Facilitating the Front-Loaded Development of Engine Control System using Simscape & Closed-Loop Simulation

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Background

Ever-Increasing Complexities of Powertrain Control System

Fuel economy  
Emissions  
Safety  
Driveability

CPU: 8bit → 16bit → 32bit
OS-less → Real-time OS (MMU-less)
Independent ECU → Inter-ECU communication (CAN)
Assembly Language → C Language → Block Diagram Language
New engine/vehicle is not available yet.

Plant model is the key for successful front-loading.

Front-loaded development of the control system is becoming essential.
1. Simscape

- Introduction
  - DC Motor & Basics of Acausal Modelling
  - Pneumatic System & Simulation Configurations
- Application Example – Engine, Drivetrain & Vehicle Model

2. Closed-Loop Simulation

- Software-in-the-Loop Simulation /SiL
- Model-and-Software-in-the-Loop Simulation /MSiL … “SiL+M”
- Application Example – Engine & Transmission Control System Simulation
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How different is Simscape from Simulink?
In Simscape, physical domain must be defined prior to other modelling tasks. Through & Across variables play key roles.
Physical Network Equations / Acausal Modelling

Mechanical Rotational Domain

Through: torque, “trq”

Across: angular velocity, “w”

Through variables \( \rightarrow \)

\[ E.R.trq + I.R.trq + F.R.trq + R.trq = 0 \]

\[ E.C.trq + F.C.trq + C.trq = 0 \]

Across variables \( \rightarrow \)

\[ E.R.w = I.R.w = F.R.w = R.w \]

\[ E.C.w = F.C.w = C.w \]
Physical Component Definitions

The “equations” section contains mathematical description of physical system.
System Equations of DC Motor ➔ Electric “Through” variable, i

\[ p.i + D.p.i = 0 \]
\[ D.n.i + S.p.i = 0 \]
\[ S.n.i + E.p.i = 0 \]

\[ p.i + D.i = 0 \]
\[ -D.i + S.i = 0 \]
\[ -S.i + E.i = 0 \]
\[ n.i + (-E.i) = 0 \]

\[ p.i + n.i = 0 \]
System Equations of DC Motor > Electric “Across” variable, V

\[ \text{p.V} = \text{D.p.V} \]
\[ \text{D.n.V} = \text{S.p.V} \]
\[ \text{S.n.V} = \text{E.p.V} \]

**Resistor (ih1)**
\[ \text{D.V} = \text{D.p.V} - \text{D.n.V} \]
\[ \text{D.V} = \text{D.R} \ast \text{D.i} \]

**Inductor (ih1)**
\[ \text{S.V} = \text{S.p.V} - \text{S.n.V} \]
\[ \text{S.V} = \text{S.L} \ast \text{der(S.i)} \]

\[ \text{E.V} = \text{E.p.V} - \text{E.n.V} \]
\[ \text{E.V} = \text{E.K} \ast \text{E.w} \]

**Other Equations**
\[ \text{p.V} - \text{n.V} = \text{D.R} \ast \text{D.i} + \text{S.L} \ast \text{der(S.i)} + \text{E.K} \ast \text{E.w} \]

\[ V_p(t) - V_n(t) = R_D \cdot i_D(t) + L_s \cdot \frac{d}{dt} i_s(t) + K_E \cdot \omega_E(t) \]
System Equations of DC Motor > Rotational “Across” variable, w

\[ E.R.w = I.R.w = F.R.w = R.w \]

\[ E.w = E.R.w - E.C.w \]

\[ E.C.w = F.C.w = C.w \]

\[ F.w = F.R.w - F.C.w \]
System Equations of DC Motor > Rotational “Through” variable, trq

\[ F.R_{trq} = F.trq \]
\[ F.C_{trq} = -F.trq \]
\[ F.trq = F.f(F.w) \]

\[ E.R_{trq} = R.trq \]
\[ E.C_{trq} = -E.trq \]
\[ E.trq = E.K \cdot E.i \]

\[ E.C_{trq} + F.C_{trq} + C.trq = 0 \]

\[ E.K \cdot E.i + F.f(F.w) + L.J \cdot \text{der}(I.w) + R.trq = 0 \]

\[ E.K \cdot E.i + F.f(F.w) + C.trq = 0 \]

\[ K_E \cdot i_E(t) + f_F(\omega_F(t)) + J_I \cdot \frac{d}{dt} \omega_I(t) + \tau_R(t) = 0 \]
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Physical Modelling of Pneumatic System – Compressible Gas Flow Dynamics

\[ p_0 = 2 \times 10^1 \text{kPa} \]
\[ T_0 = 20 \text{degC} \]

\[ p_0 = 101 \text{kPa} \]
\[ T_0 = 20 \text{degC} \]

\[ p_0 = 101 \text{kPa} \]
\[ T_0 = 20 \text{degC} \]

Inside a chamber

Mass Flow Rate

\[
\text{G} = \begin{cases} 
6 \times 10^{-3} \text{kg/s} & \text{for } t < 0.1 \\
5 \times 10^{-3} \text{kg/s} & \text{for } 0.1 \leq t < 0.5 \\
3 \times 10^{-3} \text{kg/s} & \text{for } 0.5 \leq t < 0.9 \\
1 \times 10^{-3} \text{kg/s} & \text{for } 0.9 \leq t < 1 \\
0 \text{kg/s} & \text{for } t \geq 1 
\end{cases}
\]

variables (Balancing = true)

\[
\begin{align*}
G &= 0, \ 'kg/s' \\
p &= 0, \ 'Pa' \\
Q &= 0, \ 'J/s' \\
T &= 0, \ 'K'
\end{align*}
\]
Flexible Physical Network Modelling

Main flow-path with a bypass
- e.g., Exhaust gas recirculation (EGR) system
- e.g., Air-bypass valve in intake & waste-gate valve in exhaust in turbo-charged engine
MathWorks recommends “implicit solvers” for Simscape-based models.

**Variable-step Solver**
- **Zero-crossing detection**: On
- **ode15s** (stiff/NDF)
  - more stable & tend to damp out oscillations

**Fixed-step Solver**
- **ode23t** (mod. stiff/Trapezoidal)
  - less stable & captures oscillations better

**Simscape Local Solver**
- **Backward Euler**
  - Code-Generation

*Help: Simscape / Getting Started with Simscape / How Simscape Models Represent Physical Systems*
Simulation Data Logging

ssc_explore" is available at MATLAB Central File Exchange #28184
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Custom Domain for Multiple Gas Species System (Air, Fuel Vapour, Burned Gas)

Domain Definition

E.g., Intake Pipe Subsystem

Domain parameters:
- Degrees of freedom of a molecule (-)
- Specific gas constant (J/kg/K)
- Viscosity (Pa*s)
For each species (Perfect gas is assumed.)

```
domain gas3

variables (Balancing = true)
edot = { 0 'J/s' }; % enthalpy flow
n1dot = { 0 'mol/s' }; % mole flow (air)
n2dot = { 0 'mol/s' }; % mole flow (fuel)
n3dot = { 0 'mol/s' }; % mole flow (burned gas)
end

variables
T = { 0 'K' }; % gas temp
p1 = { 0 'Pa' }; % gas pressure (air)
p2 = { 0 'Pa' }; % gas pressure (fuel)
p3 = { 0 'Pa' }; % gas pressure (burned gas)
end

end
```
Control-Oriented Combustion Cylinder Model

28 parameters

440 lines of code
Causal Modelling with Physical Signals (Torque Converter Model)

Lookup tables (1D, 2D) are available too.
Topics

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Closed-Loop Simulation Technologies in MBD V-Process

High-level goals

Control design

Virtual system evaluation

Legacy SW

Prototype control system

New design

Real system evaluation

Model-in-the-Loop (MiL)

Model-and-Software-in-the-Loop (MSiL)

Control SW rqmt spec.

Software design spec.

Code

Hardware-in-the-Loop (HiL)

Software-in-the-Loop (SiL)
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Configurability of Input/Output between Controller and Plant

Toyota’s New Simulator

Case #3
- Physical Values: ✔ ✔ ✔ ✔
- Low-level (Voltage) Buffers: ✔ ✔ X X
- AD Converter: X X X X
- MCU Registers: ✔ X X X
- MCU Connectors: X X X X
- ECU Connectors: X X X X

Case #2
- Analog/Switch Inputs to Controller: Real
- Inputs to Plant: Real

Case #1
- Real Case #1

Case #B

Minimum code-change required

Case #A

Real Case #A

Low-level IO, Slower simulation: Less modification in software
High-level IO, Faster simulation: More SiL-dedicated code

Practical balance has been chosen.
SiL+M provides integrated control-design mechanism.

**Simplified Task Scheduler**
- Priority ignored & zero execution time
- Precise execution timings of ISRs and timers
- Independent of Simulink sample time

Low-level CPU op’s in assem are omitted. Basic arithmetic assem is altered with C library.

(No voltage level simulation)
(No arbitration)
(No data loss (No CRC))

High-level CAN simulation
- Main data only
- Configurable transmission cycle

**SiL+M** provides integrated control-design mechanism.
Accurate execution timings of ISRs, together with timers, is essential.
Sample Block Diagram of "SiL+M"

SiL Production Simulation Result

Controllers – Production control software: EFI & ECT
Plant – Engine in Simulink & 8AT+vehicle in Simscape

LA#4 mode (30s – 650s)

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedal angle</td>
</tr>
<tr>
<td>Engine rev</td>
</tr>
<tr>
<td>Vehicle speed</td>
</tr>
<tr>
<td>Throttle angle</td>
</tr>
</tbody>
</table>
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Simscape is...
✓ Acausal modelling & simulation environment
✓ Tightly integrated with Simulink

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✓ SiL & MSiL (SiL+M) are very powerful tools for fully-fledged powertrain control system development