Overview

- **Introduction**
  
  Trends - Problems - Needs

- **Mono-Simulation with Modelica**
  
  Modelica Standard Library - LBNL Buildings Library - Applications

- **Co-Simulation with Building Controls Virtual Test Bed**
  
  Building Controls Virtual Test Bed - Applications

- **R&D Needs**
Building systems become more complex

- Interaction: Continuous time, discrete time, events.
- States: Multiple operating modes.
- Controls integration: Floating setpoints, electrical grid, active façade.
- Thermal integration: Geothermal systems, heat storage and recovery.

Figure adapted from: Oehler, Grosse Passivhaeuser, Kohlhammer, 2004
Building systems are multi-scale, multi-physics systems

- Flow friction in piping and duct networks
- Thermodynamics of moist air and refrigerants
- Heat and mass transfer through solids (walls, windows)

- Airflow inside and outside of building
- Distribution of direct and diffuse radiation
  - daylight
  - short-wave radiation
  - long-wave radiation
- Evolution (physics & controls)
  - continuous time
  - discrete time
  - event-driven

Figure adapted from: Oehler, Grosse Passivhaeuser, Kohlhammer, 2004
How do we accelerate RD&D of next generation technologies?

Decentralized dehumidification with liquid desiccant

Phase change material to increase thermal storage

Provide user-extensible tools for rapid prototyping, model-based design and controls, built on open-source standards.

Cyprus grass to humidify supply air

Web-server at the size of 25 cents
R&D Needs for Whole-Building Model-Based Design and Operation

What modeling framework enables model-based design and operation?
Challenges -- Controls

Integration of subsystems (grid, HVAC, active facade, lighting).

Enable optimal
- energy storage
- equipment scheduling
- setpoint scheduling
- grid interaction.

Making inefficiencies visible to end-user.

Detect and diagnose faults at the system-level.

Close disconnect between design and operation, using executable specification, to
- increase productivity.
- reuse design across platforms.
- enforce accountability across hand-off points.
- reduce human error.
Today’s building simulation programs (EnergyPlus, DOE-2):

These tools have not been designed to support controls.

Large simulators (500,000 lines of code).

**Dynamic models**
- Heat transfer (opaque constructions & room air).
- Energy storage in water tanks.

**Steady-state models**
- HVAC components and system (written for 10 minutes to 1 hour time step).
- Controls.

**Controls semantics**
- “Ideal controller” that meets load (cooling power etc.) by computing how much mass flow and what temperature a component needs to deliver, subject to capacity constraints.
- No notion of continuous time systems or hybrid systems.

**Solution method**
- 10 to 20 nested solvers, no global error control, many components integrate their own solver, which introduces large discontinuities in approximate transfer function.
Express models in a modeling language, not a programming language!

- Modular objects with standard interfaces (thermodynamics, controls, ...)
- Hierarchies to manage complexity vertically and horizontally
- Code generation for control hardware
- Different evolutions within modules
  - continuous time (seconds to minute time scale)
  - discrete time
  - finite state machine

Model feedback control of measured states (temperature, pressure), not heating/cooling load. (This requires models and solvers that are different from today's standard building simulation.)

Analysis support through application programming interfaces (API)
- Building Information Models
- link to domain-specific tools (such as MATLAB/Simulink)
- reduced order model extraction
- optimization
Increase Level of Abstraction

Higher-level of abstraction to
- increase productivity
- facilitate model-reuse
- preserve system topology
- enable analysis
- generate code for target hardware

Procedural modeling ≈ 1970

Equation-based, object-oriented modeling ≈ 2000
Separation of Concerns

**Describes the phenomena**
- Standardized interfaces
- Acausal models
- Across & through variables
- Hierarchical modeling
- Class inheritance

**Solves the equations**
- Partitioning
- Tearing
- Inline integration
- Adaptive solver
  - Integration
  - Nonlinear equations
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- R&D Needs
Modelica Buildings Library

Enable

- Rapid prototyping of innovative systems
- Controls design
- Model-based operation

Available from
http://simulationresearch.lbl.gov/modelica
What is Modelica?

- Object-oriented equation-based modeling language
- Open standard
- Developed since 1996 because conventional approach for modeling was inadequate for integrated engineered systems
- Well positioned to become de-facto open standard for modeling multi-engineering systems
  - ITEA2: 370 person years investment over next three years.

```
a := 2;
b := 2*a;
C*der(T) = Q_flow;
0 = T - TBoundary;
```

Graphical modeling
- input/output free
- block-diagram
- state machines
- bond-graphs

Algorithmic code

Acausal equations

C code

solver

executable
Modeling of Components with Dissimilar Mathematics

Schematic diagram couples PDE, ODE, algebraic equations, state graph and discrete time systems.

\[
T = \text{port}.T;
C*\text{der}(T) = \text{port}.Q_{\text{flow}}
\]

// Water content and pressure
port_a.p * (VGas) = p0 * VGas0;
medium.p = port.p;
# Modelica Standard Library

1300 models & functions.

<table>
<thead>
<tr>
<th>Analog</th>
<th>Digital</th>
<th>Machines</th>
<th>Translational</th>
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<td>[ |v|<em>p = \left( \sum</em>{i=1}^{n}</td>
<td>v[i]</td>
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</tbody>
</table>
Modelica Buildings Library

Extends and simplifies models from Modelica.Fluid

http://www.modelica.org/libraries/Buildings

150+ HVAC Models
Current Applications

**Advanced Control**
- Dynamic evaluation of control sequences
- Tool chain for model-based design and operation, including automatic code generation from models (proposed for FY11)
- Reusability of models from different domains

**Integrated Building System**
- Rapid prototyping of new energy systems
- Coupled simulation of HVAC, control and energy.
  E.g. EnergyPlus + Modelica

**Education**
- Virtual Building Lab.
  E.g. LearnHVAC

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Modelica Buildings Library
LBNL Buildings Library. 150+ models and functions.


The biggest barrier to adoption is the lack of robustness of numerical solvers for these DAE systems with continuous and discrete state variables.
Applications

1) **Rapid prototyping**
   Analyzed novel hydronic heating system with radiator pumps and hierarchical system controls.

2) **Supervisory controls**
   Simulated & auto-tuned “trim and response” sequence for variable air volume flow systems.

3) **Local loop controls**
   Reused high-order model for controls design in frequency domain.
Rapid Prototyping: Wilo GENIAX

**Original system model**
- 2400 components
- 13,200 equations

**After symbolic manipulations**
- 300 state variables
- 8,700 equations
Rapid Prototyping: Wilo GENIAIX

Thermostatic radiator valves

- Boiler set point, supply and return temperatures
- Room temperatures
- Boiler and radiator valve signals
- Normalized radiator mass flow rates

Radiator pumps

- Boiler set point, supply and return temperatures
- Room temperatures
- Boiler and radiator pump signals
- Normalized radiator mass flow rates

Reproduced trends published by Wilo.

Developed boiler model, radiator model, simple room model and both system models in one week.
Applications – VAV System Controls

VAV System
(ASHRAE 825-RP)

Trim & response control for fan static pressure reset
(Taylor, 2007)

Original system model
730 components
4,420 equations
40 state variables
Stabilized control and reduced energy by solving optimization problem with state constraints

\[
\min_{x \in X} \{ f(x) \mid g(x) = 0 \},
\]

\[
f(x) = \frac{1}{E_0} \int_0^T P_f(x, t) \, dt,
\]

\[
g(x) = \frac{1}{T} \int_0^T \left[ \max\{0, (y_j(x, t)/\hat{x}_s) - \right.
\]

\[
\left. 1/(2K_p) - 1 \mid j \in \mathbf{J}(x, t) \} \right)^2 \, dt
\]
Heat exchanger feedback control

2632 equations
40 states
37x37 (linear) + 6x6 (nonlinear) ➔ 0 (linear) + 2x2 (nonlinear)
Applications – Feedback Loop Stability

\[ u(t) = K(y) e(t) \]

\[ \dot{x}(t) = A x(t) + B u(t) \]

\[ x(t) \in \mathbb{R}^{40} \]

\[ \tilde{x}(t) = \tilde{A} \tilde{x}(t) + \tilde{B} u(t) \]

\[ \tilde{x}(t) \in \mathbb{R}^{3} \]

Bode Diagram

Step Response

\[ u(t) = K(y) e(t) \]
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- R&D Needs
Building Controls Virtual Test Bed (BCVTB)

Enable

● Co-simulation for integrated multidisciplinary analysis
● Use of domain-specific tools
● Model-based system-level design
● Model-based operation

Available from
http://simulationresearch.lbl.gov/bcvtb

Based on Ptolemy II from UC Berkeley, which will include BCVTB interface.

Acknowledgements

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Building Controls Virtual Test Bed

Open-source middle-ware based on UC Berkeley’s Ptolemy II program. Synchronizes and exchanges data as (simulation-)time progresses.
Simple Example: Room Heater

Controller: Discrete time proportional controller

\[
y(k + 1) = \max(0, \min(1, K_p (T_{set} - T(k))))
\]

Plant: Room model

\[
T(k + 1) = T(k) + \frac{\Delta t}{C} \left( U A (T_{out} - T(k)) + \dot{Q}_0 y(k) \right)
\]
Simple Example: Room Heater

Discrete Time Proportional Controller

\[ y(k + 1) = \max(0, \min(1, K_p (T_{set} - T(k)))) \]

Implementation in Simulink

Diagram of Simulink model for the controller.
Simple Example: Room Heater

Room model

\[ T(k+1) = T(k) + \frac{\Delta t}{C} \left( UA (T_{out} - T(k)) + \dot{Q}_0 y(k) \right) \]

Implementation in Modelica
Simple Example: Room Heater
BCVTB Time Synchronization

Legend
- Call to a Ptolemy II Simulator actor.
- Exchange of data between two Ptolemy II Simulator actors.
- Exchange of data between a Ptolemy II Simulator actor and a simulation program.
- Initialization step in Ptolemy II, and in simulation programs.
- Time step in Ptolemy II, and in simulation programs.
- Variable $x_1$ of simulator 1 at time step 3.
BCVTB Architecture

Simulator 1

- BCVTB C library
- BSD Socket Client

Simulator 2

- BCVTB C library
- BSD Socket Client

Ptolemy II

Director

- system call
- configuration file

Actor

- system call
- configuration file

BSD Socket Server

- TCP/IP

BSD Socket Server

- TCP/IP
Ex: HVAC in Modelica, Building in EnergyPlus

Rapid virtual prototyping. Path towards embedded computing.

Whole building energy analysis. Reuse of 500,000 lines of code.
Variable Air Volume Flow (VAV) System
Terminal reheat.
Finite state machine for supervisory mode transition.
Local loop control with P and PI controllers.

Original system model
1200 components
4,300 equations
150 state variables
Can execute realistic supervisory and local loop control in Modelica linked to EnergyPlus through co-simulation.

**R&D Needs:**
Support for rapid virtual prototyping.

Robustness of DAE solver.

Computing time.

“Packaging” to make technology easier accessible to non-experts.

Scope of validated model library (HVAC & control components and systems).

Code generation to link design to operation.
This model illustrates the implementation of an EnergyPlus model that communicates with Ptolemy II through BSD sockets. Input into EnergyPlus is a signal for an EMS actuator of a shading device.

Output simulation time and wall clock time. This is for illustration purposes only and not needed by the above model.

Author: Michael Wetter
BACnet

Enables simulation and/or data analysis coupled to Building Automation Systems.

Can read to and write from BACnet devices.

* BACnet stack from http://bacnet.sourceforge.net (Steve Karg)
Reusable modules for model-based operation

Tool selection depends on required:
- model resolution
- emulation of actual control & operation
- dynamics of equipment
- analysis capabilities
- smoothness
- state initialization

Hybrid systems, emulate actual feedback control

Discrete time, idealized controls

www/xml
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- **R&D Needs**
R&D Needs

Model-based design process & deployment
- development of design flows that are based on executable specifications (process & supporting tools)
- extension of Building Information Models to support controls through executable controls specifications

Equation-based object-oriented modeling
- computationally efficient and numerically robust model formulation
- standardized libraries

Equation-based object-oriented simulation
- robust DAE solvers for thermo-fluid & control systems
- multi-rate solvers
- mapping equations to parallel hardware

Co-simulation
- semantics of exchanged data
- standardized data exchange
- adaptive step size

Model Predictive Controls
- MPC that can be deployed to 100,000’s of buildings

Others....
- system-level fault detection and diagnostics
- cybernetic buildings
Vision

Use open standards to enable model-based design and operation for very low energy buildings.

http://www.bacnet.org/
http://www.buildingsmart.com/

http://functional-mockup-interface.org/
http://www.modelica.org/

\[ \dot{x} = f(x) \]