiSS
  - Synchro/Resolver, LVDT/RVDT
  - Cam / Crank

- **Emulation of passive components**
  - High precision resistors (thermocouples / RTD)
  - Potentiometer
  - Reed relays
  - Strain gauges, pressure sensors

- **Fault insertion**
  - Wide range of channel counts and fault bus configurations
  - Designed for safety critical applications
Controller for Final RCP Integration
Model Integration
Simulink Real-Time (SLRT)

- Step 1 – SLRT Target Machine Only
- Step 2 – SLRT Target Machine with Loopback
- Step 3 – SLRT Target Machine with RCP
I/O for Step 1: SLRT Target Machine Only
I/O for Step 2: SLRT Target Machine with Loopback

Simulink Real-Time Target Machine

Terminal boards with loopback connections
I/O for Step 3: SLRT Target Machine with RCP

Simulink Real-Time Target Machine

Terminal boards

RCP
Electric Drive – 1kHz Switching Frequency
Embedded Coder ➔ C ➔ CPU
Electric Drive – 1kHz Switching Frequency
Embedded Coder ➔ C ➔ CPU

- Generate C-code directly from Simscape model
- I/O using custom or preconfigured FPGA bitstream
- Fixed-Step simulation - 10kHz/100us

**Target Machine**

<table>
<thead>
<tr>
<th>Task Execution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control &amp; Plant</td>
</tr>
<tr>
<td>With loopback</td>
</tr>
<tr>
<td>With RPC</td>
</tr>
</tbody>
</table>
Electric Drive – 1kHz Switching Frequency

Embedded Coder ➔ C ➔ CPU

- FPGA D/A output ➔ real-world
- Real-world ➔ FPGA A/D input

<table>
<thead>
<tr>
<th>Freq, Hz</th>
<th>Sim</th>
<th>HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASM</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Switch (L)</td>
<td>928</td>
<td>925</td>
</tr>
<tr>
<td>Switch (H)</td>
<td>1031</td>
<td>1030</td>
</tr>
</tbody>
</table>
SLRT Explorer Desktop Instrument Panel

THREE-PHASE ASYNCHRONOUS DRIVE WITH SENSOR

ASM Speed [rpm]

Torque [p.u.]

DC Link Voltage [V]

Load Torque [p.u.]

OPEN PHASE FAULTS

Phase A Open

Phase B Open

Phase C Open

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SLRT Target Machine Display
Overview

- Introduction

- Hardware-in-the-Loop Demonstration

- Conclusion
Model Configuration: Balance fidelity and speed for simulating in real-time

Computational Time vs. Model Complexity

- Ideal Actuators
- Linearized Systems
- Averaged Voltage
- Realistic Actuators
- Nonlinear Effects
- PWM Driver

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Performance

- Uniform entry point for desktop and real-time performance:

```matlab
>> performanceadvisor('modelName')
```
Profiling
What have we reviewed today?

Hardware-in-the-Loop workflow:
- Foundation for Model-Based Design
  - MATLAB®
  - Simulink®
  - Simscape™ Product Family
- Code generation
  - MATLAB Coder™ and Simulink Coder™
  - Embedded Coder®
  - Embedded Coder Support Package for Texas Instruments C2000 Processors
- Hardware-in-the-Loop Deployment
  - Simulink Real-Time™
Conclusion

- Integrated environment: Balance fidelity and simulation speed
- Simulation-platform flexibility:
  - Variable-step or fixed-step desktop simulation
  - Fixed-step deployment for HIL simulation on real-time targets
- MATLAB analysis and visualization tools
  - Evaluate simulation performance
  - Plot results
- Early verification and validation provide significant benefits
  - Increase complexity of design
  - Reduce time
  - Reduce cost
  - Reduce risk
Can I get on-site help to ramp my team up on how to use these tools?

- **Product-focused Training Services** teach you how to:
  - Get started with Model Based Design
  - Understand options and tradeoffs for architecture and fidelity

- **Project-focused Consulting Services** help you with:
  - Process assessment
  - Configuration management and adaptors
  - Collaborative Model-Based Design

Work with your account manager to identify topics of interest and to customize services to meet your needs.
Related talks/materials

- **14:00 : Application Track 2**
  - Physical Modelling Integration and Co-simulation in a Real-Time Environment
    - Andrew Ramsay, BAE
  - Connection to Hardware and Rapid Prototyping
    - Nicolas Gautier, MathWorks

- **15:45 : Introductory Sessions**
  - Modelling Physical Systems in Simscape
    - Steve Miller, MathWorks

- **Whitepaper**
  - [Real-Time Simulation of Physical Systems Using Simscape](#)