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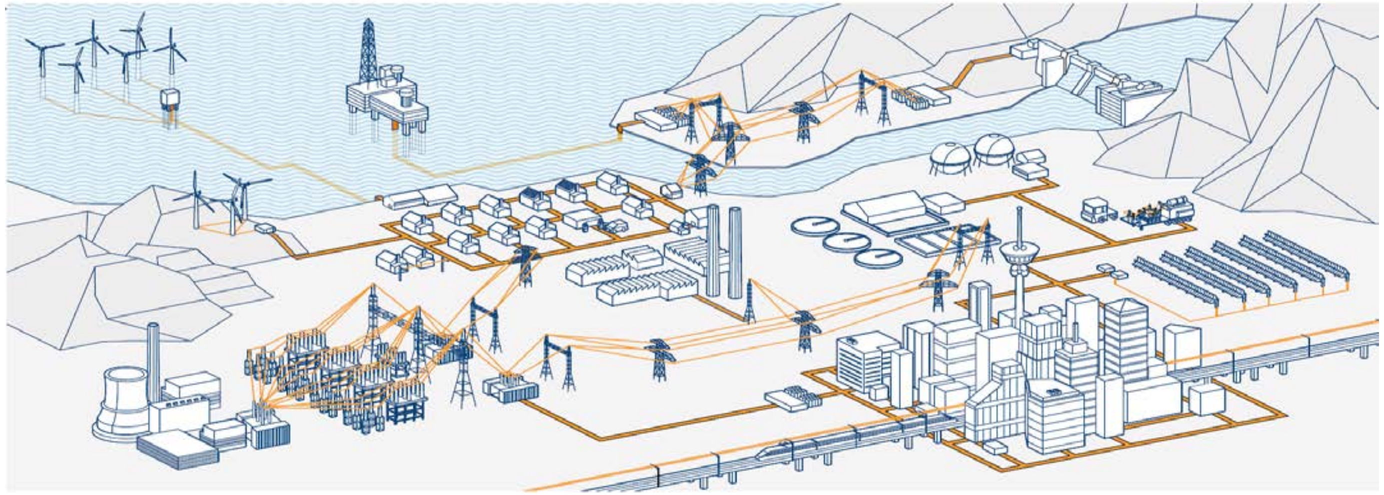
Embedded optimizing control using the OpenModelica C++ runtime

OpenModelica Workshop 2016

Overview

- Motivation and treatment of optimal control programs
- Embedded revolution
- C++ for a modern real-time runtime
- New development: synchronous equations



Dynamic Optimization
Treat optimal control programs basing on simulation models

For dynamic system model and sample time points t_k , $t_0 < t_1 < \ldots < t_K$

- find control *u* (and/or initial states *x(0)*) that minimize criterion *J*
- **subject to mixed discrete/continuous model, initial conditions**
- and further constraints g

$$\mathrm{J} = \sum_{k=0}^{K} f_0\left[k, \begin{pmatrix} x_d(k) \\ x_c(t_k) \end{pmatrix}, \begin{pmatrix} u_d(k) \\ u_c(t_k) \end{pmatrix}\right] \rightarrow \min_{\substack{x_d(0)\; u_d(k) \\ x_c(t_0)\; u_c(t_\mathrm{k})}}$$

FMU ME

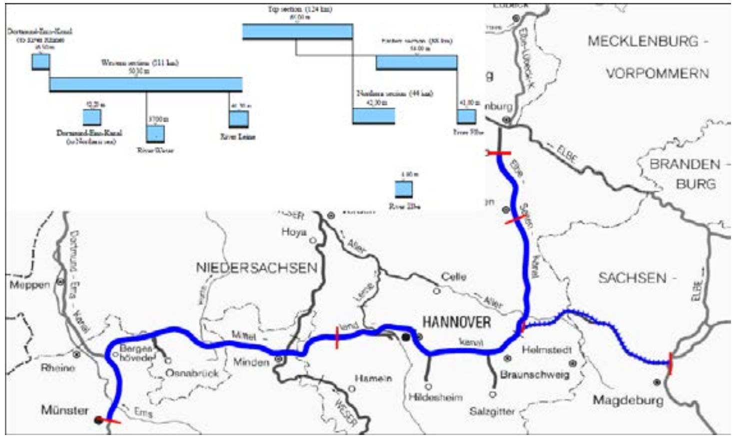
$$x_d(k+1) = f_d[k, x_d(k), x_c(t_k), u_d(k)], \qquad x_d(0) = x_{d0}, \qquad k = 0,1, \ldots, K$$

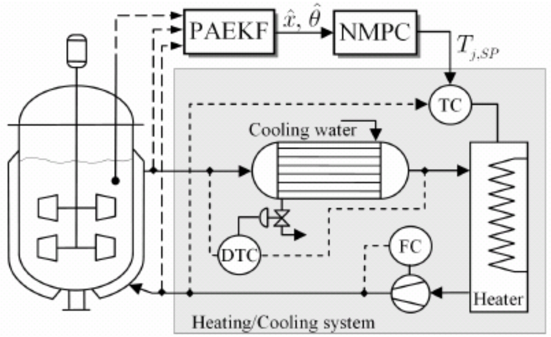
$$\frac{dx_c(t)}{dt} = f_c\big[t, x_d\big(k(t)\big), x_c(t), u_c(t)\big], \qquad x_c(t_0) = x_{c0}, \qquad t \in [t_0, t_K]$$

$$g\big[t, x_d\big(k(t)\big), x_c(t), u_d\big(k(t)\big), u_c(t)\big] \geq 0$$

Some industrial applications of model-based control with HQP solver
The power of mathematical programming

- Wagenpfeil et al, 2014: Water canal system (Uni Stuttgart)
- Franke et al, 2014: Virtual power plants (ABB)
- Neupert et al, 2010: Boom cranes (Uni Stuttgart, Liebherr)
- Nagy et al, 2007: Polymerization reactors (Uni Stuttgart, BASF)
- Franke et al, 2006: Power plant start-up (ABB)
- Linke et al, 1997: Water canal system (Uni Ilmenau, MLK)





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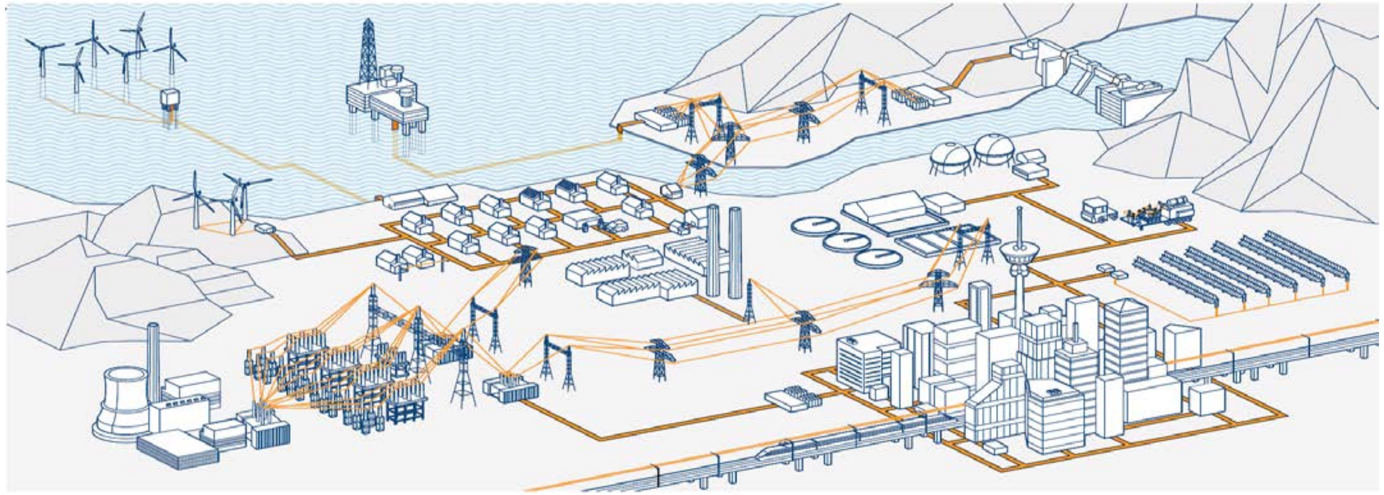

Embedded revolution
Hardware leaped ahead during last decade – Software still too expensive

Embedded traditional

- Special purpose hardware
- Very low computing resources – kHz, kBytes, no floating point, …
- Simple special purpose operating systems

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Embedded in the 21st century

- General purpose hardware (mobile platforms) – cf. Raspberry PI starting at 5$
- High computing power – GHz, GBytes, HD Graphics, System on Chip (SoC)
- General purpose operating systems

Way forward

- Powerful hardware has become available for embedded at low cost
- Software still too expensive – need to increase productivity
- need to develop and exploit appropriate software technologies, such as C++

C++
High-level programming / type safety / high runtime performance

Initiated by Bjarne Stroustrup in 1979; motivated by object-oriented Simula 67

C++98 (ISO/IEC 14882:1998)

- Including Standard Template Library

C++03 (ISO/IEC 14882:2003)

- revised C++98

C++11 (ISO/IEC 14882:2011)

- New library modules, largely impacted by boost library: regular expressions, threads, time, containers, static array, …
- auto keyword, simpler array initialization, lambdas, …

Basis for Cpp runtime

C++14 (ISO/IEC 14882:2014)

- revised C++11

C++17 (upcoming)

C++ features used by the OpenModelica Cpp runtime

- Classes with public interfaces and protected implementations
- Deterministic memory management (no need for garbage collection)
- Templates (e.g. Arrays of different types, up to array of std::string or records)
- Type safety (e.g. dimension of static array being part of type)
- Exception handling

➔High-level features reduce implementation effort while C++ compilers generate very fast code

C++ aims to “leave no room for a lower-level language …
(except for assembly code in rare cases)” (Stroustrup, 2014)

Obtained CPU times with different runtimes for same DrumBoiler example

Considerable speed-ups, in particular with C++ compiler optimization

Modelica Tool for FMU export	CPU time with gcc 4.9.2 flag		
	-O0	-O2	-Ofast
OpenModelica 1.9.3	9.1 s	8.1 s	7.0 s
OpenModelica 1.9.3 +cseCall	4.0 s	3.3 s	3.1 s
Dymola 2015FD01	3.4 s	1.7 s	1.3 s
OpenModelica 1.9.3 +simCodeTaget=Cpp	5.6 s	1.9 s	1.0 s
OpenModelica 1.9.3 +simCodeTaget=Cpp +cseCall	2.7 s	1.0 s	0.6 s

See: R. Franke, M. Walther, N. Worschech, W. Braun, B. Bachmann: Model-based control with FMI and a C++ runtime for Modelica, Modelica Conference, Paris 2015.

ABB

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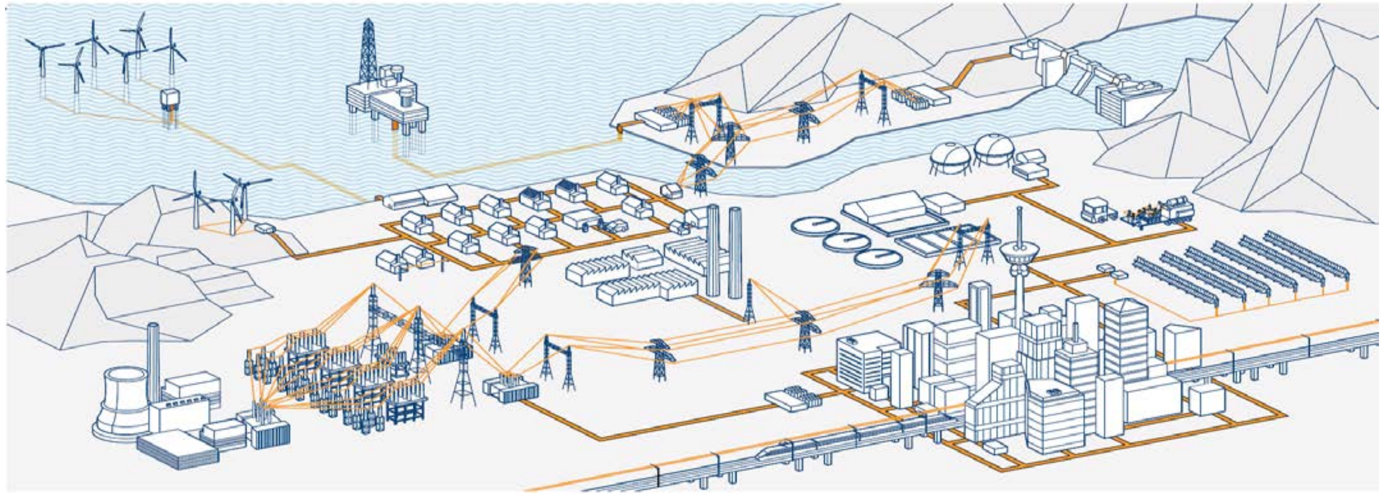
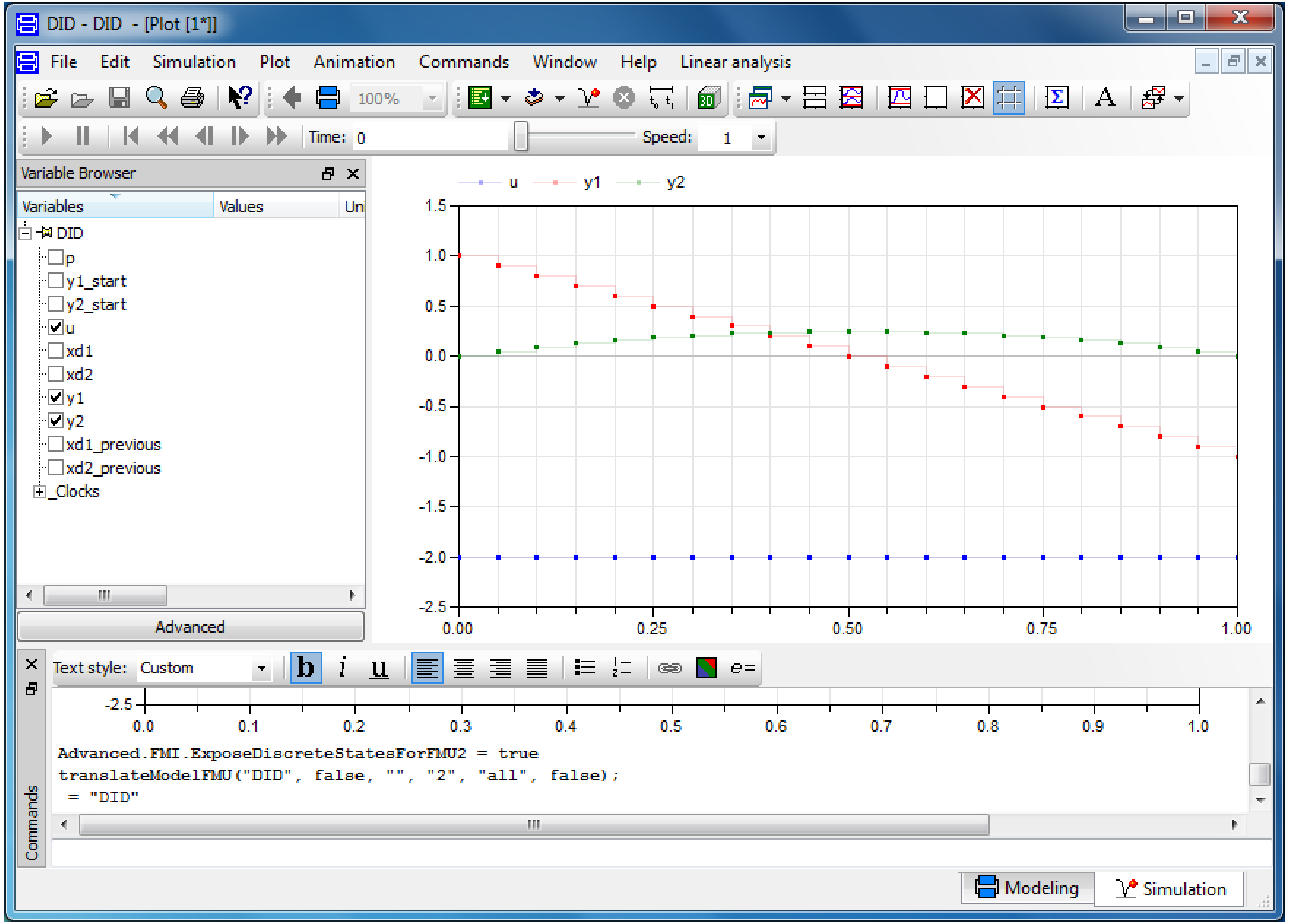


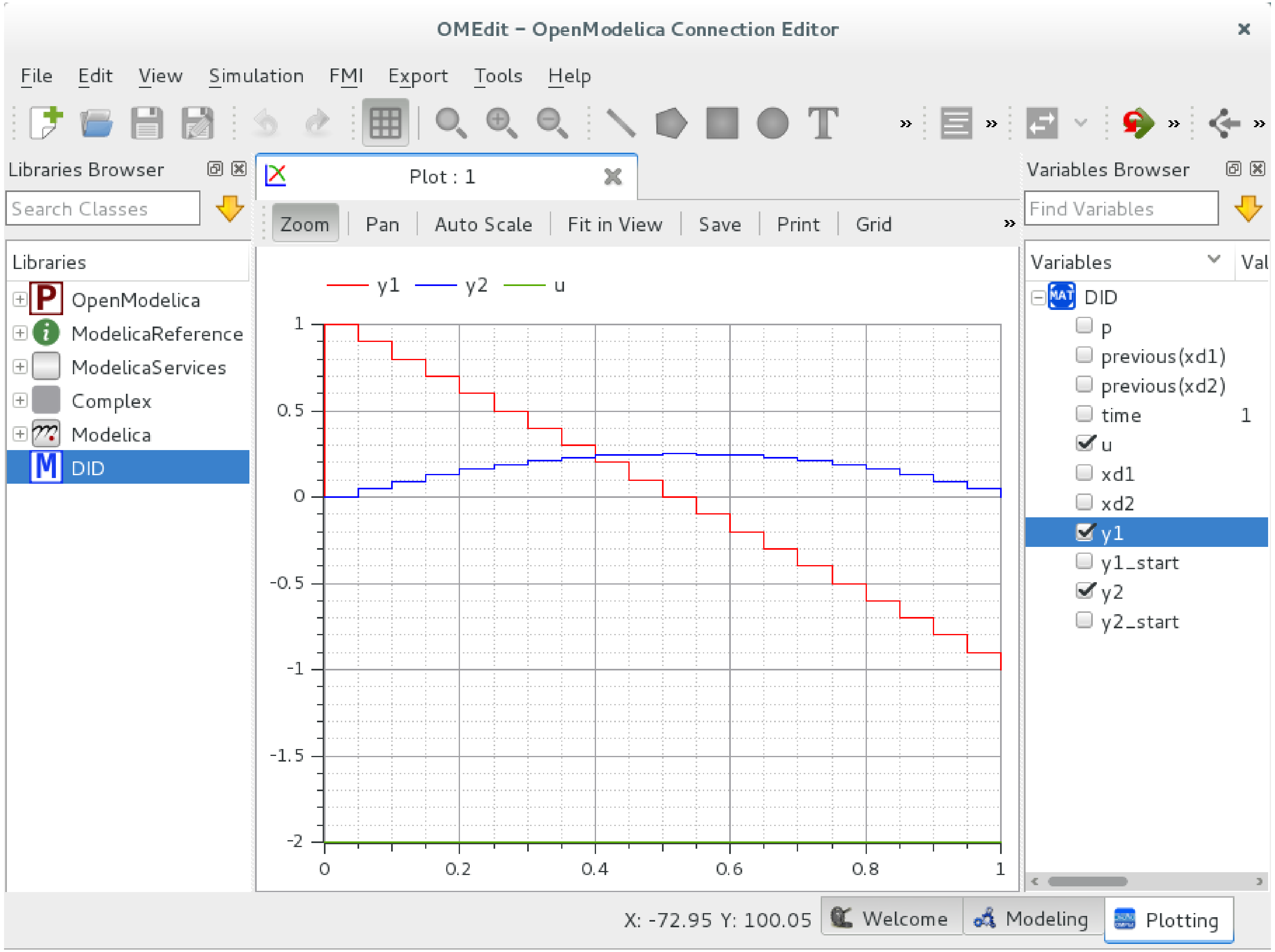
Example: Double Integrator Discrete-time

```
model DID "Double Integrator Discrete-time"
  parameter Real p = 1 "gain for input";
  parameter Real y1_start = 1 "start value for first state";
  parameter Real y2_start = 0 "start value for second state";
  input Real u(start = -2);
  Real xd1(start = y1_start), xd2(start = y2_start);
  output Real y1, y2;
equation
  when Clock(1, 20) then
    xd1 = previous(xd1) + p * u * interval(u);
    xd2 = previous(xd2) + previous(xd1) * interval(u) + 0.5 * u * interval(u)^2;
    y1 = previous(xd1);
    y2 = previous(xd2);
  end when;
end DID;
```

Example: simulation in Dymola 2015 FD01



Example: simulation in OpenModelica (simCodeTarget=Cpp)



Double Integrator optimal control example

Minimize

- control effort

$$J = \sum_{k=0}^{K} u^2(k) \xrightarrow[u(k)]{} min$$

subject to model equations and

- initial states

$$y_1(t_0) = 1, \qquad y_2(t_0) = 0$$

- final states

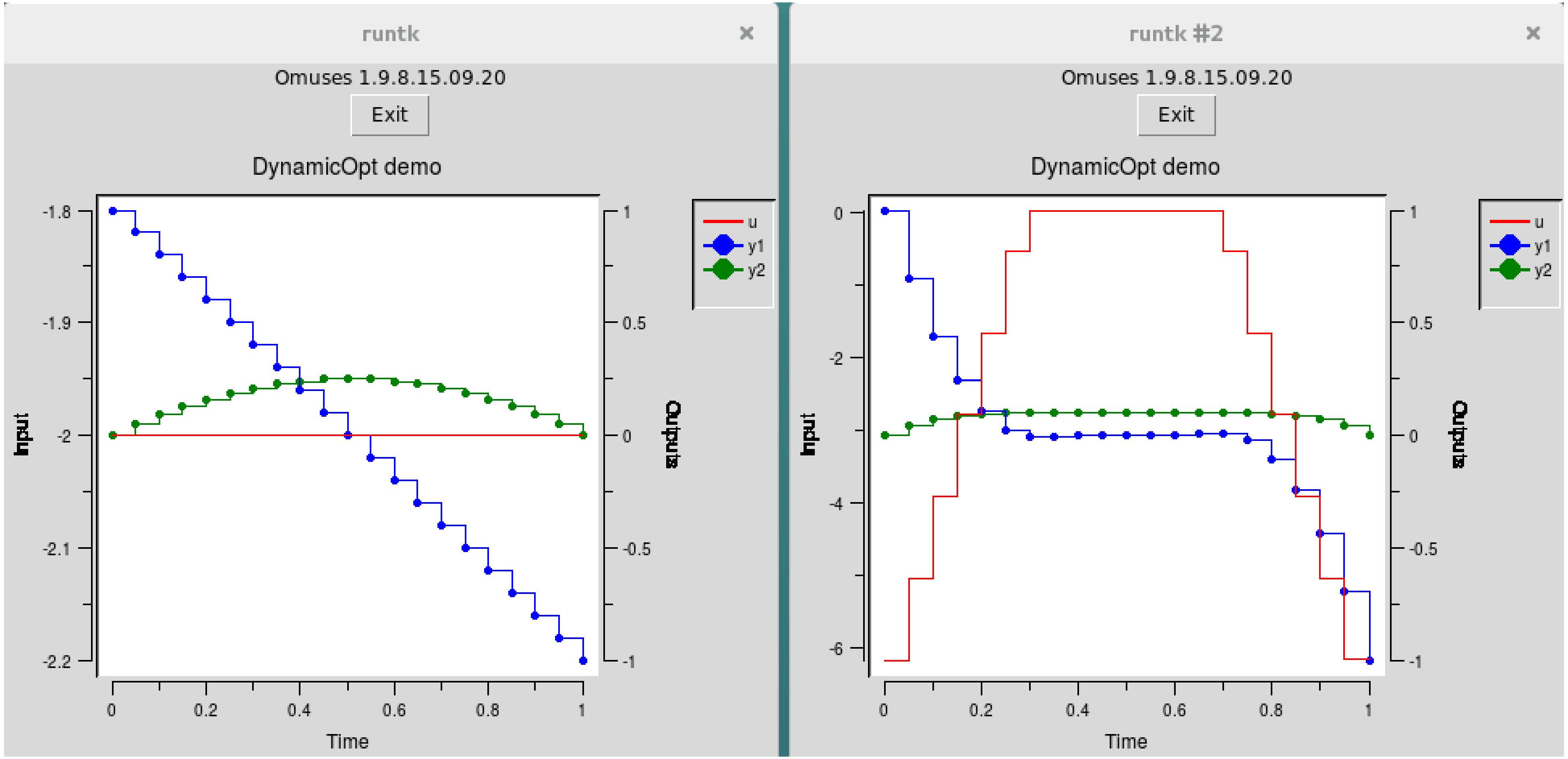
$$y_1(t_K) = -1, \qquad y_2(t_K) = 0$$

- state/output constraint

$$y_2(t) \leq 0.1, \qquad t \in [t_0, t_K]$$

Example: simulation and optimization using HQP

Importing FMU exported with OpenModelica (simCodeTarget=Cpp)



Conclusions

- Model-based applications are often treated as optimal control programs
- New embedded trends enable more applications
  - Powerful hardware has become available at low cost
  - Software still too expensive – need to increase productivity
  - Need to develop and exploit appropriate software technologies, such as C++
- OpenModelica C++ runtime
  - Exploit C++ features (e.g. memory management, templates, type safety)
  - Achieved superior results, compared to other Modelica tools or runtimes
  - Drawback of C++: higher compile/linker requirements – encapsulate in FMI
  - Increased maturity with new compilers supporting C++11 (replacing boost)
  - Serve as basis for new development of FMI export with clocked equations

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for a better world™

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