Using OpenModelica for Bleeding-Edge System Simulations of Large Energy System *Models*

Francesco Casella

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OpenModelica

Outline

- Motivation
- The Delta Robot and Stewart Platform
- An Advanced Fuell Cell Model
- The SOS-CO2 Oxy-Combustion Power Plant Model
- Generation and Transmission System Modelling with PowerGrids 2.0.0
- Conclusions & Outlook

Motivation

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- *You can try innovative approaches*

The Even Bigger Question

DOES IT WORK?

Case Study #1:

The Delta Robot & The Stewart Platform

Credits

Object-Oriented Models of Parallel Manipulators

Paolo Campanini[1] Gianni Ferretti[2]

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[2]Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Piazza Leonardo da Vinci 32, 20133 Milano, Italy, gianni.ferretti@polimi.it

Abstract

In this paper, the development of models of parallel manipulator is described, based on components of the Modelica standard library only. At first, the dynamic model of a Delta robot is illustrated and validated with respect to experimental data. Then, the model of a Stewart platform is discussed. Thanks to the symbolic manipulation capabilities of the OpenModelica compiler, the model is then used to automatically generate the inverse dynamics, which is in general is a quite difficult task.

Keywords: Object-oriented modelling; simulation; parallel manipulators; Modelica; DAE systems; closed chains

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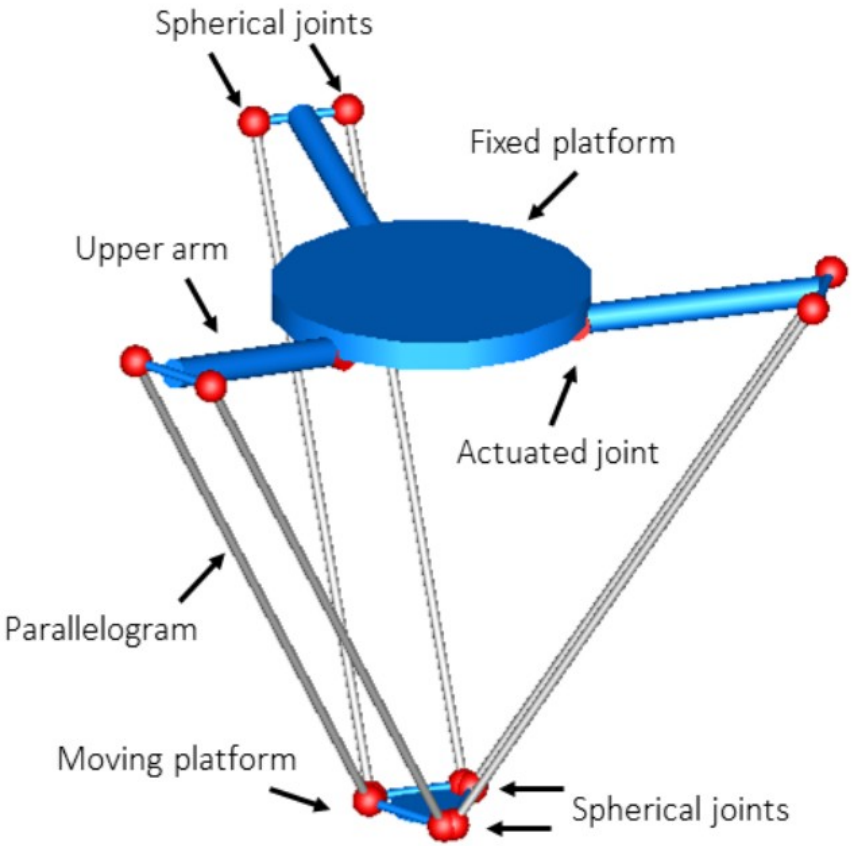
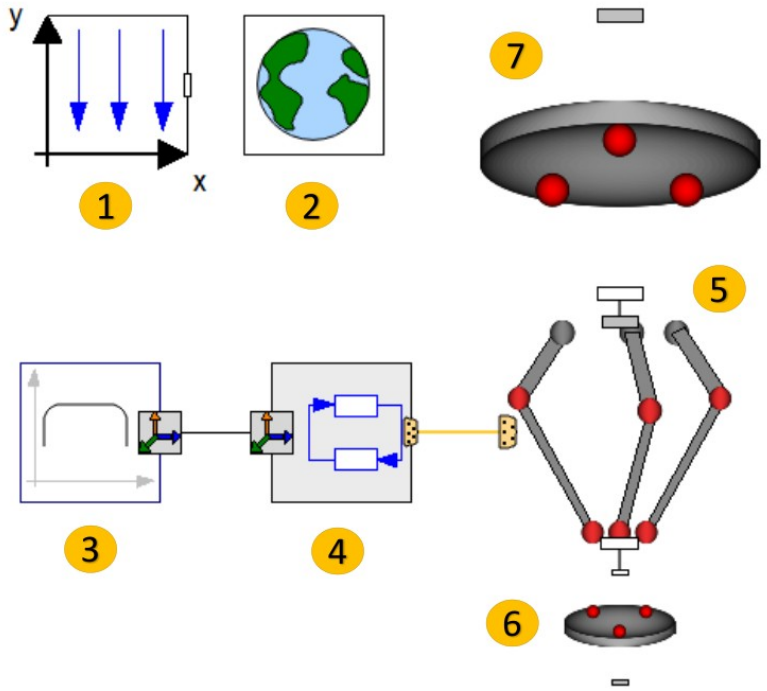
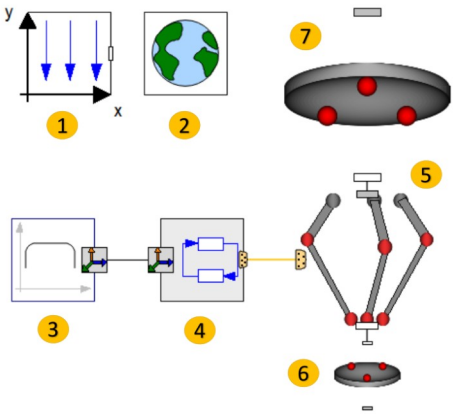
The Delta Robot

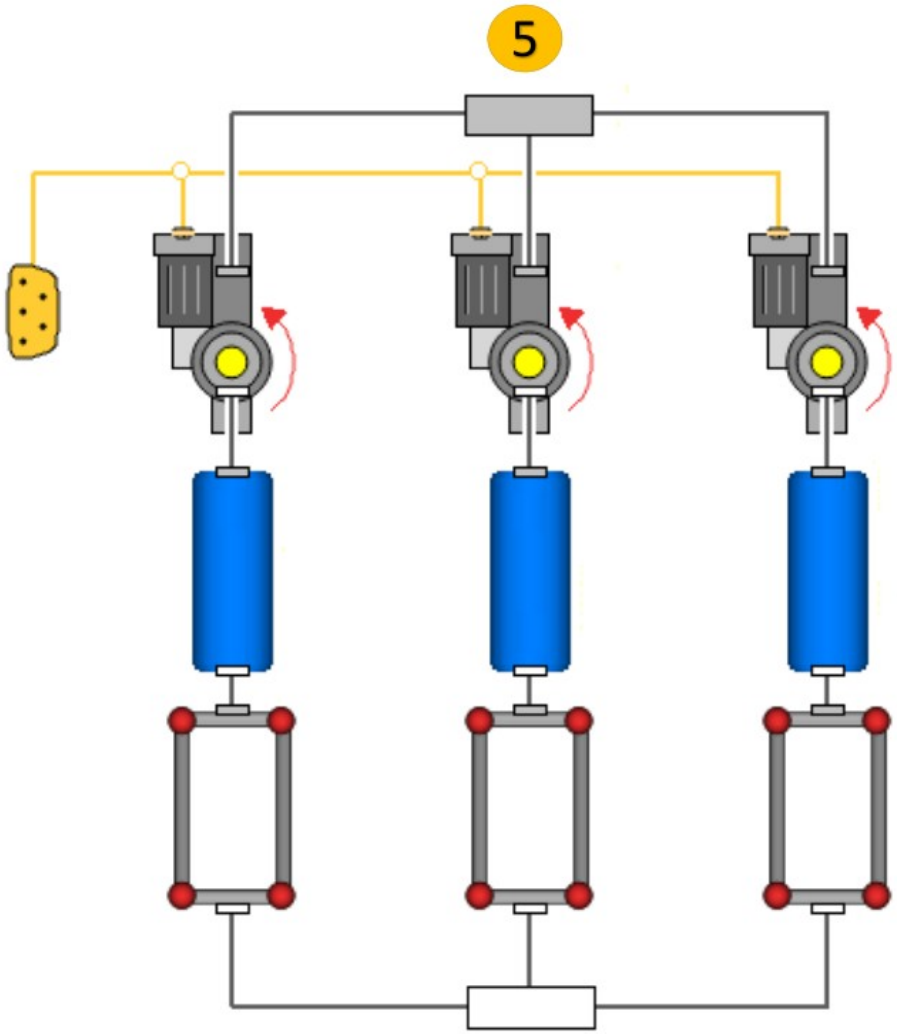
The Model - I


Spherical joints
Fixed platform
Upper arm
Actuated joint
Parallelogram
Moving platform
Spherical joints

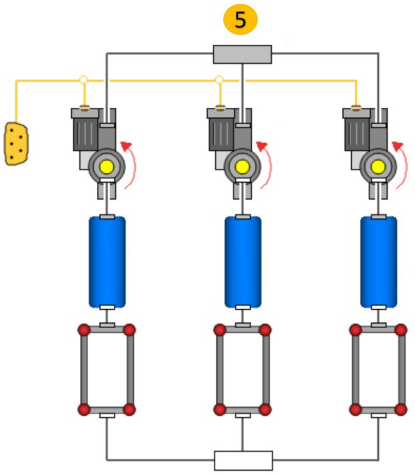

y
x
1
2
7
5
3
4
6

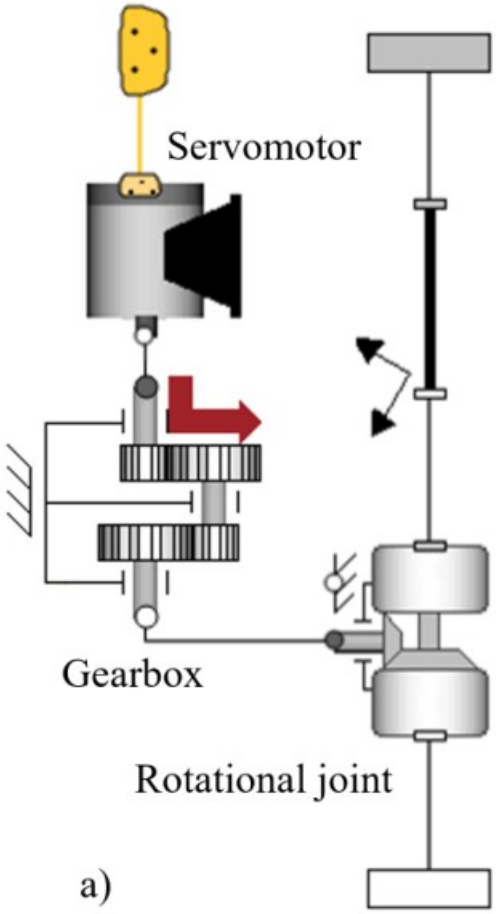
The Model - II

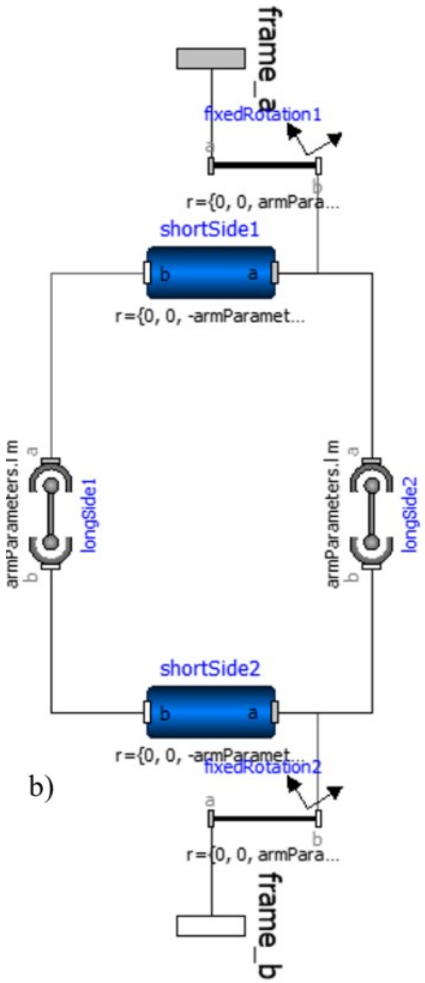




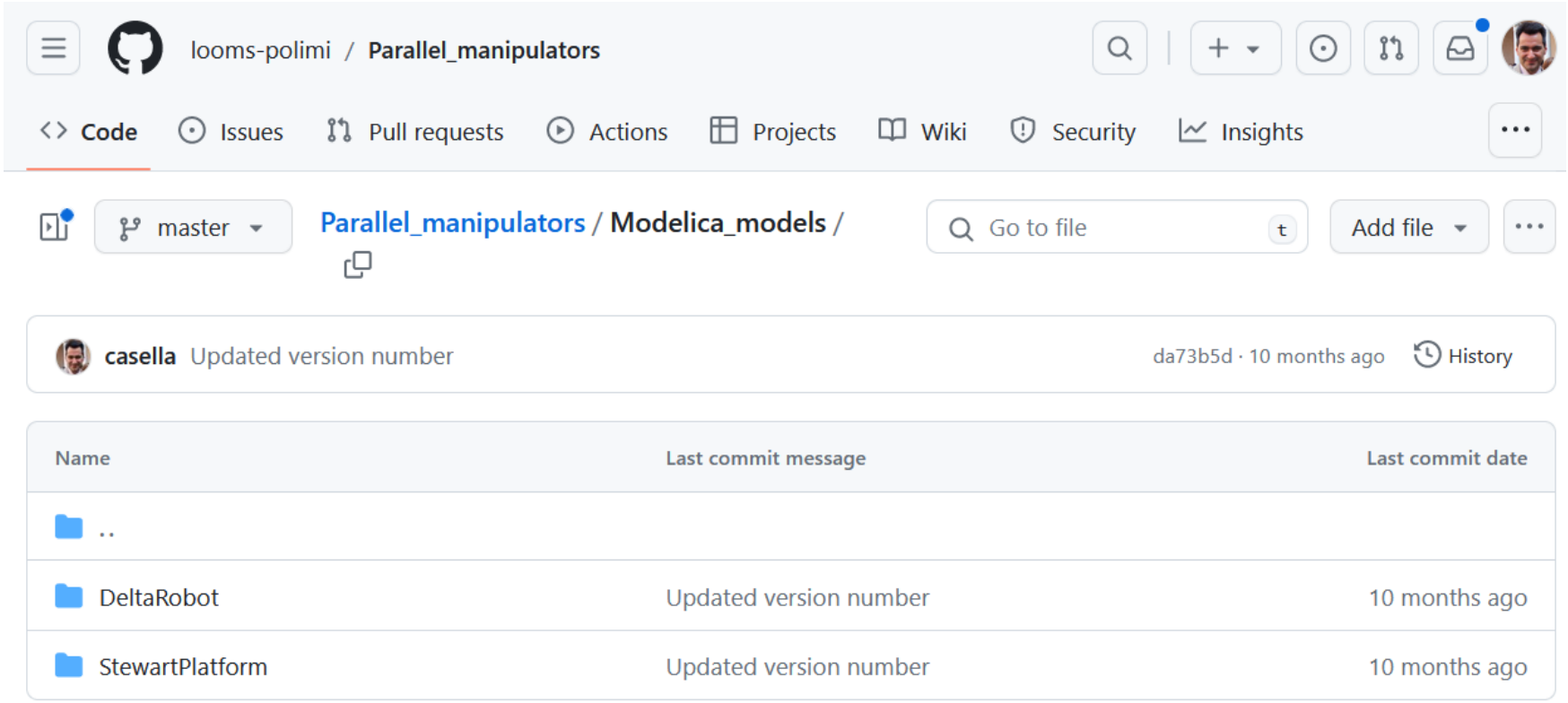
The Model - III







Open Source Code on GitHub



Highlights

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- Tested daily in the OSMC CI

Performance

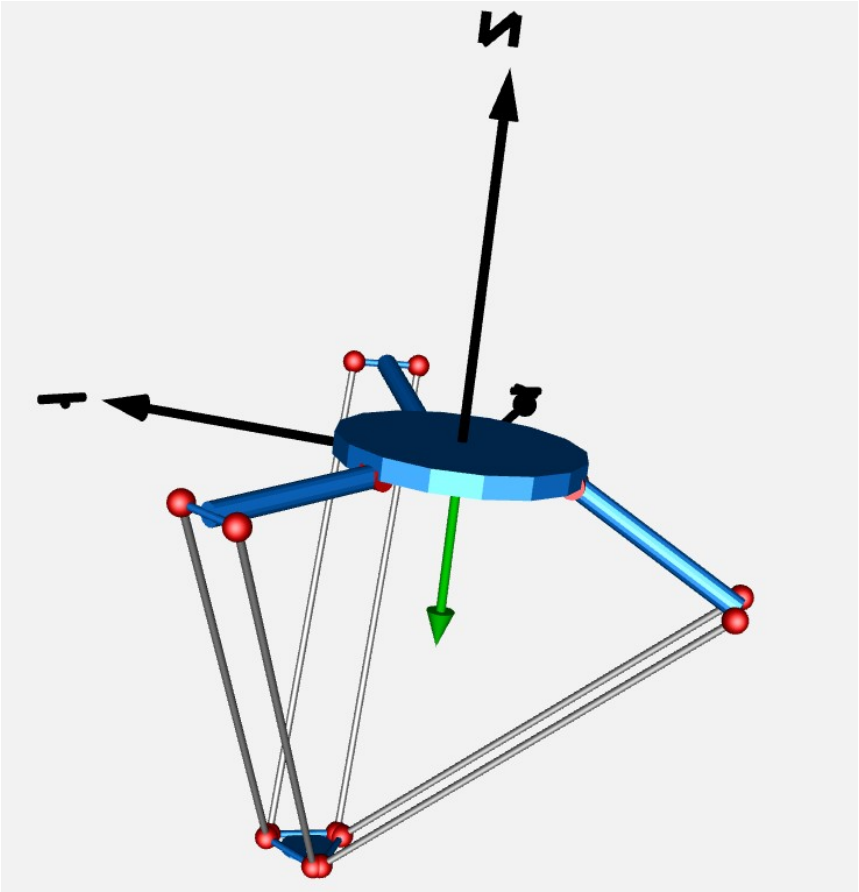
-

DeltaRobot test using OpenModelica

Total	Frontend	Backend	SimCode	Templates	Compilation	Simulation	Verification
9	9	9	9	9	9	9	0

Model	Verified	Simulate	Total build	Model Parsing	Frontend	Backend	SimCode	Templates	Compile
DeltaRobot.Scenarios.DeltaRobot_IdealActPos_PositionValidation (sim)		1.65	59.11	1.80	1.22	31.16	2.22	3.36	21.14
DeltaRobot.Scenarios.DeltaRobot_IdealActPos_Scenario1 (sim)		0.16	40.02	1.79	1.22	22.80	1.44	3.47	11.08
DeltaRobot.Scenarios.DeltaRobot_IdealActVel_Scenario1 (sim)		0.20	38.99	1.76	1.18	23.42	0.96	3.15	10.29
DeltaRobot.Scenarios.DeltaRobot_IdealActVel_VelocityValidation (sim)		1.97	34.26	1.83	1.14	19.78	1.30	2.25	9.79
DeltaRobot.Tests.IdealActuatorPos_test (sim)		0.03	3.17	1.86	0.33	0.17	0.04	0.25	2.39
DeltaRobot.Tests.IdealActuatorVel_test (sim)		0.03	2.88	1.79	0.33	0.15	0.02	0.05	2.33
DeltaRobot.Tests.ServoMotor_test (sim)		0.01	2.01	1.74	0.11	0.01	0.00	0.18	1.71
DeltaRobot.Tests.Switch2_test (sim)		0.02	2.46	1.74	0.11	0.22	0.01	0.04	2.08
DeltaRobot.Tests.Trajectory_test (sim)		0.02	3.52	1.72	0.31	0.30	0.07	0.05	2.80

Demo



The Stewart Platform

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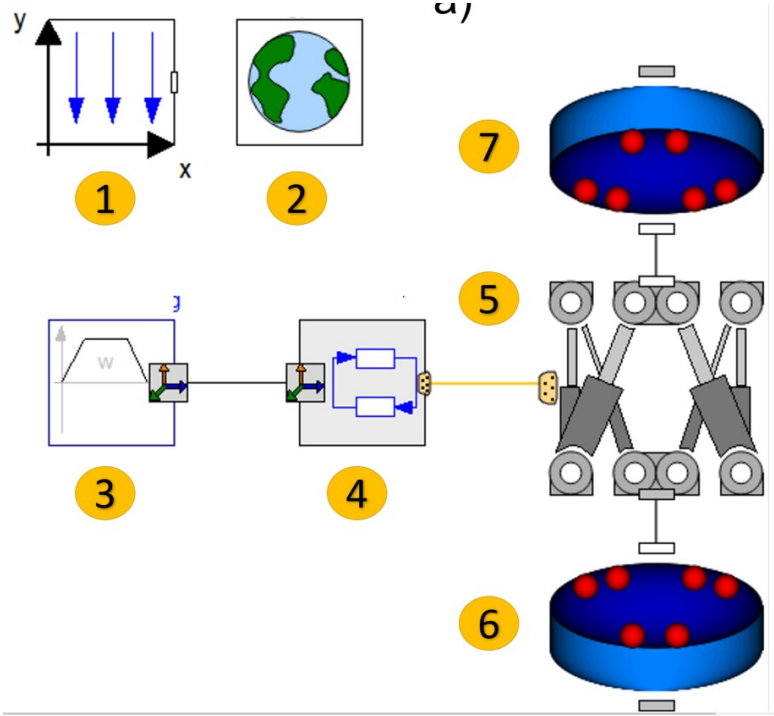
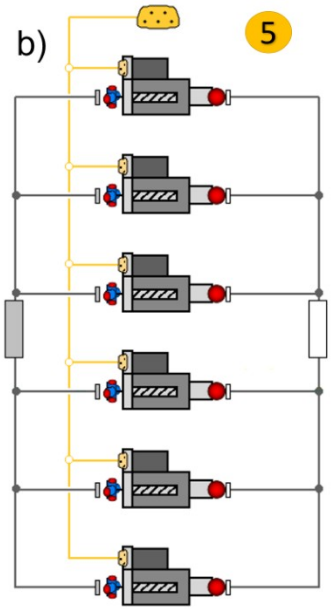
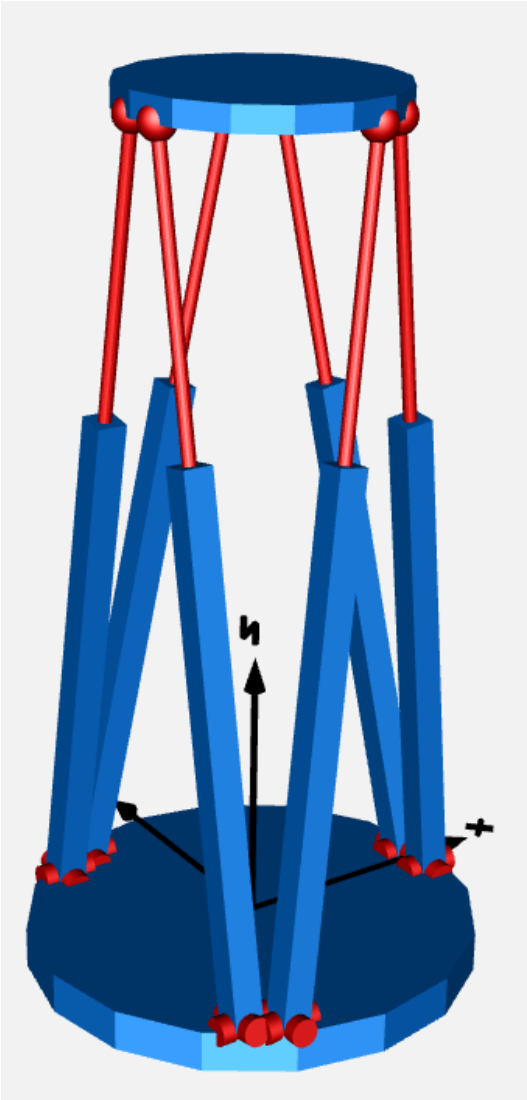




9389 equations
12 state variables

Demo



Outlook

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- Open-Source Base Library: MSL
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Imagine the potential...

Case Study #2:

A Fuel-Cell Model for Oxy-Combustion Cycles

Credits

2023 IEEE Conference on Control Technology and Applications (CCTA)
August 16-18, 2023. Bridgetown, Barbados

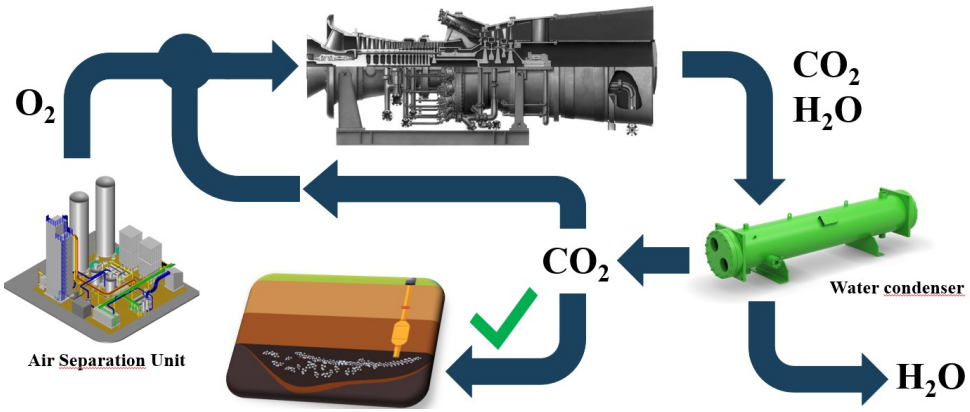
A Control-Oriented Modelica 1-D Model of a Planar Solid-Oxide Fuel Cell for Oxy-Combustion Cycles

Matteo Luigi De Pascali[1], Alessandro Donazzi[2], Emanuele Martelli[2] and Francesco Casella[1]

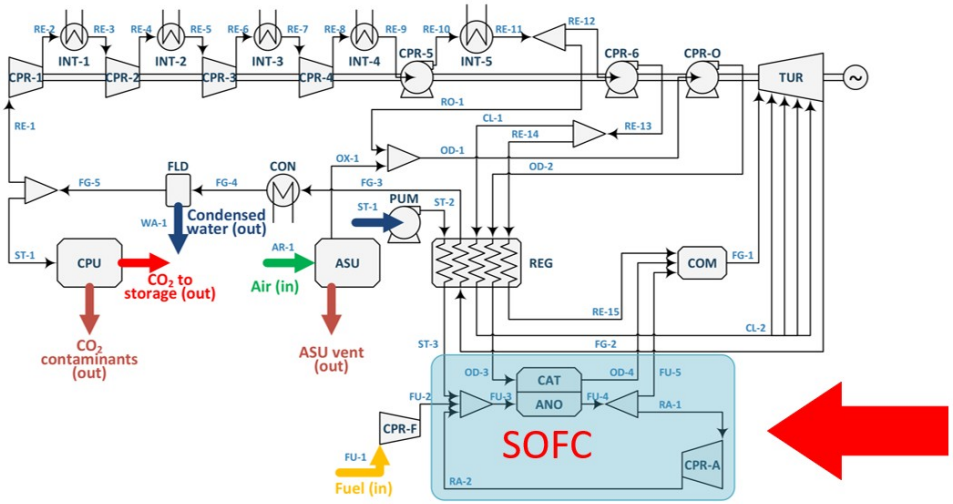
***Abstract*— The authors propose an object-oriented Modelica 1-D SOFC model following the indications of a previous work. The model is intended to be used in the study of the SOS-CO_2 cycle for control studies purposes. The SOFC working conditions are challenging and require adapting the model to handle properly reformate mixtures at the anode and carbon dioxide-rich mixtures at the cathode while keeping its formulation as simple as possible. This paper reviews the previous contribution, adapts the model for the new working conditions, provides insights related to the Modelica implementation, reproduces the tests presented in literature and extends the validation through a comparison with experimental data. Finally the model is tested under SOS-CO_2 cycle operative conditions.**

Context

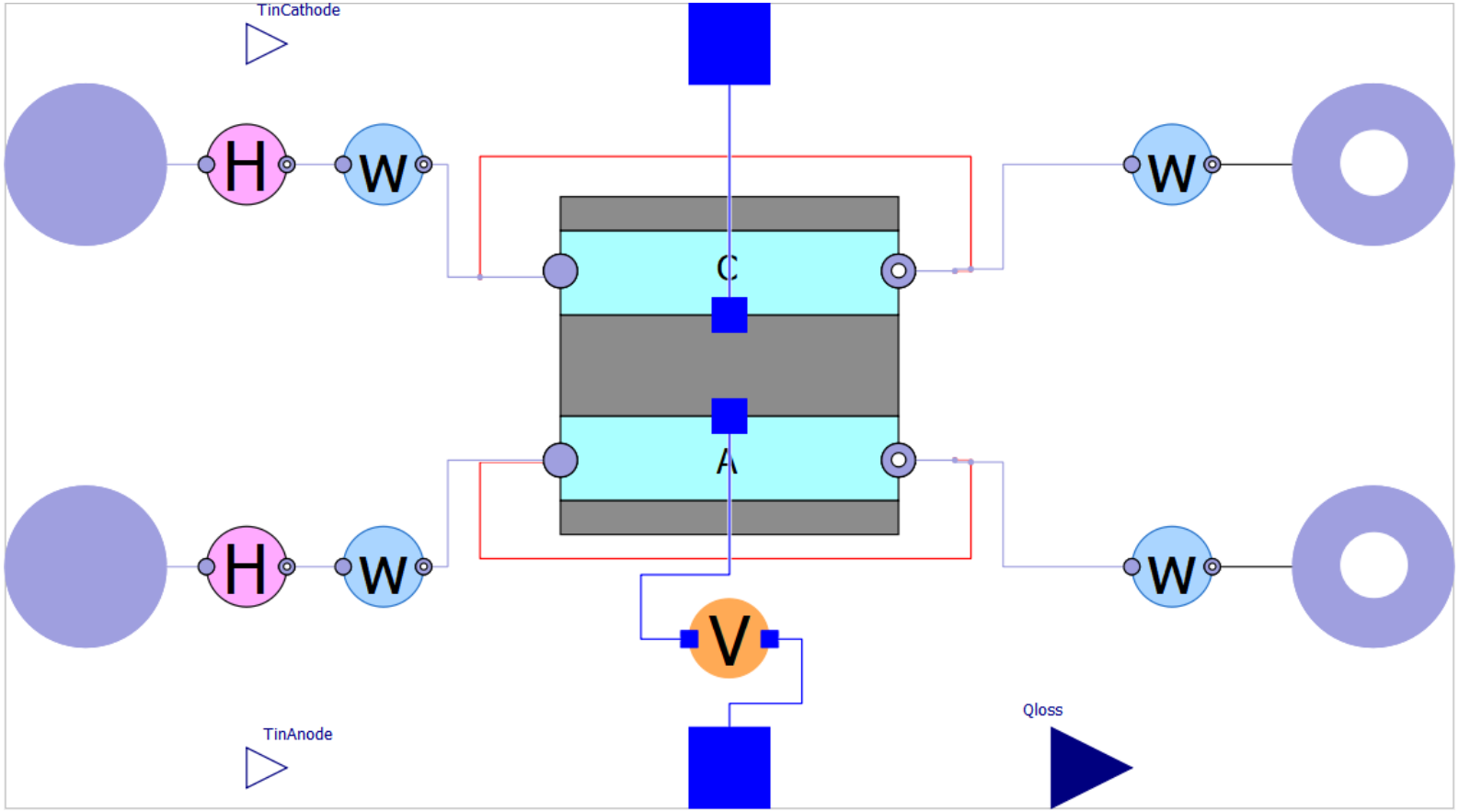
Oxy-Combusion Thermal Power Plant Concept



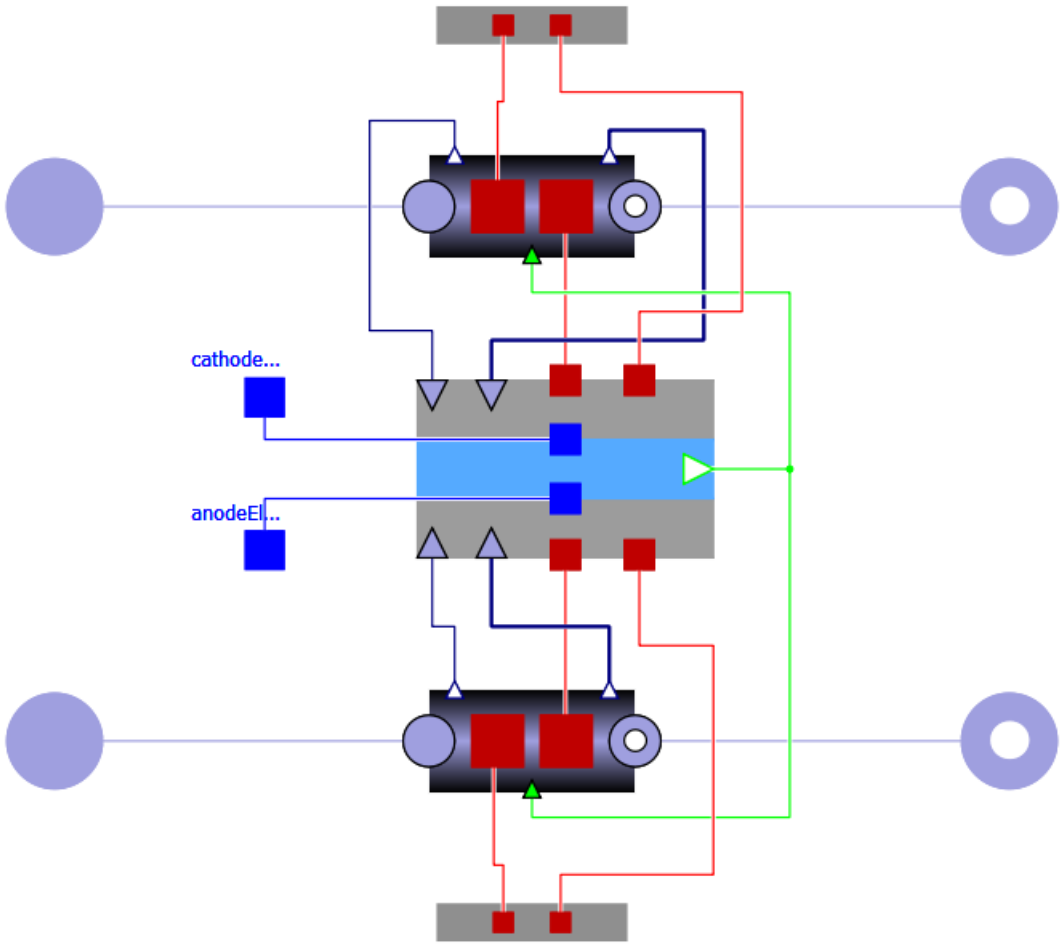
The SOS-CO_2 power plant



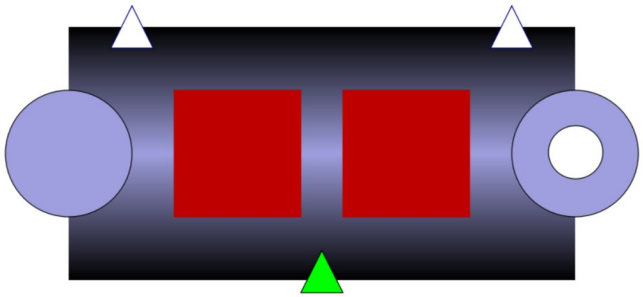
The Stack Model

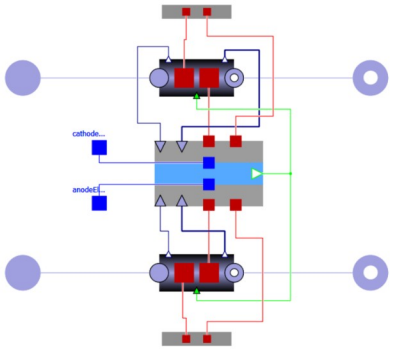


The Single Module Model



The 1D Channel Model



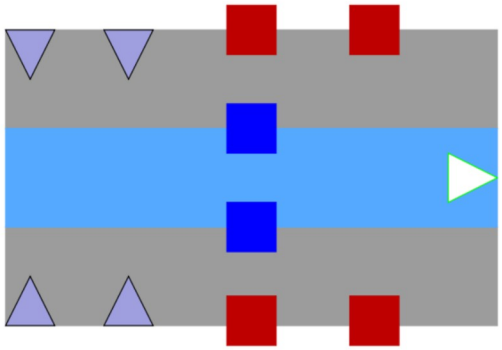


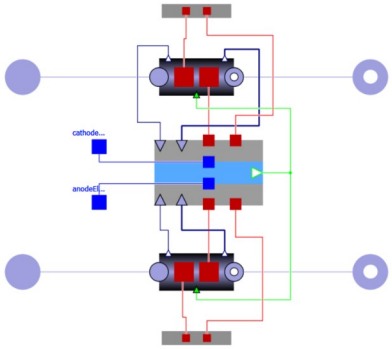
$$\frac{\mathrm{d}M}{\mathrm{d}t} = -V\rho^2 \left(\frac{\partial v_o}{\partial T_o} \frac{\mathrm{d}T_o}{\mathrm{d}t} + \frac{\partial v_o}{\partial p_o} \frac{\mathrm{d}p_o}{\mathrm{d}t} + \frac{\partial v_o}{\partial \bar{X}_o} \frac{\mathrm{d}\bar{X}_o}{\mathrm{d}t} \right)$$

$$M \frac{\mathrm{d}X_{j,o}}{\mathrm{d}t} = w_i \left(X_{j,i} - X_{j,o} \right) + S \cdot \mathrm{MM}_j \sum_{r=1,3} a_{j,r} r_r - X_{j,o} w_{O_2} + w_{j,O2}$$

$$M \left(\frac{\partial u_o}{\partial T_o} \frac{\mathrm{d}T_o}{\mathrm{d}t} + \frac{\partial u_o}{\partial p_o} \frac{\mathrm{d}p_o}{\mathrm{d}t} + \frac{\partial u_o}{\partial \bar{X}_o} \frac{\mathrm{d}\bar{X}_o}{\mathrm{d}t} \right) = w_i \cdot h_i - w_o \cdot h_o + Q_{PEN} + Q_{Plate}$$

The Proton Exchange Membrane Model





$$V_{OCP} = -\frac{\Delta g_{0,hor}}{nF} - \frac{RT}{nF} \cdot \ln\left(\frac{p_{H_2O}}{p_{H2} \cdot \sqrt{\frac{p_{O2}}{p_{ref}}}}\right)$$

$$v_{act}^{el} = \frac{RT_{PEN}}{\beta nF} \ln\left(\frac{j}{2j_0^{el}} + \sqrt{\left(\frac{j}{2j_0^{el}}\right)^2 + 1}\right)$$

$$j_0^{el} = \frac{RT_{PEN}}{nF} k_{el} \cdot \exp\left(-\frac{E_{el}}{RT_{PEN}}\right)$$

$$r_{sr} = k_{0,sr} \cdot \exp\left(-\frac{E_{a,sr}}{RT}\right) p_{CH_4}\, p_{H_2O} \left(1 - \frac{k_{P,sr}}{k_{Eq,sr}}\right)$$

Highlights

- About 10,000 equations
- Strongly nonlinear equations:
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- Model initially developed with Dymola
- We wanted to make it fully open-source for publication → run in OMC

Adapting the Model to OMC

- Steady-state initialization succeeded in Dymola but not in OMC
- Two issues:
  - Insufficient symbolic manipulation for the required $\lambda = 0$ simplifications $\rightarrow$ sequential computations
  - Bad tearing

Insufficient Symbolic Manipulation

```
dM_dt = wIn - wOut + wO2 "Overall mass balance";
```

```
dM_dt = -V*rhoOut^2*(fluidOut.dv_dT*der(Tout) +
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```
initial equation
  if initType == InitType.steadyState then
    if initialEquation then
      der(pOut) = 0;
    end if;
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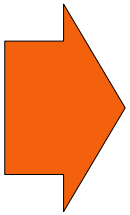

The Tearing Dilemma:

Rely on fantastic tearing algorithms

vs.

Rely on the modeller's experience?

Outlook

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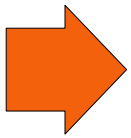

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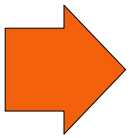

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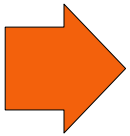

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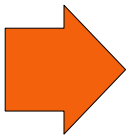

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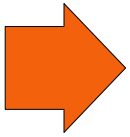
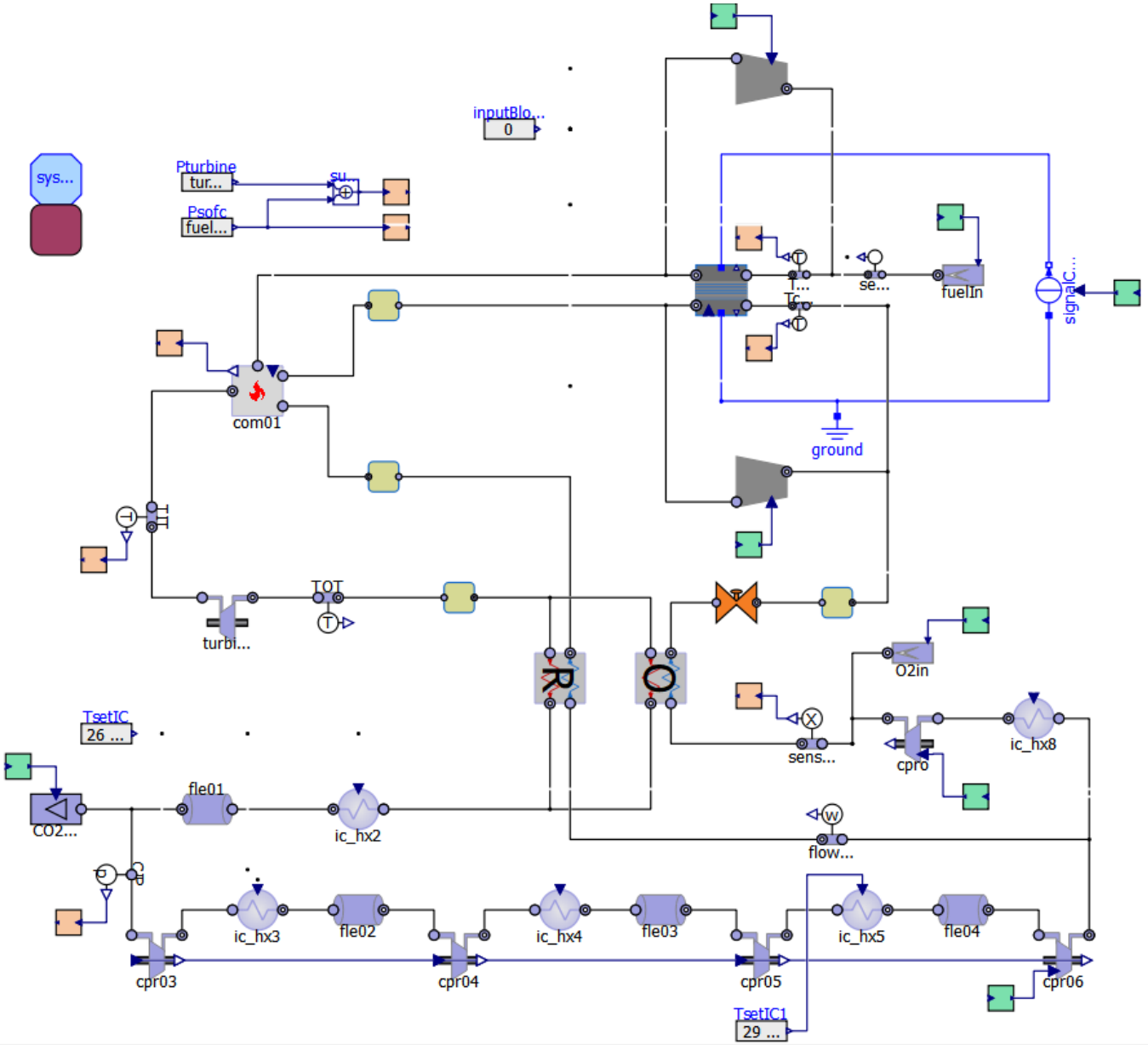


Fully open-source (incl. Modelica tool)

Case Study #3:

The SOS-CO2 Power Plant

The SOS-CO2 Plant Model



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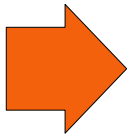
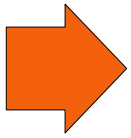


Usable, but not very practical yet



Further optimizations required in the backend and code generation phases

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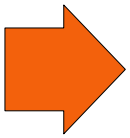

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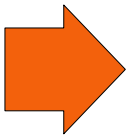

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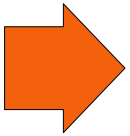

Dymola: dead end because of IP issues

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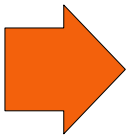

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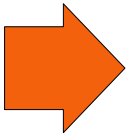

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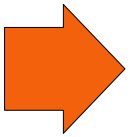

OMC: we can still look under the hood

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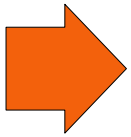
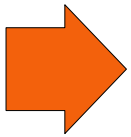


Further investigation required



Most likely a scaling issue

Outlook

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With some further optimization, it could match or even surpass Dymola's performance (e.g. handling backward init to 20% load)

Case Study #4:

Power System Modelling with PowerGrids 2.0.0

Power Grids 1.0.0 (now 1.0.3)

Towards Pan-European Power Grid Modelling in Modelica: Design Principles and a Prototype for a Reference Power System Library

Andrea Bartolini[1] Francesco Casella[2] Adrien Guironnet[3]

[1]Dynamica s.r.l., Italy, andrea.bartolini@dynamica-it.com
[2]Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Italy, francesco.casella@polimi.it
[3]RTE, France, adrien.guironnet@rte-france.com

Abstract

This paper presents the PowerGrids library, which is aimed at the modelling of large-scale power transmission and distribution system. The requirements and design principles of the library are extensively discussed, as well as some key implementation details. The library represents a prototype implementation of the presented requirements and design guidelines, and will form the basis for the future development of an industrial-grade open-source library to be used by European TSOs and DSOs.

Keywords: Power System Modelling, Power Generation and Transmission, Pan-European Power System

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  - Significant refactoring of interfaces, based on experience with 1.0.x
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- Many thanks to:
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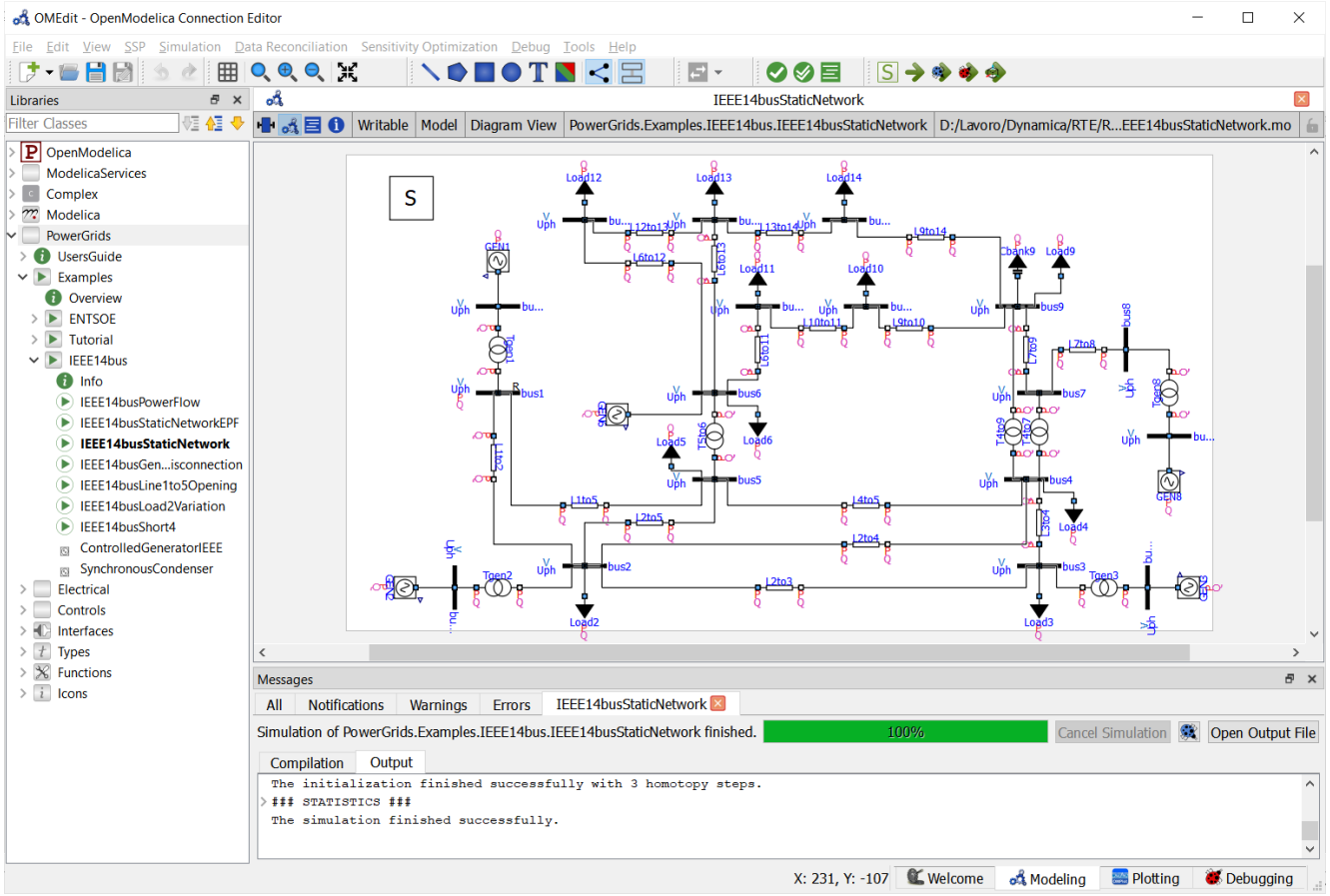
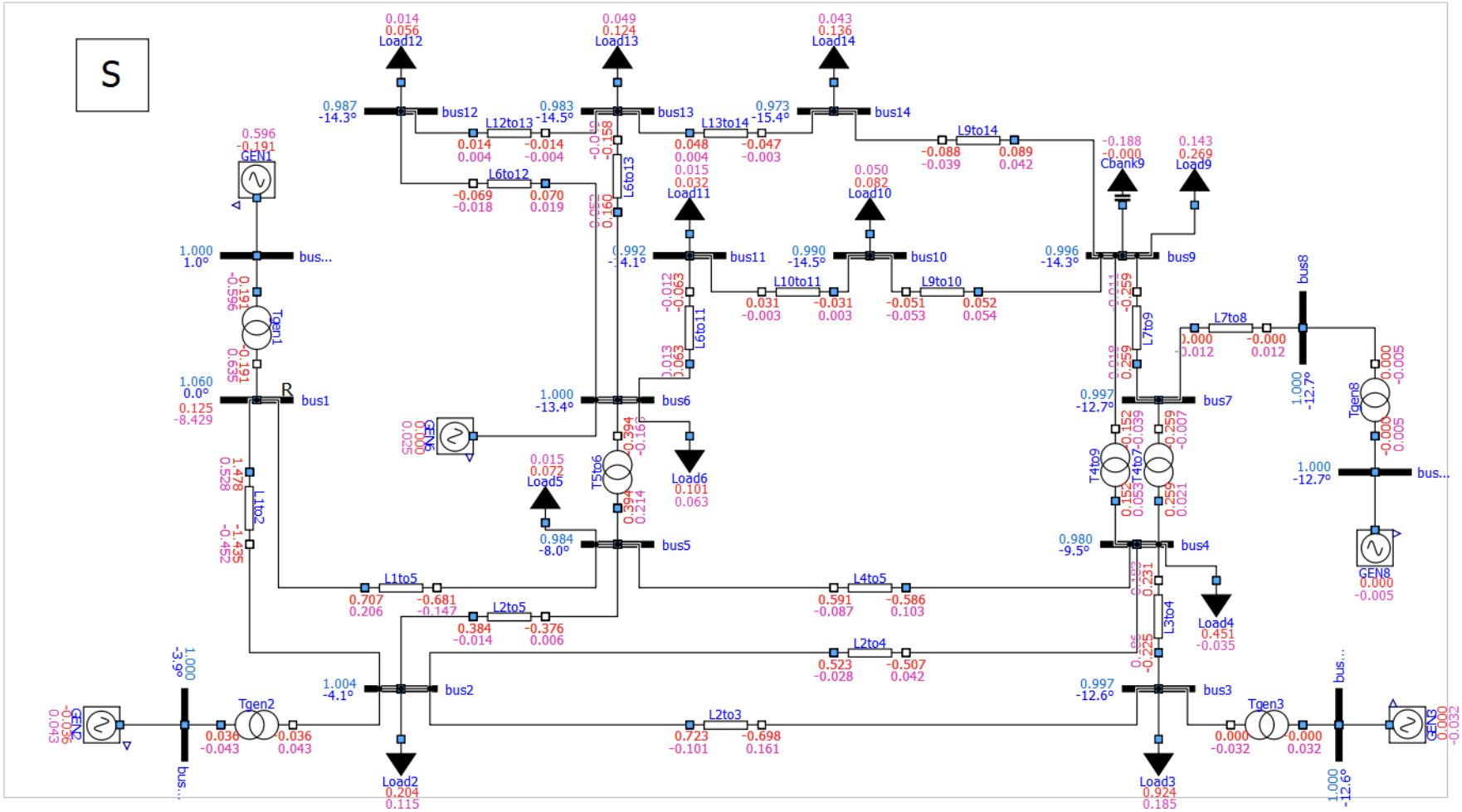
  - Prof. **Massimo Ceraolo** (Univ. Pisa) for the financial support to the development of PowerGrids 2.0.0 and for the (relentless!) end-user feedback

PowerGrids 2.0.0 + OpenModelica

- A fully open-source integrated environment for power system simulation
  - Usable for teaching and research
  - Integrated power flow computation for initialization
  - GUI for building and editing models and for simulation results display
  - State of the art numerical solvers (IDA + Kinsol + KLU)



Using DynamicSelect Diagrams



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- Code generation: done
- Simulation runtime: done, using IDA+Kinsol+KLU

Current Test Results with New Backend

Model	Verified	Simulate	Total buildModel	Parsing	Frontend	Backend	SimCode	Templates	Compile
PowerGrids.Controls.Test.TestDeadBand (sim)	0.00 (1/8 failed)	0.01	1.61	1.62	0.00	0.00	0.00	0.01	1.59
PowerGrids.Controls.Test.TestDerivativeLag (sim)	0.01 (1/35 failed)	0.01	1.59	1.70	0.01	0.01	0.00	0.01	1.55
PowerGrids.Controls.Test.TestDiscontinuousDeadBand (sim)	0.00 (1/8 failed)	0.01	1.64	1.62	0.00	0.00	0.00	0.01	1.62
PowerGrids.Controls.Test.TestFirstOrderWithNonWindupLimiter		0.00	0.16	1.73	0.01	0.13	0.00	0.02	0.00
PowerGrids.Controls.Test.TestIntegratorWithNonWindupLimiter		0.00	0.04	1.68	0.01	0.03	0.00	0.00	0.00
PowerGrids.Controls.Test.TestLeadLag (sim)	0.01 (1/38 failed)	0.01	1.64	1.67	0.01	0.01	0.00	0.01	1.60
PowerGrids.Controls.Test.TestLeadLagWithNonWindupLimiter		0.00	0.16	1.70	0.01	0.13	0.00	0.02	0.00
PowerGrids.Controls.Test.TestLeadMOrderLag (sim)	1.03 (301/1346 failed)	0.18	2.65	1.67	0.01	0.18	0.02	0.05	2.39
PowerGrids.Controls.Test.TestLimiterWithLag		0.00	0.03	1.64	0.01	0.02	0.00	0.00	0.00
PowerGrids.Controls.Test.TestPIWithNonWindupLimiter		0.00	0.03	1.68	0.01	0.02	0.00	0.00	0.00
PowerGrids.Controls.Test.TestRampTrackingFilter		0.00	0.00	1.72	0.00	0.00	0.00	0.00	0.00
PowerGrids.Electrical.Test.LoadImpedancePQ (sim)	0.03 (228 verified)	0.08	2.47	1.52	0.03	0.17	0.01	0.03	2.23
PowerGrids.Electrical.Test.OneBusImpedanceOneLoad (sim)	0.00 (82 verified)	0.02	2.04	1.58	0.02	0.02	0.00	0.14	1.86
PowerGrids.Electrical.Test.OneBusImpedanceOneVariableLoad (sim)	0.02 (160 verified)	0.05	2.13	1.58	0.02	0.15	0.01	0.02	1.94
PowerGrids.Electrical.Test.OneBusImpedanceVariableVoltageOneLoad (sim)	0.01 (89 verified)	0.02	1.94	1.61	0.02	0.02	0.01	0.14	1.76
PowerGrids.Electrical.Test.OneBusOneLoad (sim)	0.00 (82 verified)	0.02	2.09	1.61	0.02	0.01	0.00	0.15	1.90
PowerGrids.Electrical.Test.OneBusTransmissionLineOneLoad (sim)	0.00 (138 verified)	0.05	2.21	1.60	0.03	0.16	0.01	0.02	1.99
PowerGrids.Electrical.Test.OneBusTransmissionLineShuntOneLoad (sim)	0.00 (138 verified)	0.05	2.23	1.61	0.03	0.16	0.01	0.03	2.02
PowerGrids.Electrical.Test.SynchronousMachine4Windings (sim)	0.13 (5/148 failed)	0.29	2.26	1.60	0.03	0.15	0.01	0.02	2.05
PowerGrids.Electrical.Test.SynchronousMachine4WindingsAccurate (sim)	0.03 (5/148 failed)	0.10	2.19	1.62	0.02	0.16	0.01	0.02	1.97
PowerGrids.Electrical.Test.SynchronousMachine4WindingsExact (sim)	0.05 (15/148 failed)	0.09	2.21	1.58	0.02	0.15	0.01	0.02	2.01
PowerGrids.Electrical.Test.SynchronousMachine4WindingsNoLoad (sim)	0.48 (5/148 failed)	1.06	2.17	1.62	0.03	0.15	0.01	0.02	1.97
PowerGrids.Electrical.Test.SynchronousMachine4WindingsNoLoadAccurate (sim)	0.47 (5/148 failed)	1.35	2.18	1.62	0.02	0.14	0.01	0.02	1.99
PowerGrids.Electrical.Test.SynchronousMachine4WindingsNoLoadExact (sim)	0.48 (5/148 failed)	1.38	2.21	1.60	0.02	0.14	0.01	0.02	2.02
PowerGrids.Electrical.Test.SynchronousMachine4WindingsPowerSwing		0.00	2.16	1.53	0.03	0.15	0.01	0.02	1.94
PowerGrids.Electrical.Test.TestExciterRectifierRegulationCharacteristicIEEE (sim)		0.01	1.74	1.57	0.01	0.00	0.00	0.01	1.71
PowerGrids.Electrical.Test.TestExciterVoltageTransducerIEEE		0.00	0.03	1.53	0.01	0.02	0.00	0.00	0.00
PowerGrids.Electrical.Test.TestOneBusTransmissionLineWithBreakersOneLoad		0.00	0.19	1.61	0.03	0.16	0.00	0.00	0.00
PowerGrids.Electrical.Test.TestTapChangerLogicInterval		0.00	0.03	1.49	0.01	0.02	0.00	0.00	0.00
PowerGrids.Electrical.Test.TestTapChangerLogicMax		0.00	0.03	1.52	0.01	0.02	0.00	0.00	0.00

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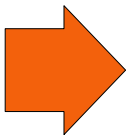

Goal: run national- and continental-size power system models out of the box in OMC

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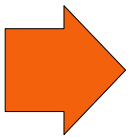

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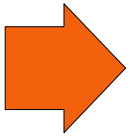

Support the challenges posed by the energy transition on the power systems in the EU and beyond

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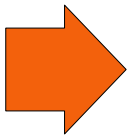
- Shortcoming and issues can be handled together with end-users thanks to the open-source model

- Work in progress to further optimize and streamline performance and numerical robustness



Bright future ahead!

Thank you for your kind attention!