Dynamic Optimization of Modelica Models – Language Extensions and Tools

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Content

- Background
- Dynamic optimization
- Software tools
- Optimica

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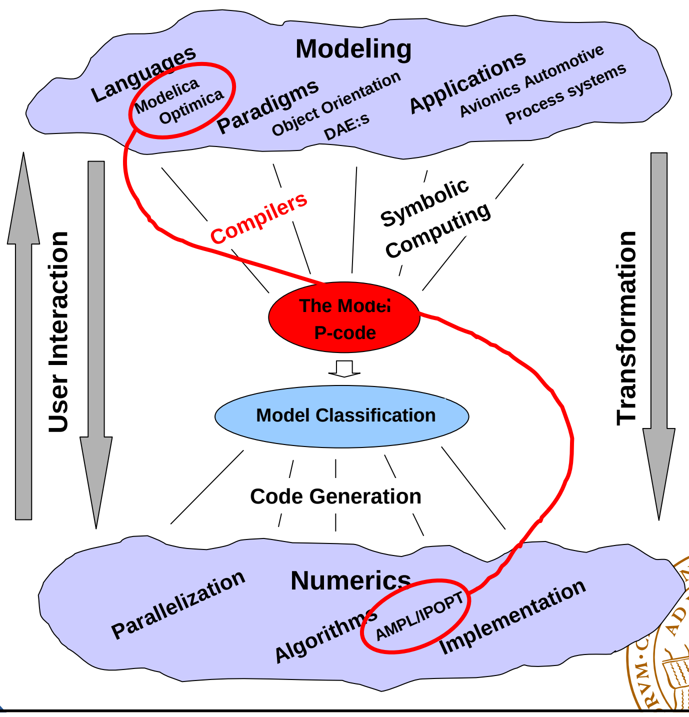

Background

- Modelica is increasingly used in industry
  - Expert knowledge
  - Capital $$$
- Usages so far
  - Simulation (mainly)
- Other usages emerge
  - Sensitivity analysis
  - Optimization
  - Model reduction
  - System identification
  - Control design
- Usages reported so far
  - Cope with with software interfaces designed for simulation…

Dynamic Optimization

- New abstractions
  - Cost (objectives), constraints, optimization of parameters and functions, cases
  - Initial guesses
  - Transcription method (discretization)
- Requirements
  - Sensitivities
  - Derivatives
    - Jacobians
    - *Hessians*
  - Sparsity patterns

JModelica – Project Objectives

- Shift focus:
  – from ***encoding*** optimization problem
  – to ***problem formulation***
- Enable dynamic optimization of Modelica models
  – State of the art numerical algorithms
- Develop a high level description language for optimization problems
  – Extension of the Modelica language
- Develop prototype tools
  – JModelica and The Optimica Compiler
- Case study
  – Plate reactor start-up optimization (see paper)

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A Dynamic Optimization Problem

$$\min_{u,p} J(x,u,p,t_f) = \min_{u,p} \left\{ \int_0^{t_f} L(x,u,p)dt + \phi(x_f) \right\}$$

subject to

$$F(\dot{x},x,u,p) = 0, \quad \text{(DAE dynamics)}$$
$$g_0(x_0) = 0 \quad \text{(initial conditions)}$$
$$g_f(x_f) = 0 \quad \text{(terminal constraint)}$$
$$r_i(x(t),u(t)) \leq 0 \quad \text{(inequality path constraints)}$$
$$r_e(x(t),u(t)) = 0 \quad \text{(equality path constraints)}$$

Dynamic Optimization

- Many algorithms
  - Applicability highly model-dependent (ODE, DAE, PDE, hybrid…)
  - Active area of research
- User must specify additional information
  - Discretization mesh
  - Discretization scheme
- Heavy programming burden to use numerical algorithms
- Engineering need for high-level descriptions
  - Extend Modelica to support dynamic optimization

Key Abstractions in Optir... ion

- Optimization parameters ... tions
- Cost – what to minimi...
- Objectives (multi-c... optimization)
- Cases
- Bounds on v...
  - Not a g... hi-jack attributes
- Cons...
- Init... ses
- ... zation information

Not available in Modelica

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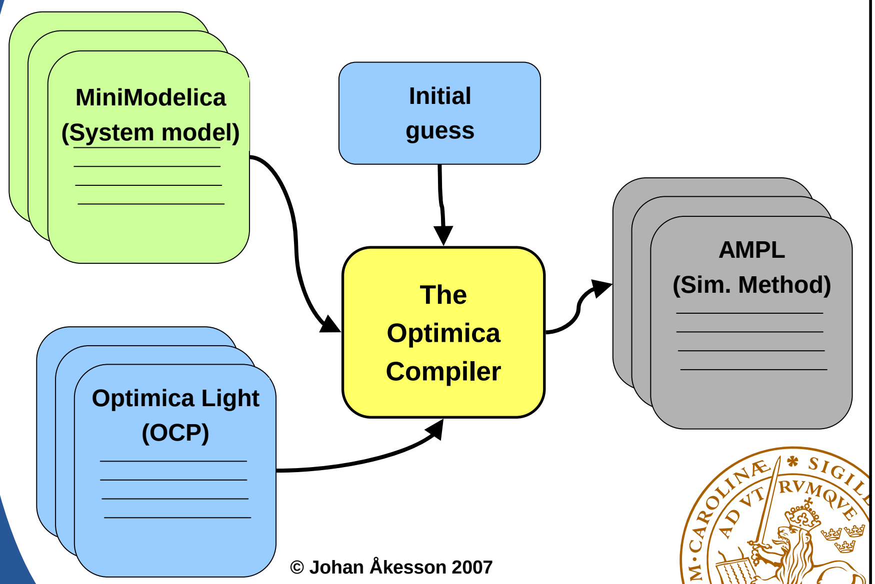
Software – Motivation

- Code generation requires syntax trees
  - *"The final syntax tree before code generation"*
  - Dymola – not available
  - OpenModelica – August 2005: RML…?
- Subset of Modelica sufficient initally
  - No "hybrid" constructs
  - Start in small scale
- Java
  - Safe language
  - Rapid development
  - Standard library
  - Not so slow…
- JastAdd
  - Compiler construction framework

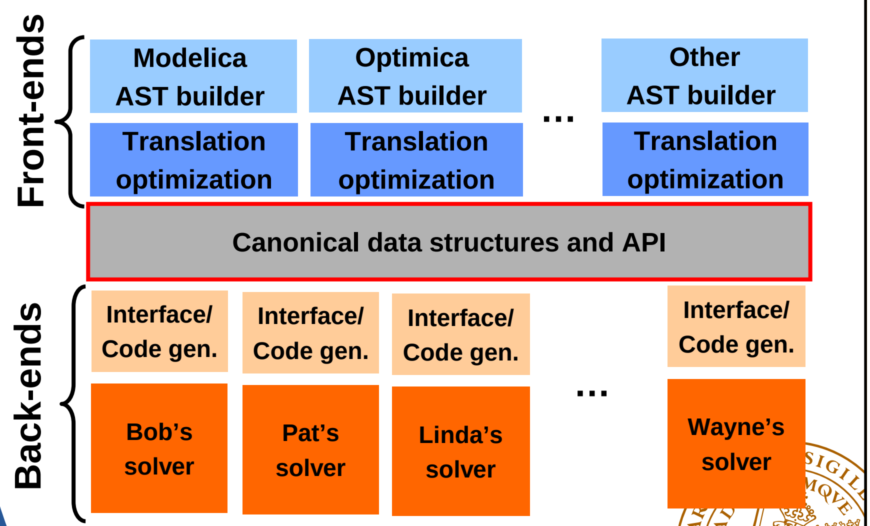
The JModelica Project – Status

- Parsing of full Modelica 2.2
  - Standard library (2.2) parsed in approx 15 s
  - Name and type lookup + error check: 5 s
  - Improved error message generation
    - Dude, don't use if-clauses. It is not good for ya…
- *Partial* support for instantiation
  - Classes, components, connections, modifications…
  - Partial support for arrays
  - Smoothing of discontinuities (min, max)
- Testing based on JUnit framework
- Prototype specification of Optimica
  - Description of an optimization problem
  - The Optimica Compiler: Code generation to AMPL/IPOPT
- Applications
  - Extensively used for start-up optimization of plate reactor
  - Two master's thesis projects spring 2007: vehicle dynamics

JModelica Software Tools



Software Architecture – Re-use



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Language Extension Objections

- Use annotations?
  - Optimization problems have a rich structure – need for efficient language constructs
  - Annotations cannot be modified
- Language maintenance?
  - Modularization of specification
  - Modularization of implementation
    - JastAdd
  - Natural evolution of Modelica
    - Simulation → Optimization

Extension Concepts

- Enhanced class: `optmodel`
- Superimpose information on elements
  - Introduce new attributes for `Real`
  - New built-in package `Optimica`
  - Concept from aspect orientation
- New sections
  - `optimization`
    - Superimpose information
    - Meshes and discretization
  - `subject to`
    - Constraints
- New built-in functions
  - `minimize`: cost function
  - `integrate`: integration
  - `instantValue`: Instant time values of variables $x(t_i)$

Optimica – Basic Constructs

$$\dot{x} = v \quad x(0) = 0$$
$$\dot{v} = u \quad v(0) = 0$$

Modelica

```
model DoubleIntegrator
  Real u;
  Real x(start=0);
  Real v(start=0);
equation
  der(x) = v;
  der(v)=u;
end DoubleIntegrator
```

$$x(1) = 1 \quad u \le 1, \quad \int_0^{t_f} 1dt$$
$$v(1) = 0 \quad u \ge -1$$

Optimica

```
optmodel OCP
  DoubleIntegrator di;
optimization
  di.u(lowerBound=1,
        upperBound=-1);
equation
  minimize(integrate(1));
subject to
  terminal di.x=1;
  terminal di.v=0;
end DoubleIntegrator
```

Optimica – Specification of Discretization Scheme

```
package Optimica
  record Mesh
    Real meshPoints[:];
    …
  end Mesh;
  package Collocation
    record LagrangeCollocation
      Real collocationPoints[:];
      …
    end LagrangeCollocation;
    record DiscretizationSpec
      Mesh mesh;
      LagrangeCollcation lc;
    end DiscretizationSpec;
  end Collocation;
end Optimica
```

- Built-in package Optimica
  - Mesh
  - Collocation
- Essential information
  - Closer to algorithms
- Data structures
- Similar to annotations

Optimica – Specification of Discretization Scheme: Example

```
optmodel OCP
  DoubleIntegrator di;
  Optimica.Mesh mesh(…);
  Optimica.LagrangeCollocation lc(..);
optimization
  di.u(lowerBound=1,
       upperBound=-1);
  extends Optimica.Collocation.
            DiscretizationScheme(mesh=mesh,
                                 lc=lc);
equation
  minimize(integrate(1));
subject to
  terminal di.x=1;
  terminal di.v=0;
end DoubleIntegrator
```

Summary

- JModelica and The Optimica Compiler
  - Extensible compiler
  - Front-end supporting subset of Modelica
  - Back-end for code generation to AMPL
- Optimica
  - Extension of Modelica for optimization
- Case study
  - See paper

Thank you!

Questions?

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