Model-Based Dynamic Optimization – Tool Demonstration

Ongoing Work in the OpenModelica Community

Approach 1: Parallel Multiple-Shooting and Collocation Optimization with OpenModelica

Paper at Modelica'2012 conference

Integrated solution, powerful symbolic methods in the OpenModelica compiler.
Available in OpenModelica in June-Sept 2013 time frame.

Approach 2: Model-Based Dynamic Optimization with OpenModelica and CasADi

Paper accepted Jan 2013 to IFAC conference
External solution, optimization problem exported via XML to external tool, Casadi

Works in current nightly builds of OpenModelica, and in coming 1.9.0 final release

Tool Demonstration, EOOLT'2013, Nottingham, April 19, 2013

Demo by Peter Fritzson

Motivation

- **Modelica** enable users to conveniently model large-scale physical systems
  - Traditionally used for simulation
- Nonlinear optimal control problems (NOCP) based on differential-algebraic equations (DAE)
  - State-of-the-art methods are using numerical algorithms
- Many other possible usages of the model
  - For example dynamic optimization for NOCP
- Current Modelica tools mainly focused on simulation, but recently also optimization
  - Dymola supports parameter and design optimization of models written in Modelica whereas
  - JModelica.org and OpenModelica have native support for optimal control, dynamic optimization.

Parallel Multiple-Shooting and Collocation Optimization with OpenModelica (Modelica'2012 conf)

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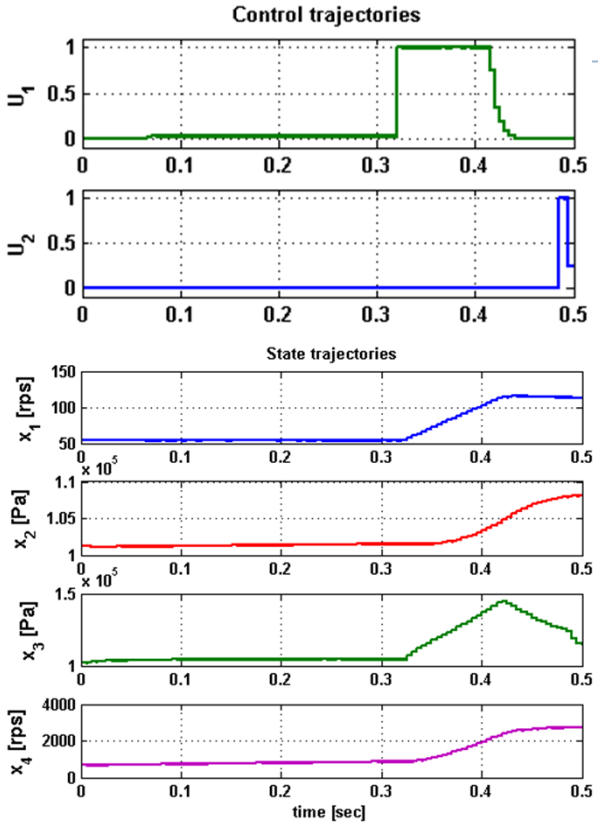
Applications – Diesel Electric Powertrain



- Mathematical problem formulation
  - Object function

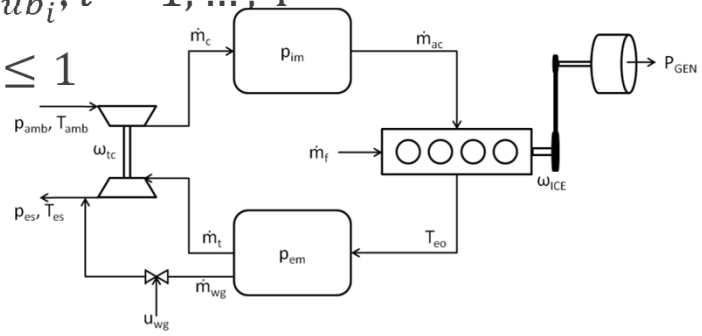
$$\min_{u(t)} \sum_{i=1}^{4} \left(x_i(t_f) - x_i^{ref}\right)^2 + \int_0^T \dot{m}_f \, dt$$

  - subject to

$$\begin{aligned} \dot{x}_1 &= f_1(x_2, x_3, u_1) \\ \dot{x}_2 &= f_2(x_1, x_2, x_4) \\ \dot{x}_3 &= f_3(x_1, x_2, x_3, u_1, u_2) \\ \dot{x}_4 &= f_4(x_2, x_3, x_4, u_2) \end{aligned}$$

$$x_{lb_i} \le x_i \le x_{ub_i}, i = 1, \ldots, 4$$

$$0 \le u_1, u_2 \le 1$$



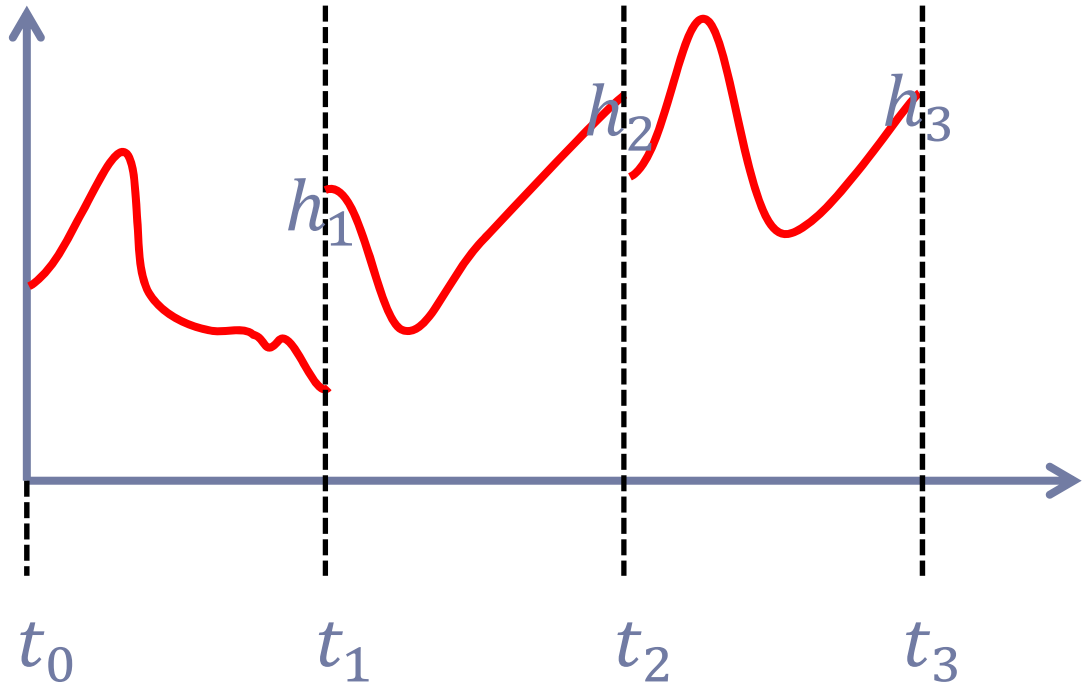
Engine is accelerated only near the end of the time interval to meet the end constraints while minimizing the fuel consumption

Theoretical Background

Multiple Shooting/Collocation

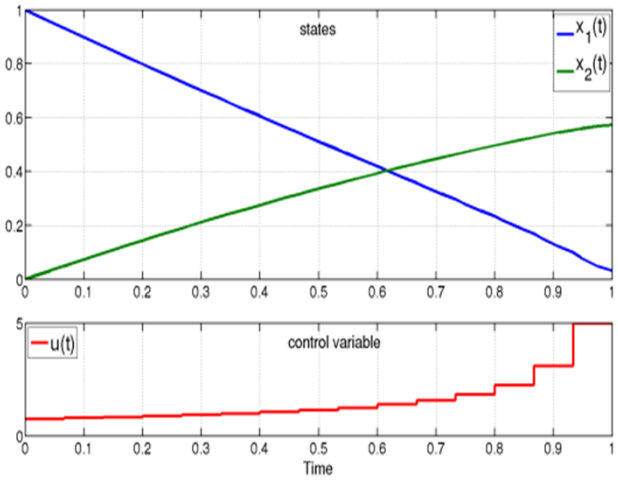
- Solve sub-problem in each sub-interval

$$x_i(t_{i+1}) = h_i + \int_{t_i}^{t_{i+1}} f(x_i(t), u(t), t)\, dt$$
$$\approx F(t_i, t_{i+1}, h_i, u_i), \qquad x_i(t_i) = h_i$$



Details – Native Implementation in OpenModelica Current Status

- Realization within OpenModelica Environment
- Optimica language extension prototype is available in OpenModelica
- Using Ipopt for solution process
- Necessary derivatives are numerically calculated
  - Gradients, Jacobians, Hessians, …
- **But:** Complete tool chain not yet implemented, first version June 2013 time frame

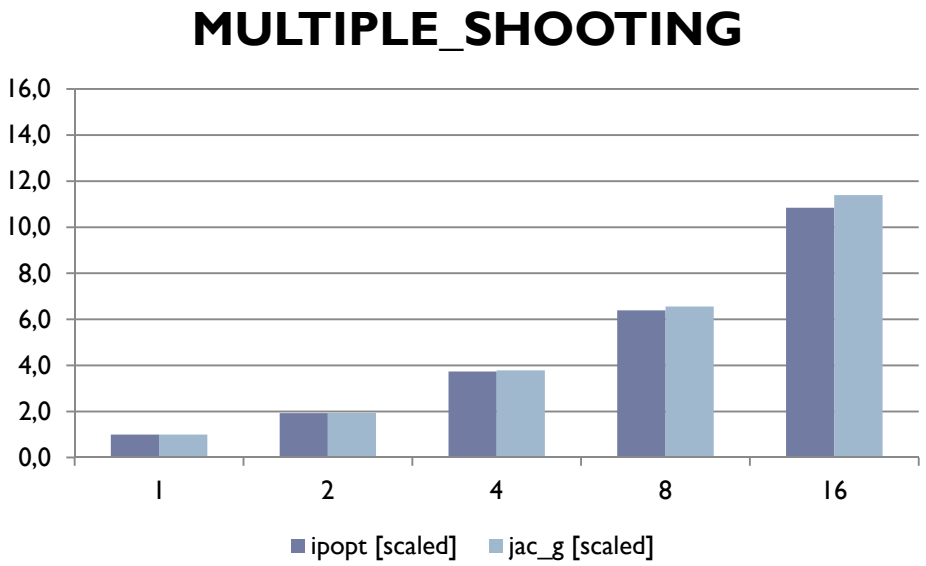


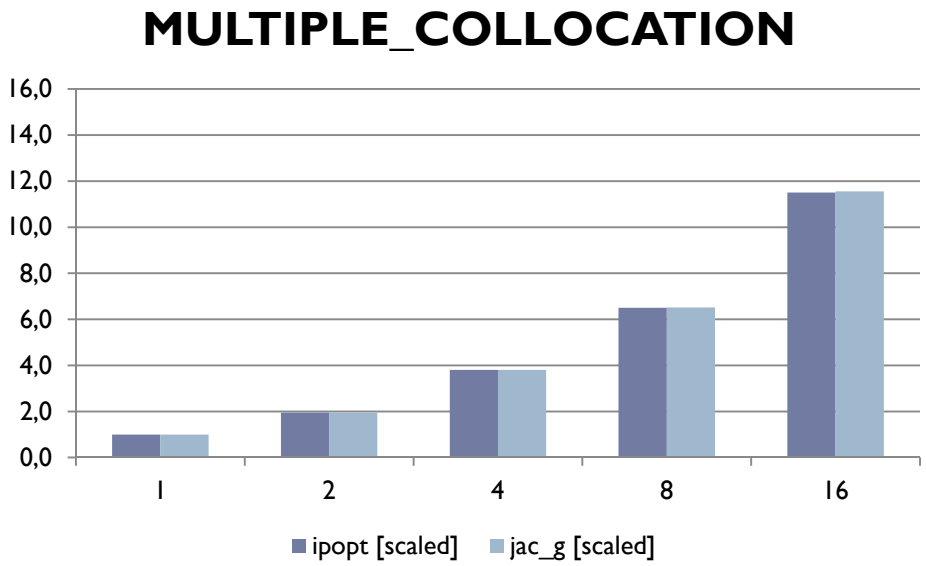
Test Environment

- Processor:
- 2xIntel Xeon CPU E5-2650
  16 cores @ 2.00GHz
- Memory: 96 GB
- OpenMP

Speedup Results Sept 2012 - Diesel Electric Powertrain

- Ipopt runs in serial mode
- Most execution time is elapsed in Jacobian calculation
- Reasonable speed-up
- Factors are non-optimal due to memory handling
  - Further investigations will be performed





Model-Based Dynamic Optimization with OpenModelica and CasADi – Tool Demonstration

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Demo at EOOLT'2013, Nottingham, April 19, 2013

Why OpenModelica-Casadi Connection?

- **Research collaboration**
- **Testing XML export**
- **Integration with more tools**

Optimization with Modelica

- Modelica has strong support for modeling of dynamic systems
- Additional elements for optimization:
  - Cost function
  - What to optimize (Variables and Parameters) and
  - Constraints
- Optimica language extension:
  - Extension of Modelica.
  - Enables formulation of optimization problems in Modelica models.
- How ?
  - Export Models in XML from OpenModelica and Import to CasADi

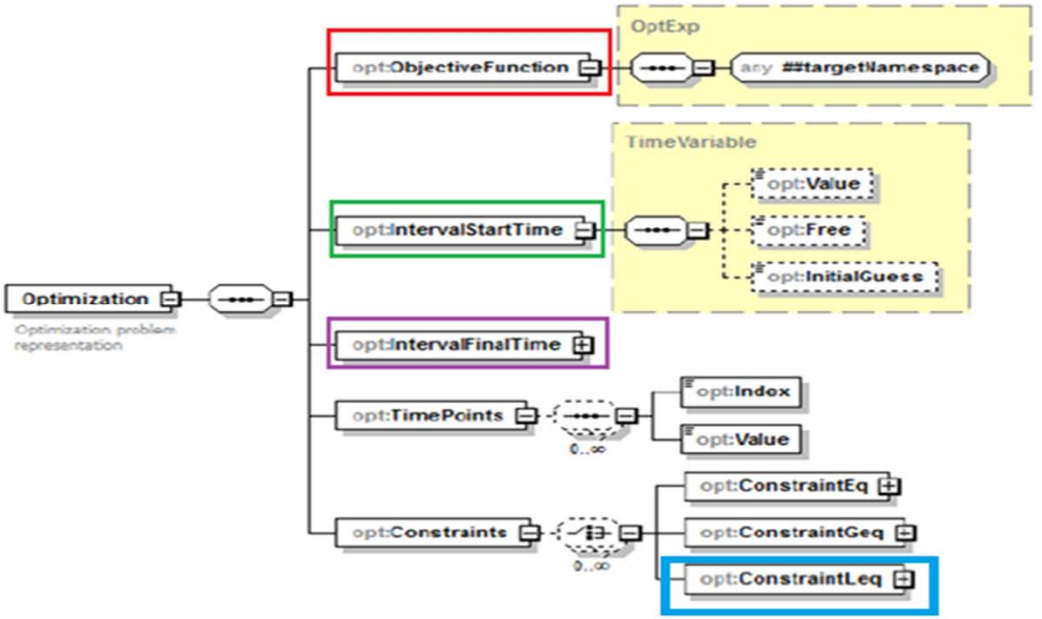
OpenModelica and CasADi

- OpenModelica
  - Modelica-based modeling and simulation platform
  - Support optimica extension
  - Extended with XML export of models based on standardized XML schema for models
  - The XML export also includes the Optimica extension
- CasADi
  - An open-source framework for numerical optimization developed by *KU Leuven*
  - Enable users to implement optimal control algorithms with a wide range of methods, including
    - Multiple shooting and
    - Collocation
  - Imports XML for dynamic optimization

XML Code Generation in OpenModelica

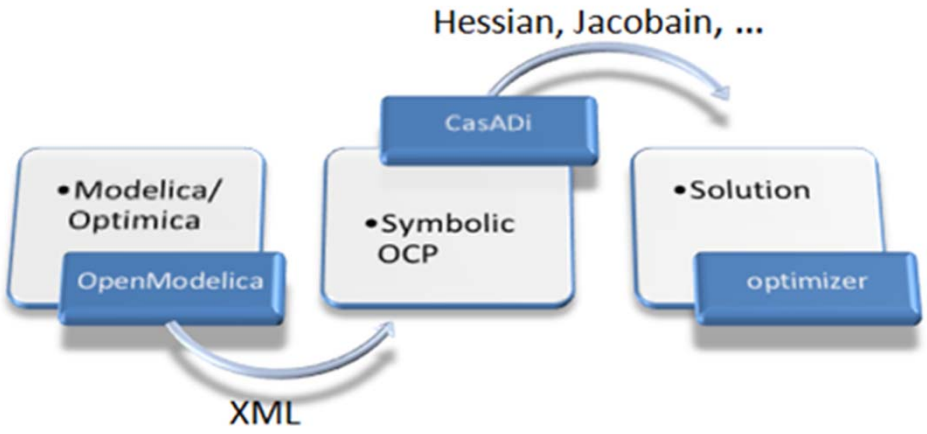
- Modelica models are first flattened.
- XML schema structure mapped to the abstract syntax tree of OpenModelica compiler
- Text template based implementation of the code generation to XML

```
optimization VDP_Opt (objective = cost(finalTime),
                      startTime = 0, finalTime = 20
  parameter Real p1 = 1;
  parameter Real p2 = 1;
  parameter Real p3 = 2;

  Real x1(start = 0);
  Real x2(start = 1);

  input Real u;

  Real cost(start=0);

equation
  der(x1) = (1 - x2 ^ 2) * x1 - x2 + u;
  der(x2) = p1 * x1;
  der(cost)=exp(p3*1/*time*/) * (x1^2 + x2^2 + u^2);

  constraint    u<=0.75;

end VDP_Opt;
```



Optimization Tool Chain for OpenModelica and CasADi

- **Export** of model from OpenModelica platform
- **Import** the model in CasADi
- **Solve** optimization problem in CasADi



Test Cases - Diesel Electric Powertrain

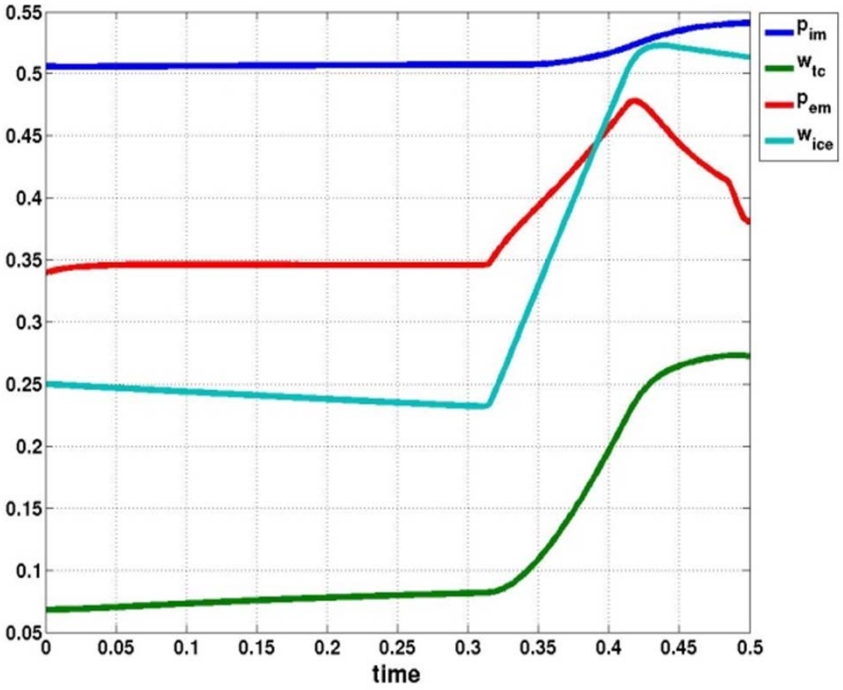
- Presented by
  - **Martin Sivertsson** and **Lars Eriksson**. (2012)
  - **Bernhard Bachmann and et al.** (2012).
- Nonlinear mean value engine model (MVEM)
- Find fuel optimal control and state trajectories from idling condition to a certain power level
- Mathematical problem formulation:
  - 2 inputs (uf,uwg)
  - 4 states (ωice,pim,pem,ωtc)
  - 32 algebraic equations
- The problem solved here is a minimum fuel problem for a transient from idle to 170 kW, in a certain time interval [0,0.5].

Demonstration – Work Flow

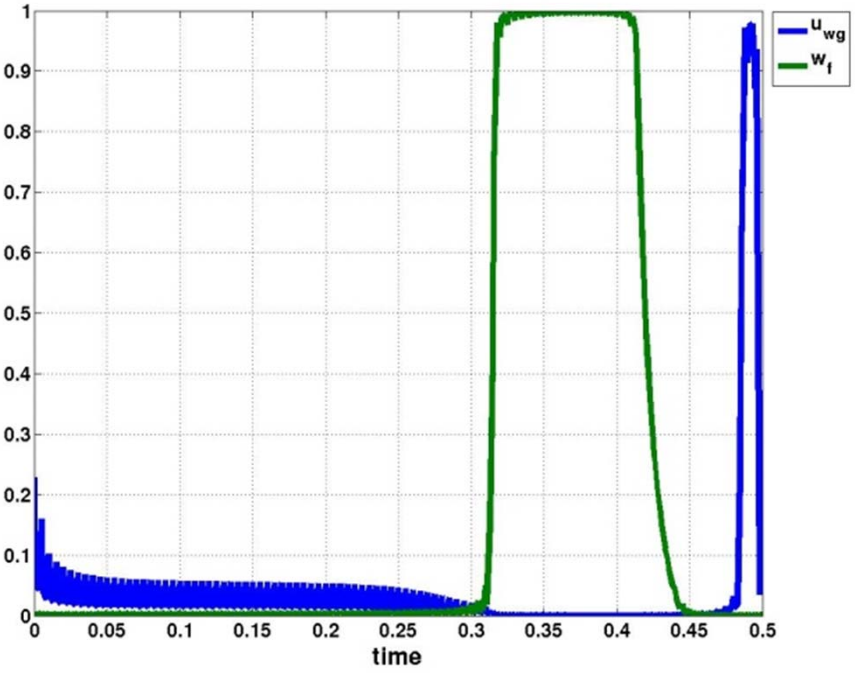
- 1. Formulate the model in Modelica + optimization extension
- 2. Export the model from OpenModelica to XML
- 3. Start a command prompt
- 4. If not python command line, add Python path
- 5. Go to the XML directory and locate XML file exported from OpenModelica
- 6. Go to the CasadiOpt directory and give the command:
  .e.g python.exe ..\casadiOpt\defaultStart.py xmlFileName.xml

Results- Diesel Electric Powertrain

State variables $(\omega ice, pim, pem, \omega tc)$



Control variables (uf, uwg)



- Engine is accelerated only near the end of the time interval to meet the end constraints while minimizing the fuel consumption

Conclusions

- Model-based dynamic optimization with OpenModelica and CasADi has been demonstrated on three industrial use cases.
- The OpenModelica platform coupling with CasADi demonstrates the use of an XML-based model exchange format for model-based optimization with OpenModelica

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