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Control of Technological and Production Processes Modeled by COMSOL Multiphysics as Distributed Parameter Systems

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Thank you for having me in your wonderful city of Bangalore!

(and thanks for Emirates airline to lose my luggage with my laptop, suit and product samples – then eventually finding it... :-))

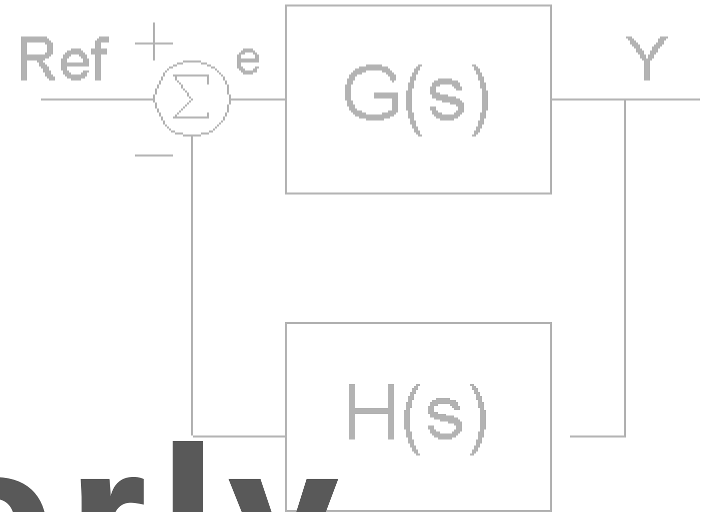
Aim and motivation

- COMSOL Makes possible to easily model intricate coupled physics over complex spatial structures
- Exponential development of computing power allows to model more and more complex shapes and phenomena using FEM

But how did control theory and practice follow and adapt to this amazing development?

Aim and motivation

As it turns out…



Very poorly.

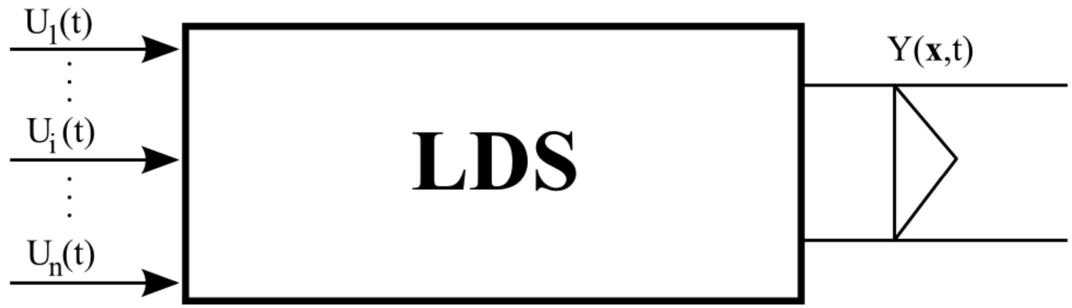
General practice in control

- Use MIMO structures with lumped input
- Consider discrete points in the output
- The control synthesis is done *exclusively* in the time domain
- Essentially neglecting the spatial domain and properties of systems

Now how can we change this?

Distributed Parameter Systems

- Use instead lumped input and distributed parameter output systems (LDS)

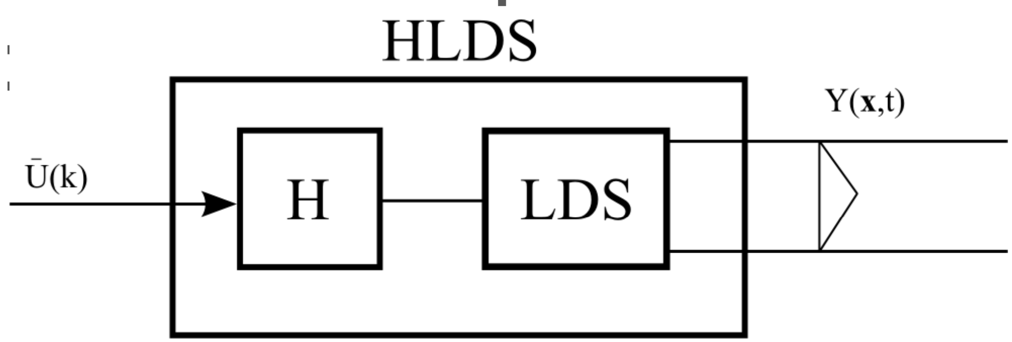


- Input is $\{U_i(t)\}_i$, output is $Y(\mathbf{x},t)$, with x=x,y,z spatial coordinates

= Distributed parameter systems (**DPS**)

Controlled DPS

- Zero order hold units couple the lumped input vector to the DPS output – this is the “HLDS” unit:



- Distributed parameter step responses are used to decompose HLDS dynamics into time and space components:

$$\left\{ H\ H_i\left(\mathbf{x}, k\right) \right\}_i$$

Controlled DPS

- To each partial particular step response a discrete transfer function is assigned:

$$\left\{\mathsf{H}\ \mathrm{H}_i\left(\mathbf{x}_i,k\right)\right\}_i \rightarrow \left\{\mathrm{SH}_i\left(\mathbf{x}_i,z\right)\right\}_i$$

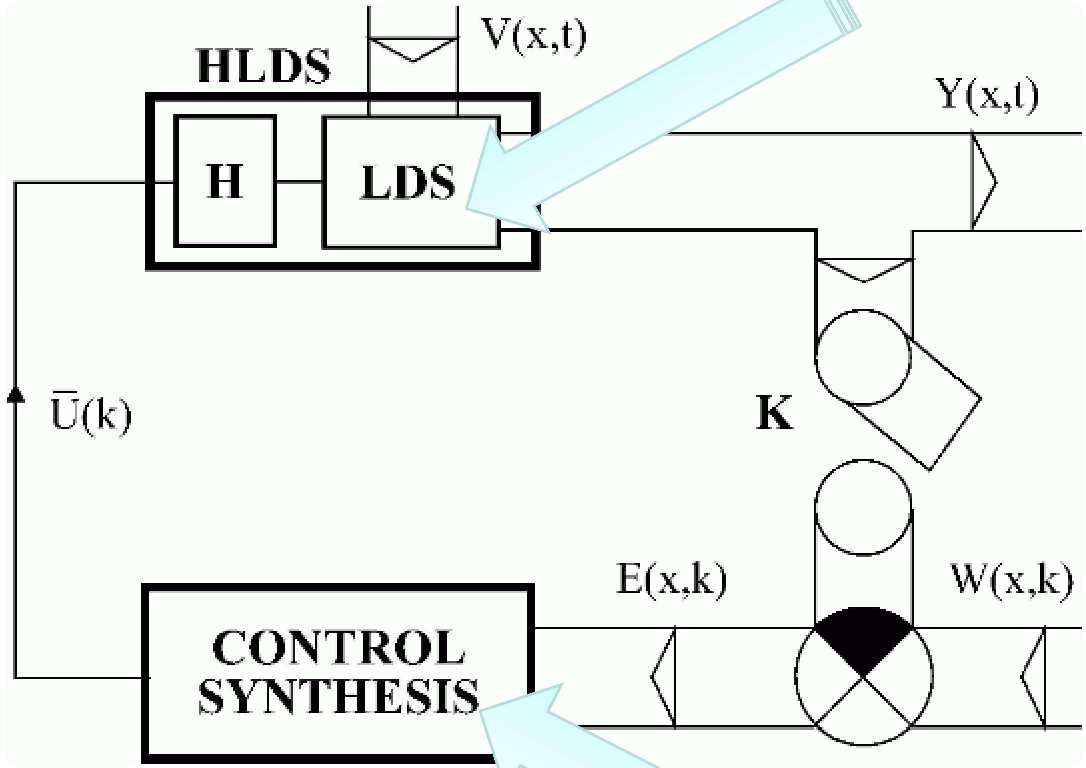
= **time componets** of LDS dynamics.

- Reduced partial particular step responses in steady-state are the **space components** of LDS dynamics:

$$\left\{\mathsf{H}\ \mathrm{HR}_i(\mathbf{x},\infty) = \mathsf{H}\ \mathrm{H}_i\left(\mathbf{x},\infty\right) / \mathsf{H}\ \mathrm{H}_i\left(\mathbf{x}_i,\infty\right)\right\}_i$$

Controlled DPS: schematic idea

COMSOL Transient Analysis Results



Measured distributed output

Vector of inputs

Distributed reference values

Based on COMSOL Transient Analysis Results

Controlled DPS in practice

- Characteristics $\left\{\mathrm{H}\ \mathrm{H}_i\left(\mathbf{x},\mathrm{k}\right)\right\}_i$ are obtained via **COMSOL Multiphysics**
- Identification of $\left\{\mathrm{SH}_i\left(\mathbf{x}_i,\mathrm{z}\right)\right\}_i$ and control synthesis is done in Matlab using our tool:

Distributed Parameter System Blockset for Matlab and Simulink

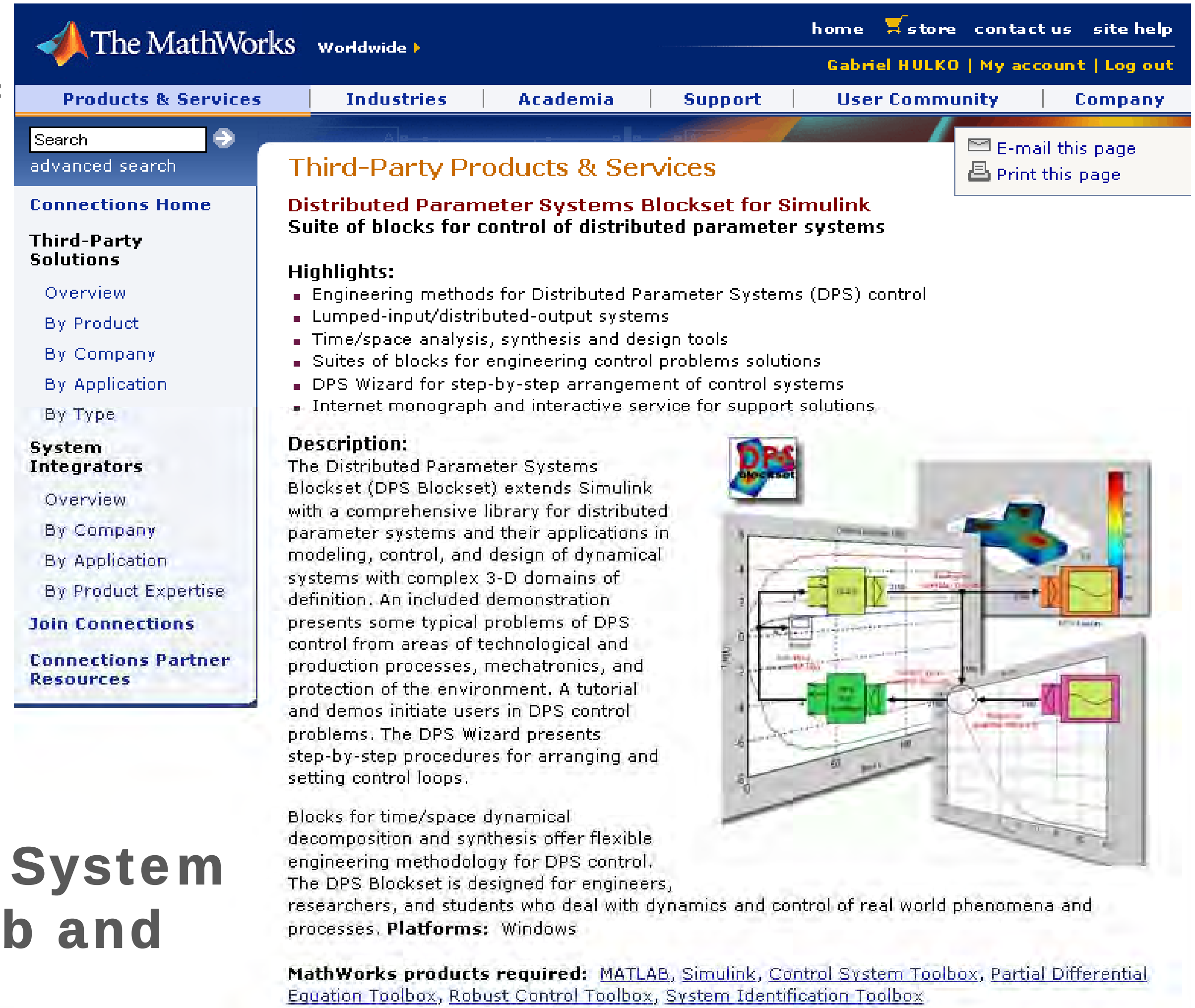
which is an official third party product of The MathWorks Corporation.

Controlled DPS in practice

Developed by the IAMAI of the Slovak University of Technology in Bratislava, DPS Blockset is an official third party product of The MathWorks, Inc.

Control any DPS by the:

Distributed Parameter System Blockset for Matlab and Simulink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Distributed Parameter Systems Blockset for Simulink
Suite of blocks for control of distributed parameter systems

Highlights:
- Engineering methods for Distributed Parameter Systems (DPS) control
- Lumped-input/distributed-output systems
- Time/space analysis, synthesis and design tools
- Suites of blocks for engineering control problems solutions
- DPS Wizard for step-by-step arrangement of control systems
- Internet monograph and interactive service for support solutions

Description:
The Distributed Parameter Systems Blockset (DPS Blockset) extends Simulink with a comprehensive library for distributed parameter systems and their applications in modeling, control, and design of dynamical systems with complex 3-D domains of definition. An included demonstration presents some typical problems of DPS control from areas of technological and production processes, mechatronics, and protection of the environment. A tutorial and demos initiate users in DPS control problems. The DPS Wizard presents step-by-step procedures for arranging and setting control loops.

Blocks for time/space dynamical decomposition and synthesis offer flexible engineering methodology for DPS control. The DPS Blockset is designed for engineers, researchers, and students who deal with dynamics and control of real world phenomena and processes. **Platforms:** Windows

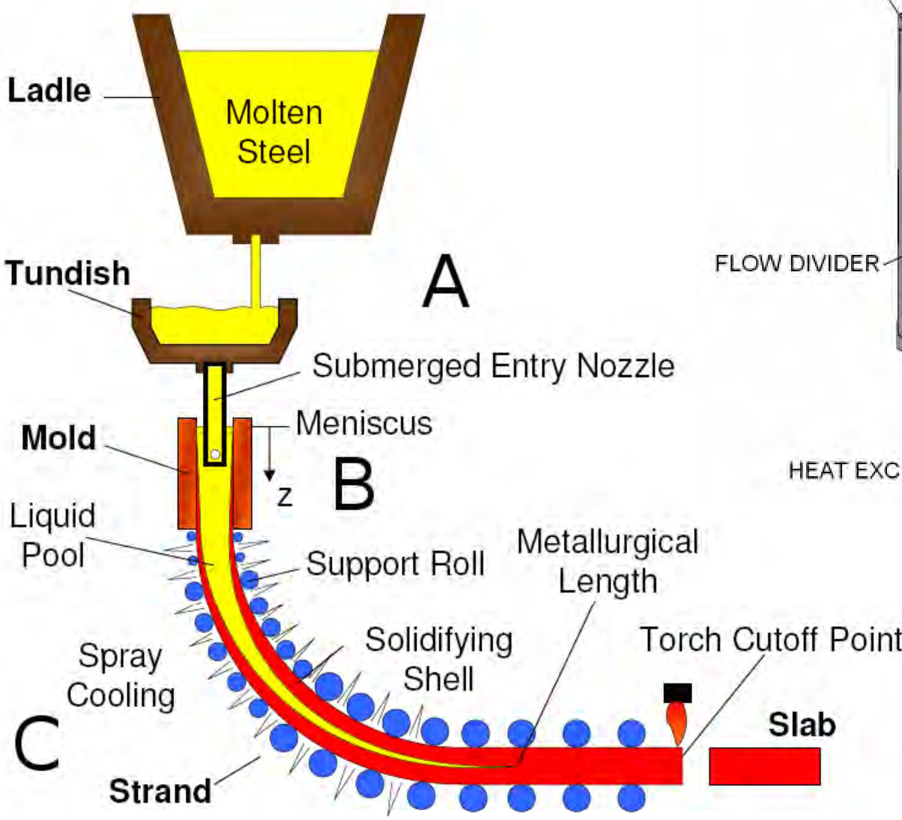
MathWorks products required: MATLAB, Simulink, Control System Toolbox, Partial Differential Equation Toolbox, Robust Control Toolbox, System Identification Toolbox

Where can we use DPS control

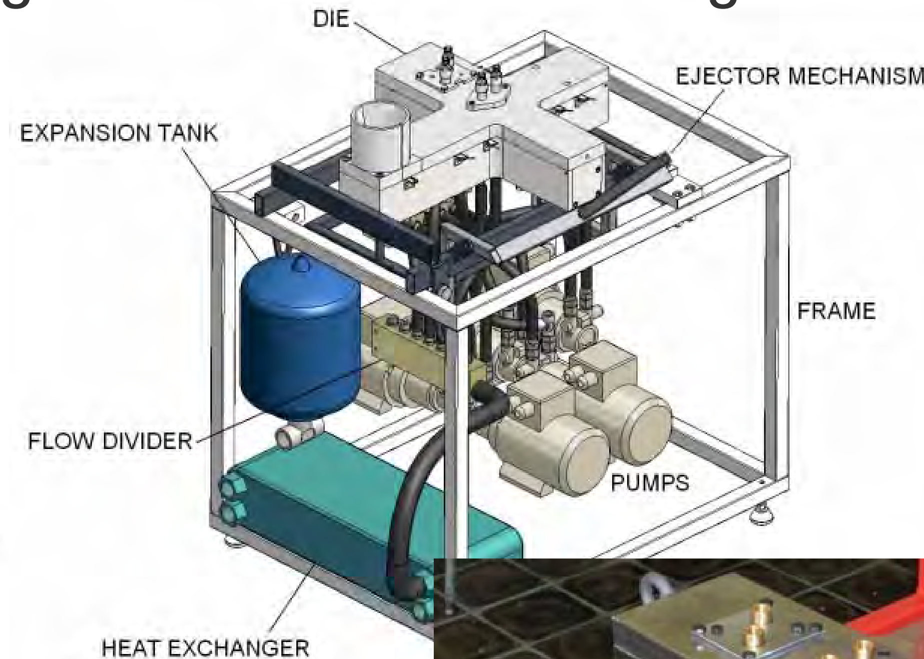
- As it turns out most real-life phenomena are better controlled as distributed parameter systems – COMSOL Multiphysics is an excellent companion for that…
- A couple examples which are possible to be modelled using COMSOL Multiphysics and for which DPS control is an excellent choice:

DPS Control: metallurgy

DPS Continous casting:

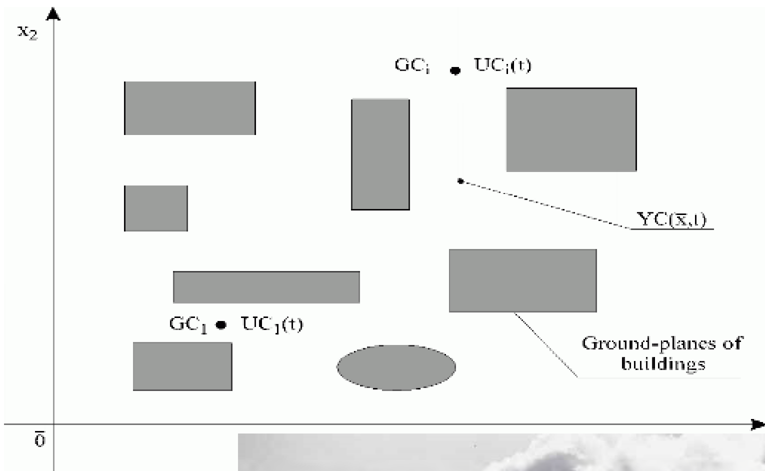


DPS casting control:

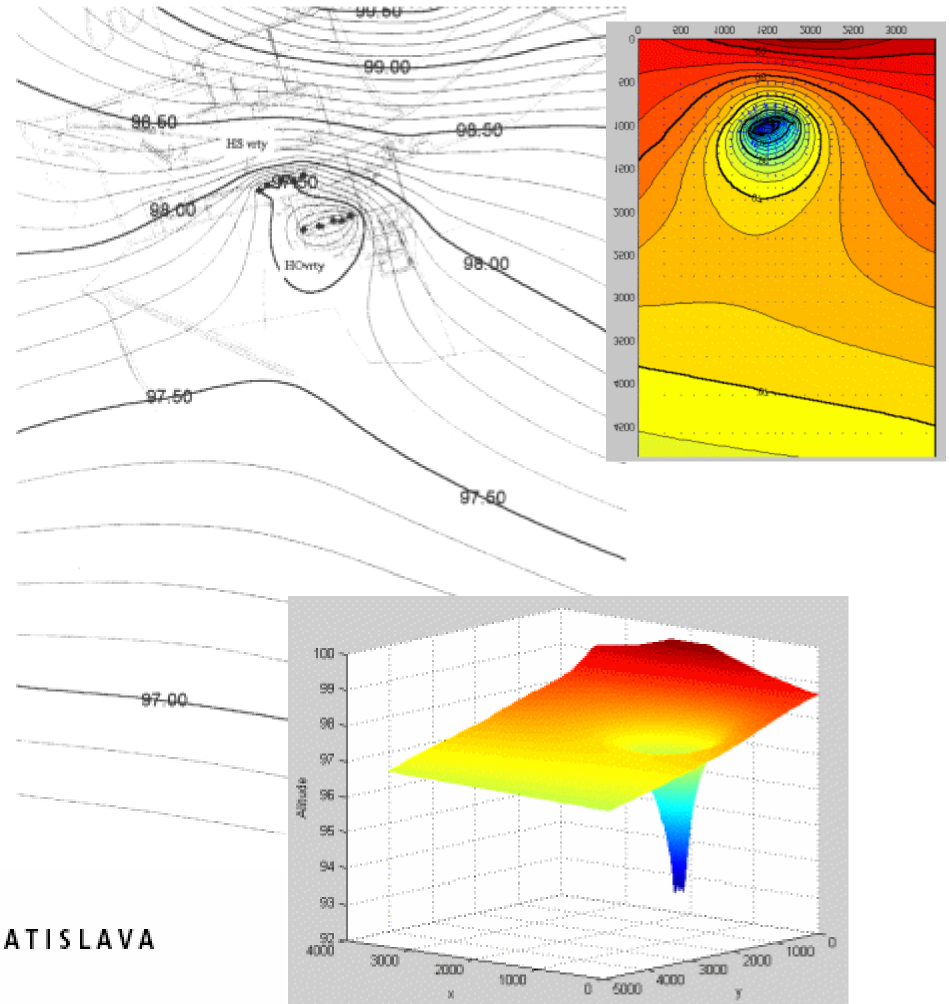


DPS Control: environmental

Pollution control of city & metropolitan agglomerations:

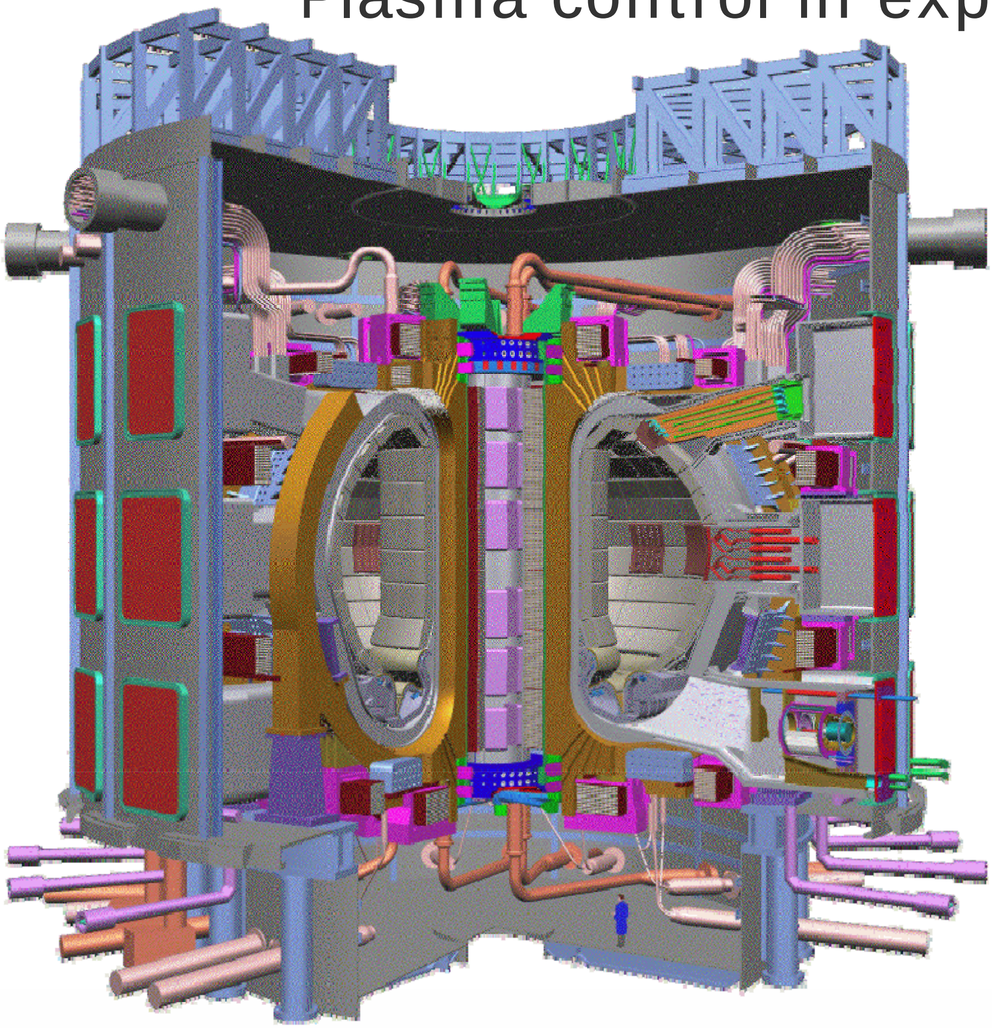


Groundwater remediation:

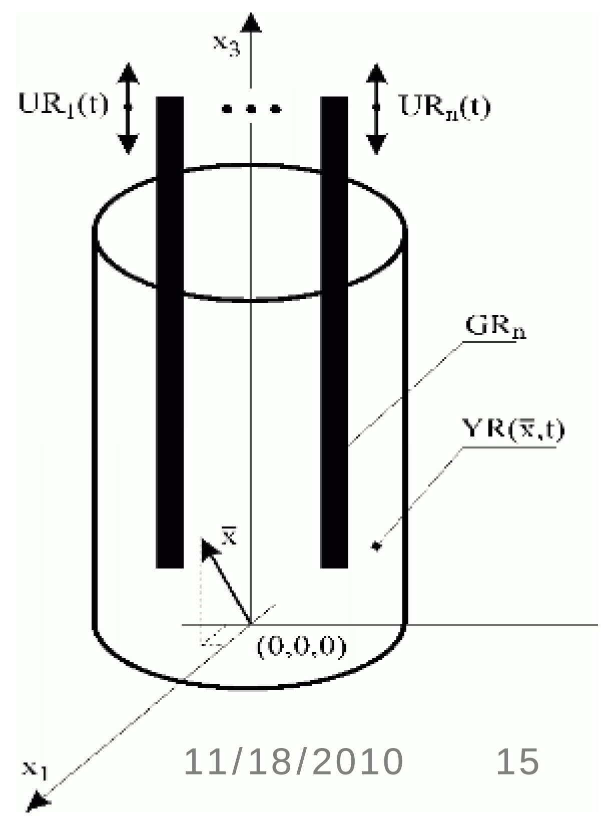


DPS Control: nuclear & TOKAMAK

Plasma control in experimental TOKAMAK



Nuclear reactor:



DPS Control: much more…

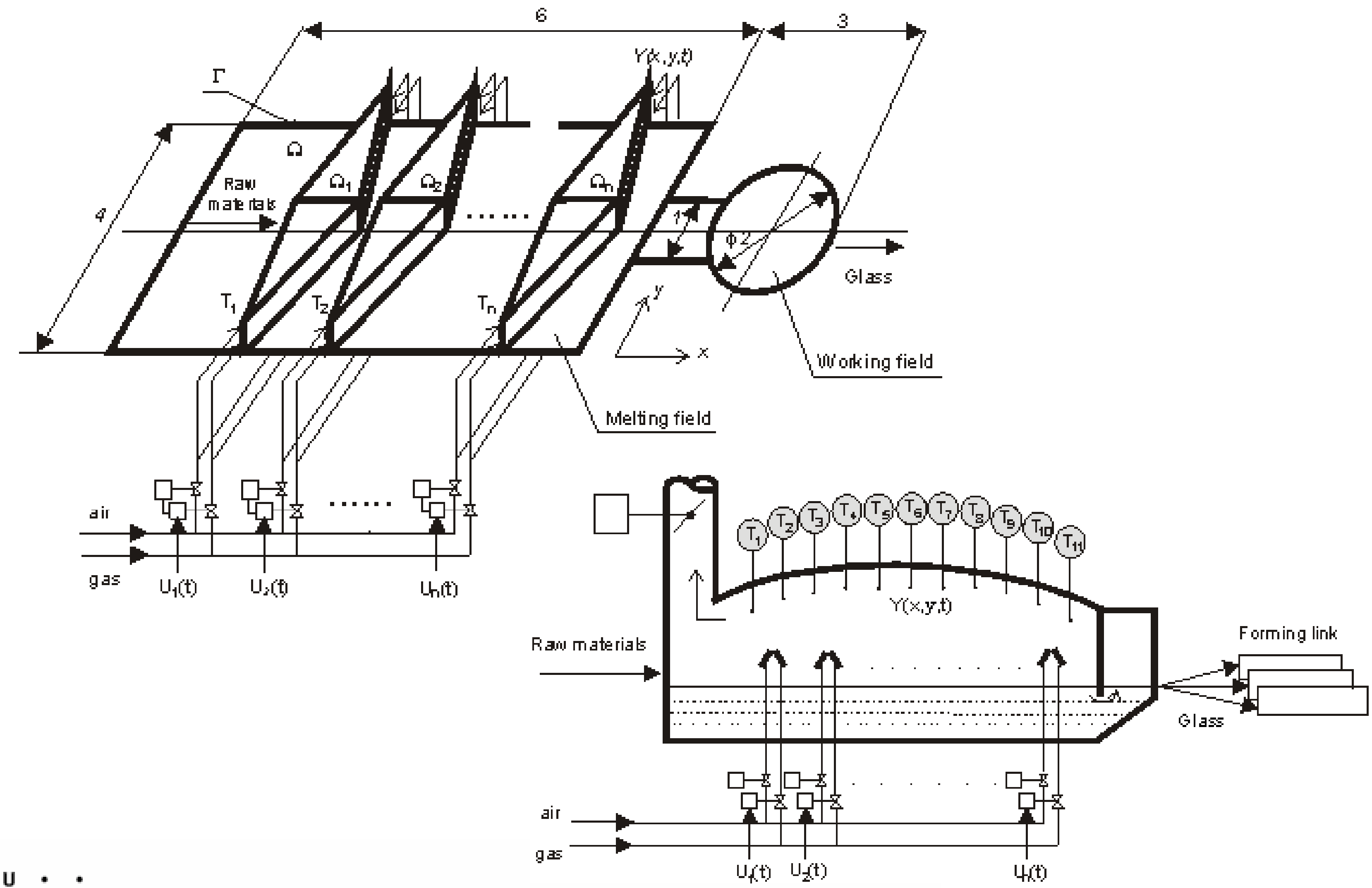
- You may design distributed parameter system controllers for anything which
  - Can be modeled via COMSOL
  - Produces transient (step) results
- Numerous other uses...

Let us now explain the process on an easy example.

Easy example: melting furnace

- To demonstrate the process we will use a **glass melting furnace**
- 4 heating zones
- Distributed output
- Control aim: **uniform temperature profile according to reference throughout the furnace** resulting in consistent product quality, with minimal economic and environmental impact

Example: glass melting furnace



How to design a controller?

Control design for such a DPS system essentially a two step process:

1. Use **COMSOL Multiphysics** to identify a system model based on a mixed numerical-experimental approach resp. parametric model tuning.
2. Based on the numerical model use the **DPS Toolbox** for controller design, synthesis and simulation

Modeling and identification

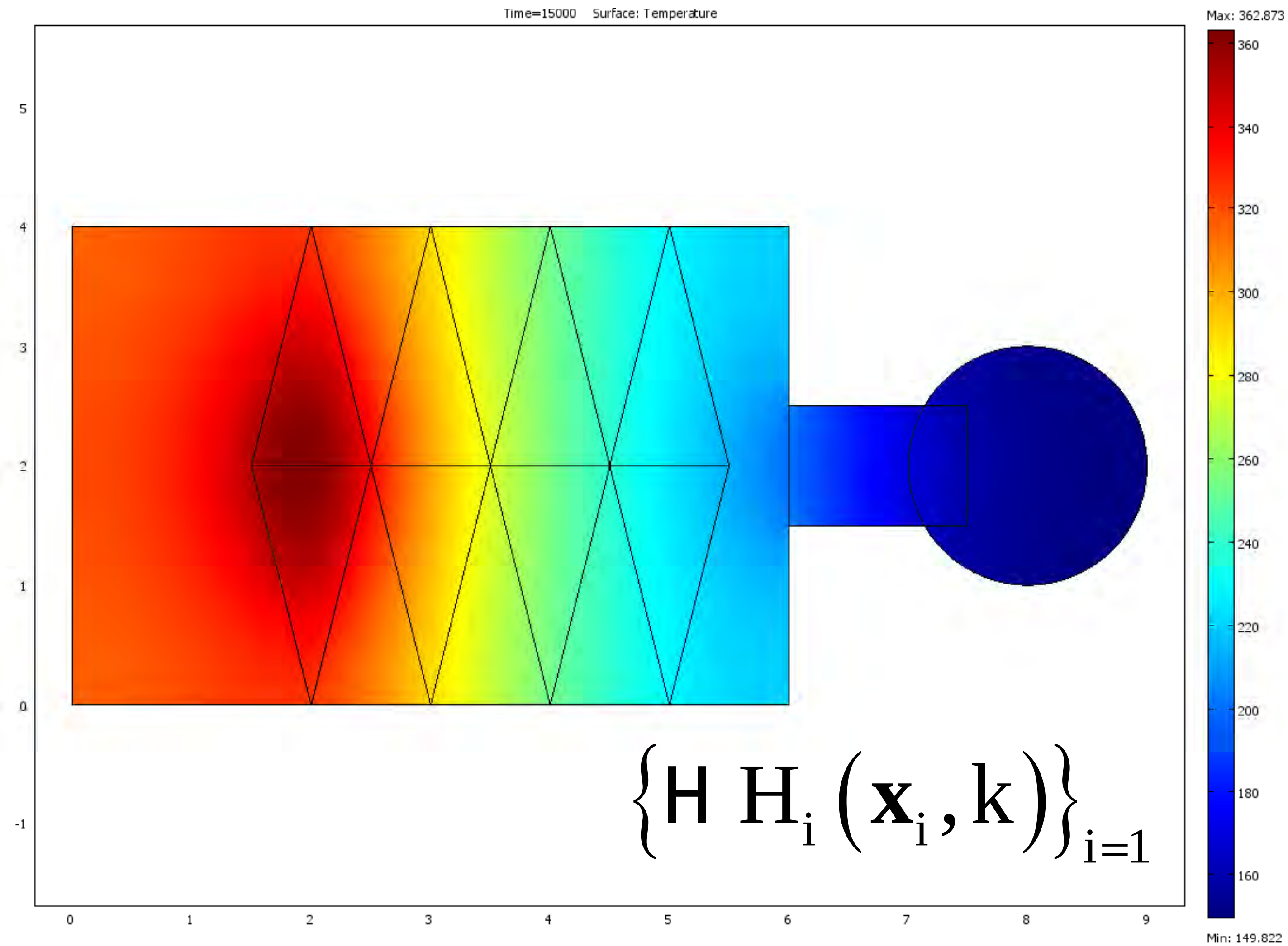
- Use COMSOL Multiphysics to get steady state responses in all lumped input zones: $\{H\ H_i(\mathbf{x}_i, k)\}_{i=1,4}$
- For the glass furnace that is a partial step change in fuel input (heat) in:

Zone 1.

(…)

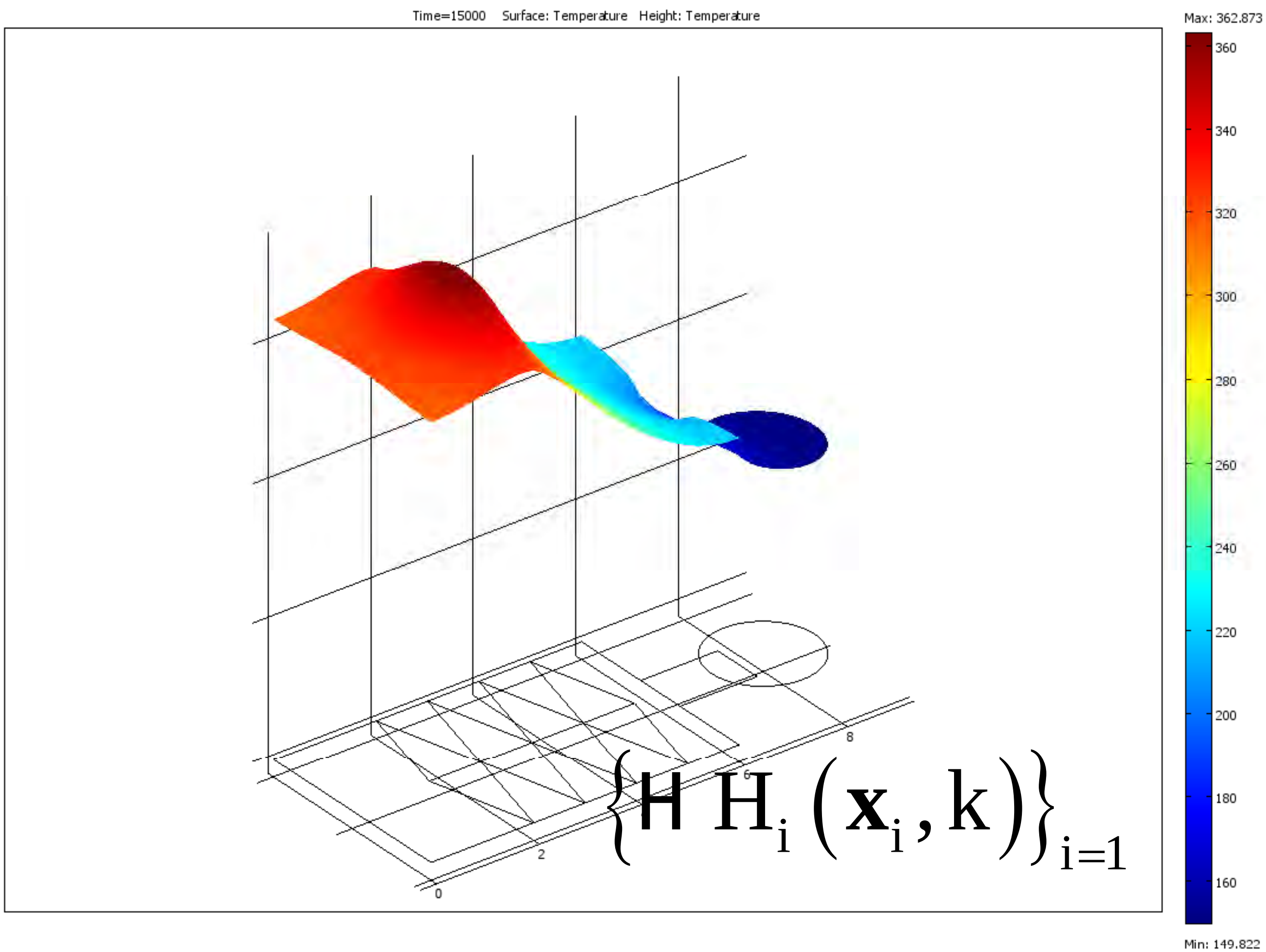
Zone 4.

Furnace: zone 1 heating



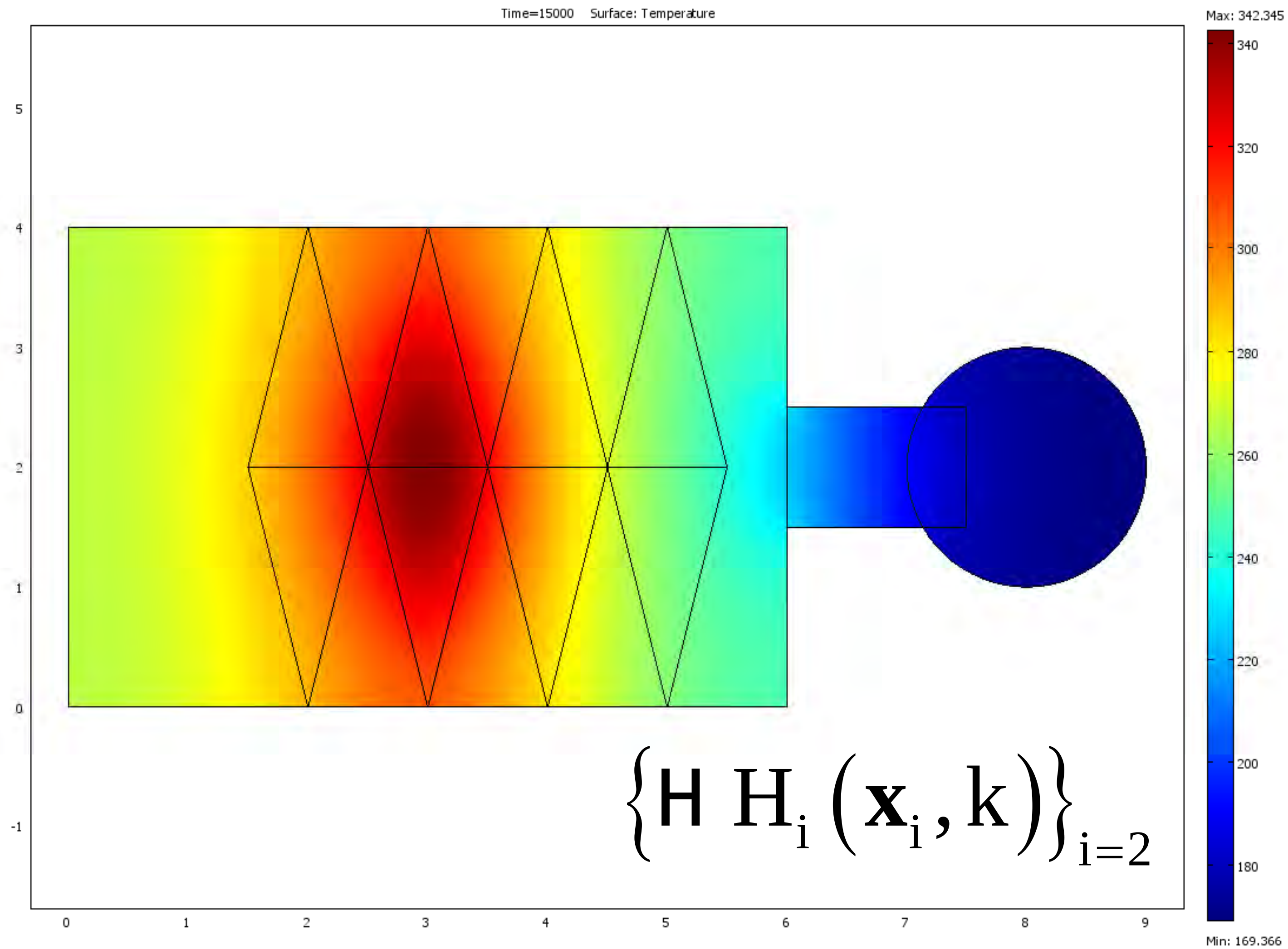
$$\left\{ H \; H_i \left(\mathbf{x}_i , k \right) \right\}_{i=1}$$

Furnace: zone 1 heating



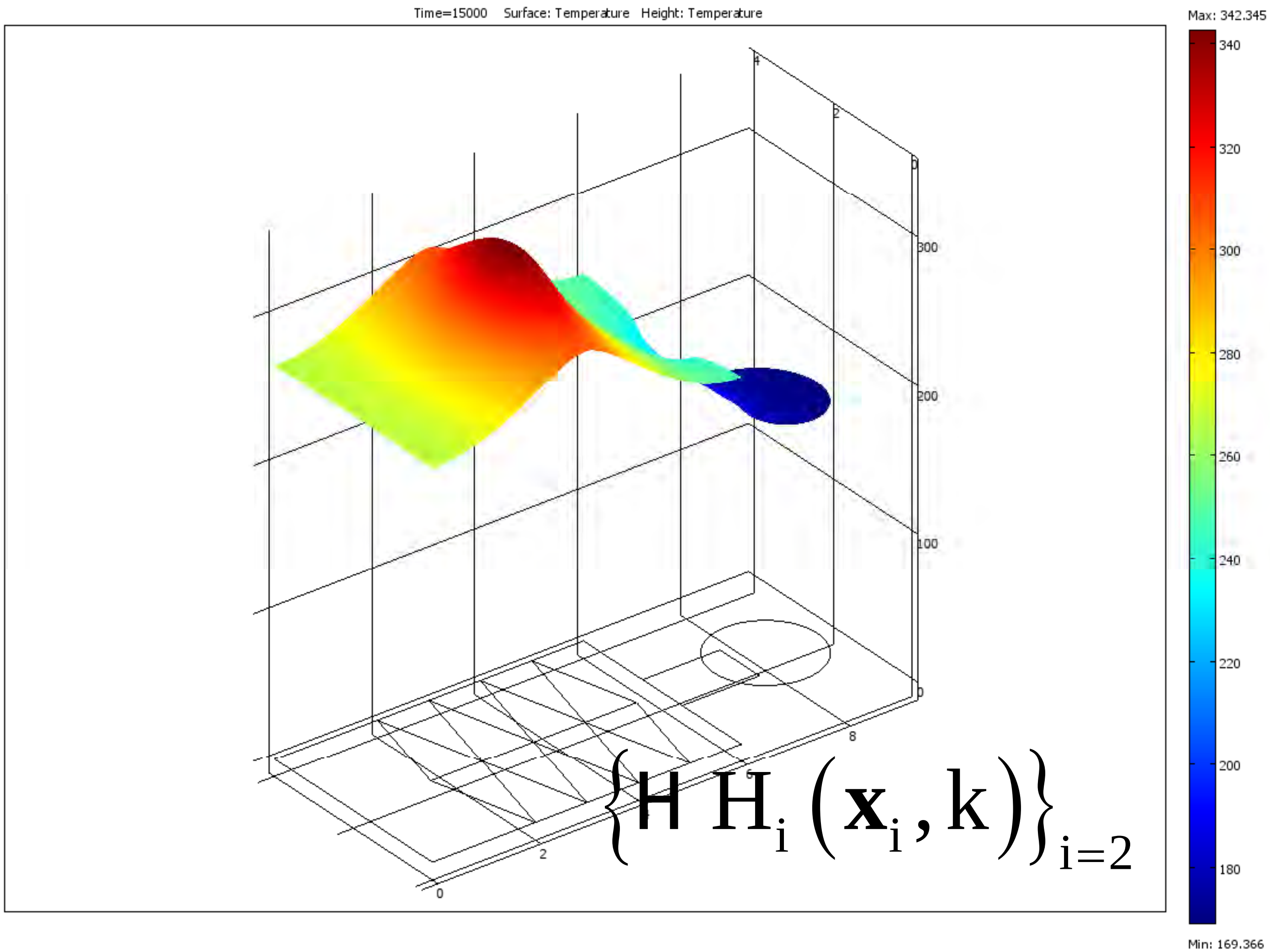
$$\left\{ H H_i \left(\mathbf{x}_i , k \right) \right\}_{i=1}$$

Furnace: zone 2 heating



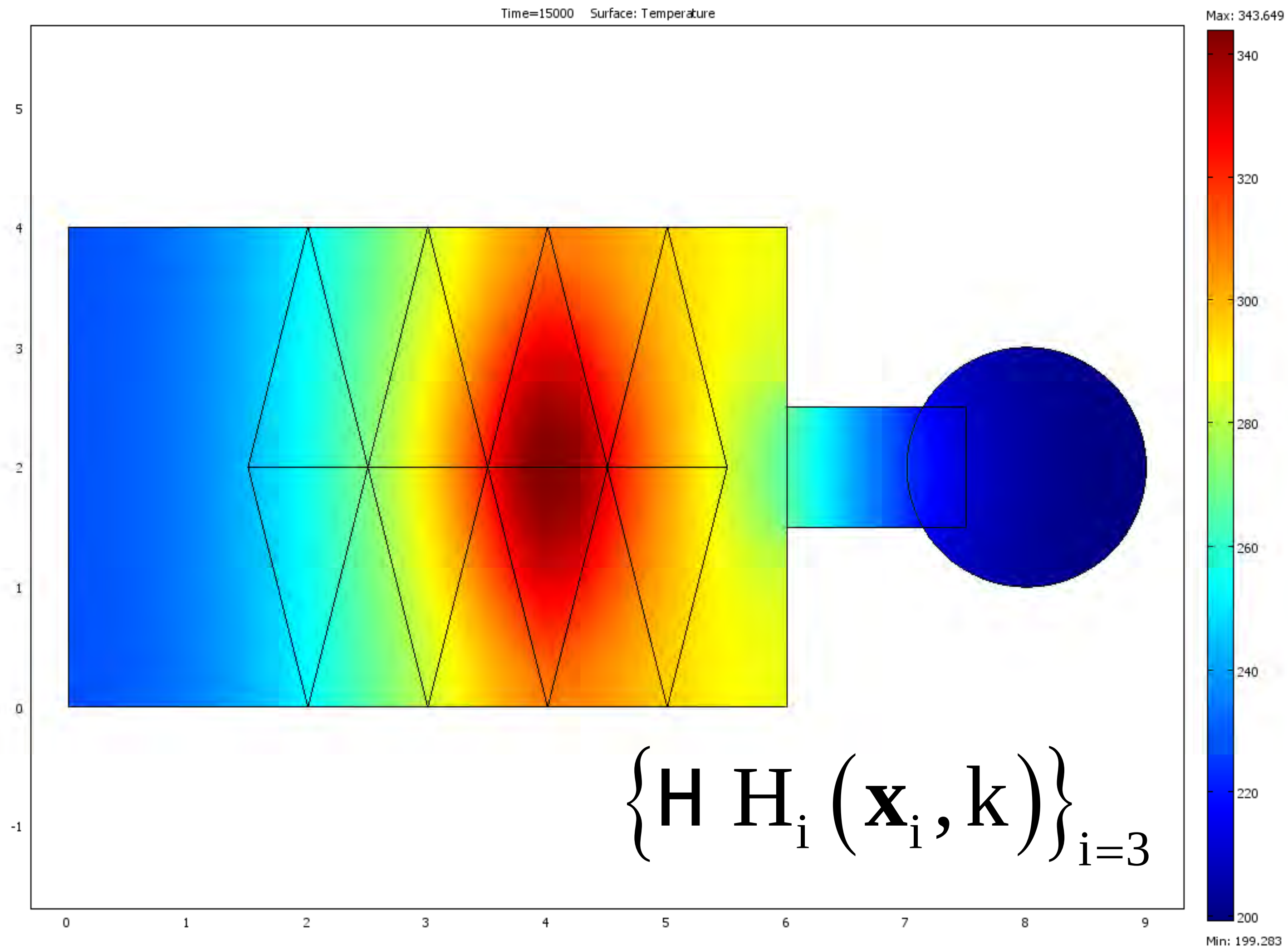
$$\{H\, H_i(\mathbf{x}_i, k)\}_{i=2}$$

Furnace: zone 2 heating



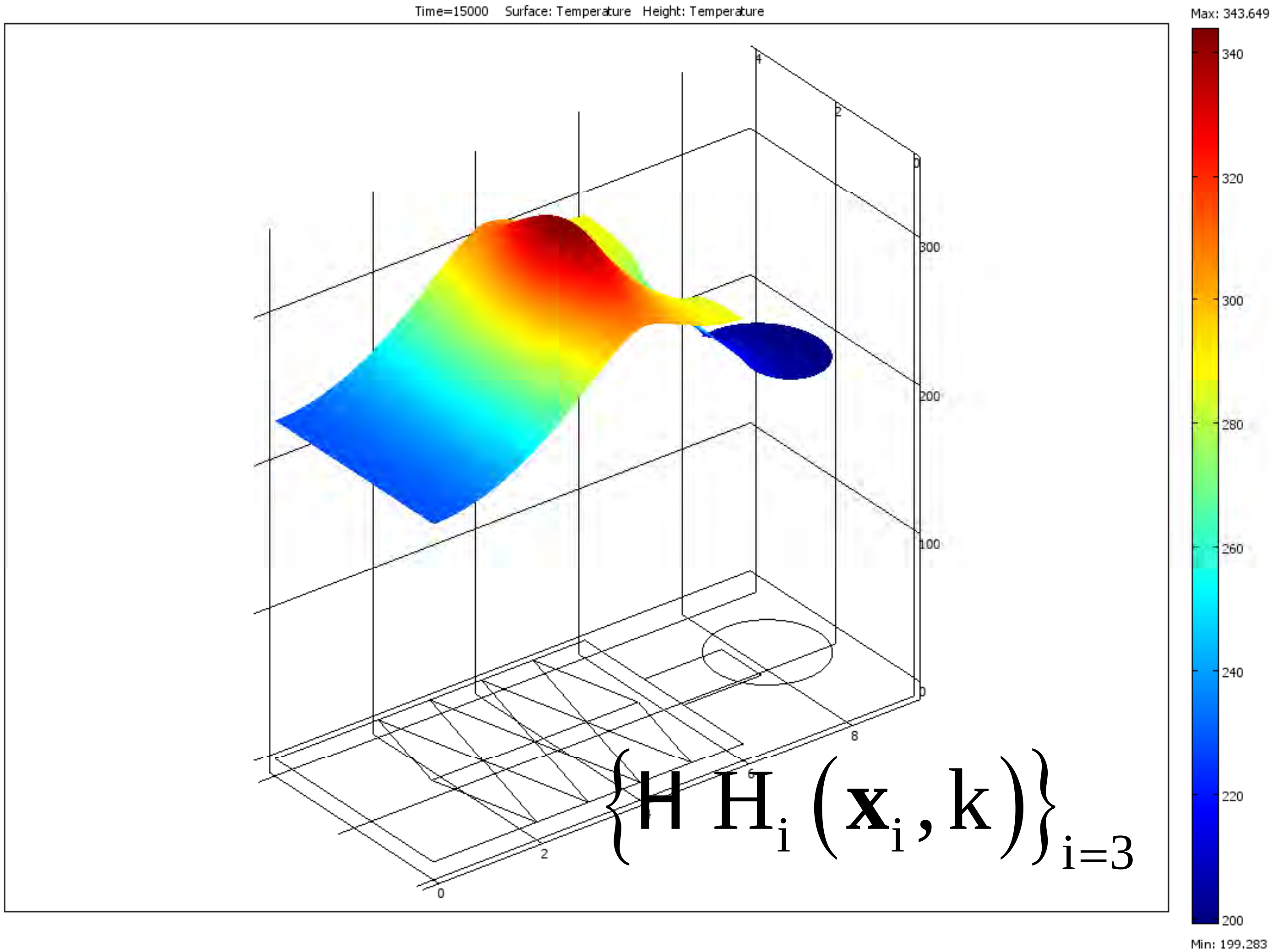
$$\left\{\mathbf{H}\,H_i\left(\mathbf{x}_i, k\right)\right\}_{i=2}$$

Furnace: zone 3 heating

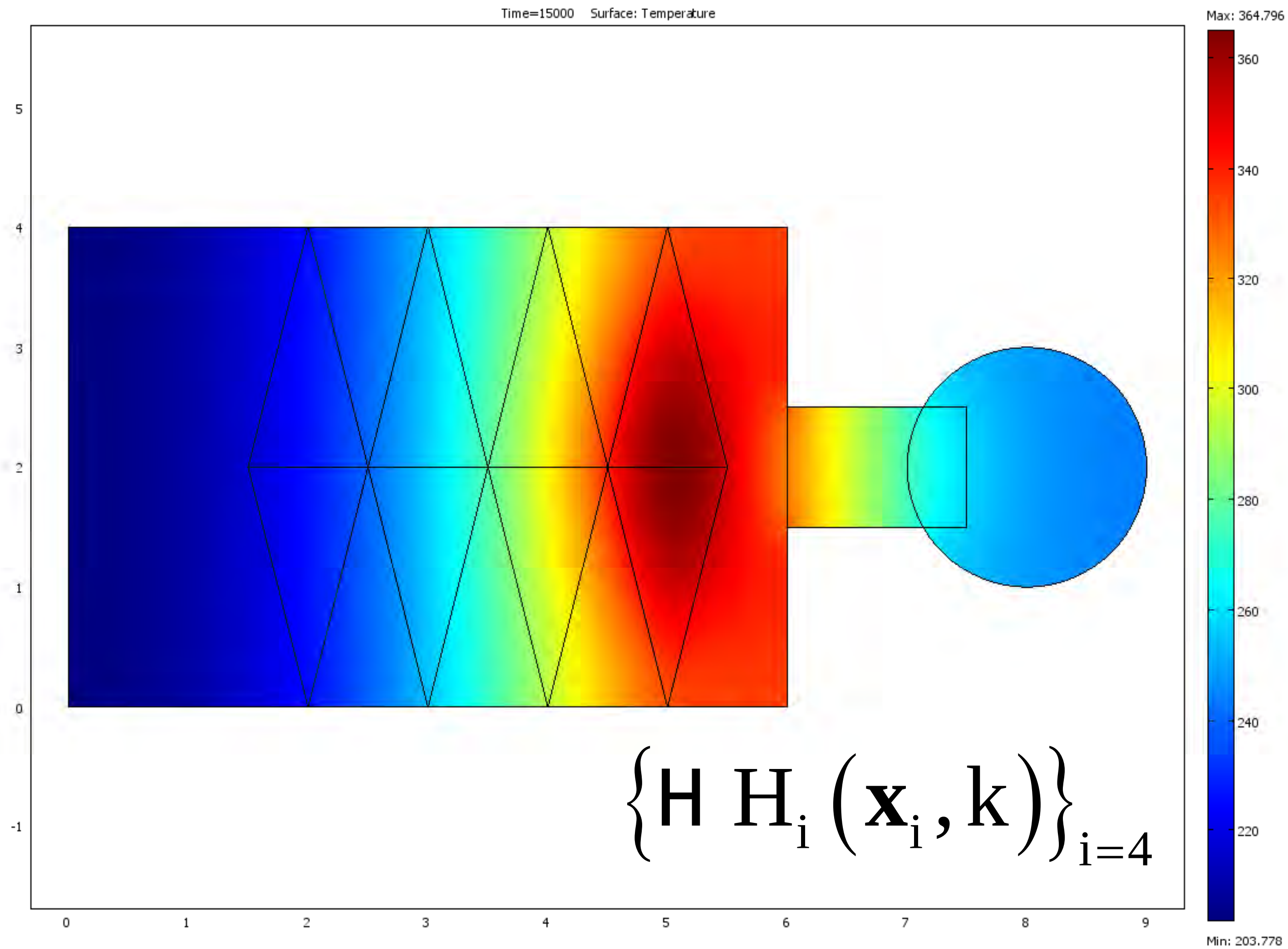


$$\left\{ H\ H_i\left(\mathbf{x}_i, k\right)\right\}_{i=3}$$

Furnace: zone 3 heating

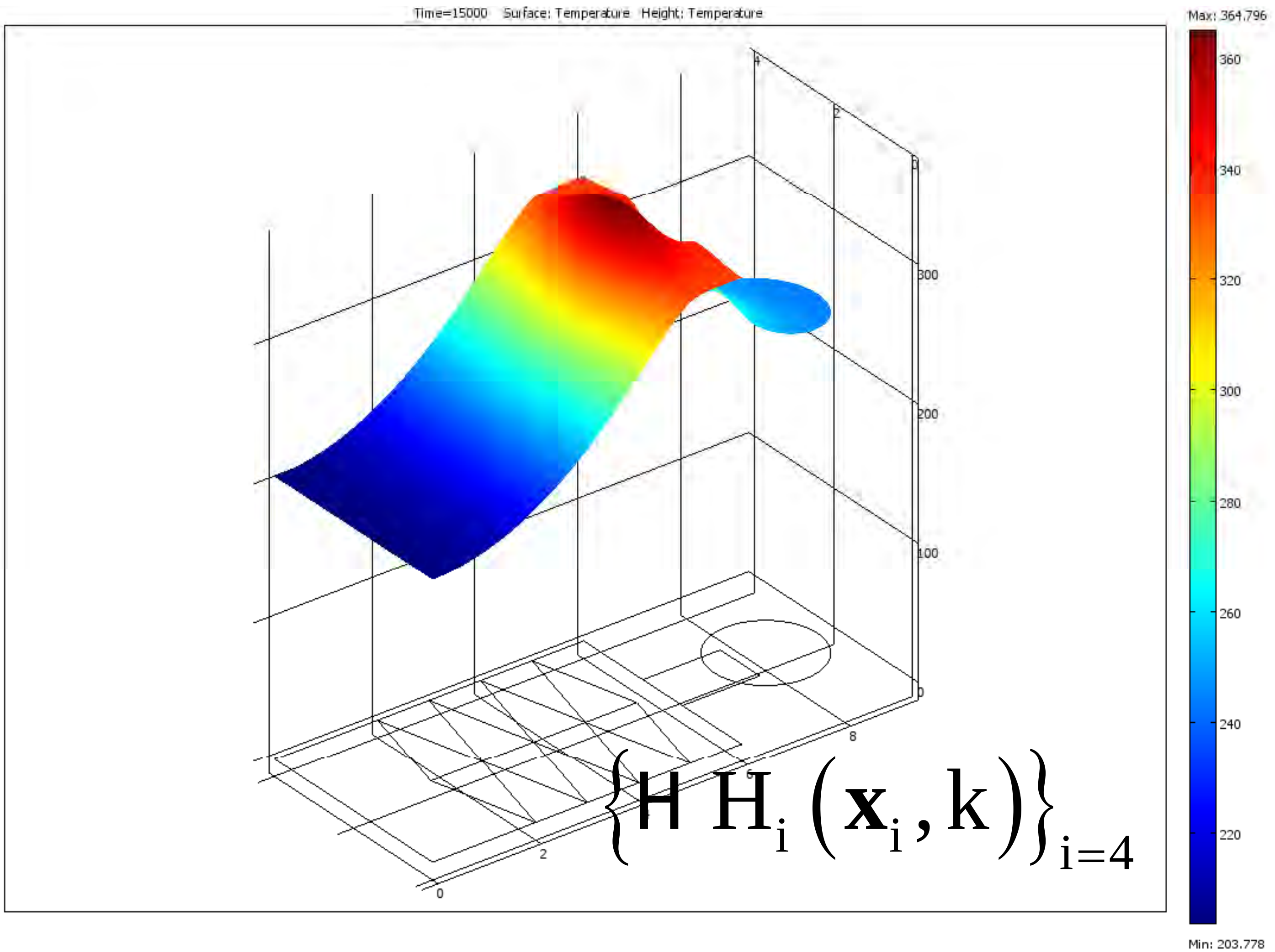


Furnace: zone 4 heating



$$\left\{ \text{H}\ H_i \left(\mathbf{x}_i , k \right) \right\}_{i=4}$$

Furnace: zone 4 heating



$$\{H\, H_i(\mathbf{x}_i, k)\}_{i=4}$$

The result of identification:

- Discrete transfer functions to input U_1:

$$\left\{ \mathrm{SH_i}\left(\mathbf{x}_\mathrm{i},\mathrm{z}\right)\right\}_1 = \frac{1{,}329.10^8 z^2 \; + \; 5{,}072.10^5 z^2 \; + \; 365.6}{1{,}901.10^8 z^3 \; + \; 2{,}731.10^6 z^2 \; + \; 4284\,\mathrm{z} \; + \; 1}$$

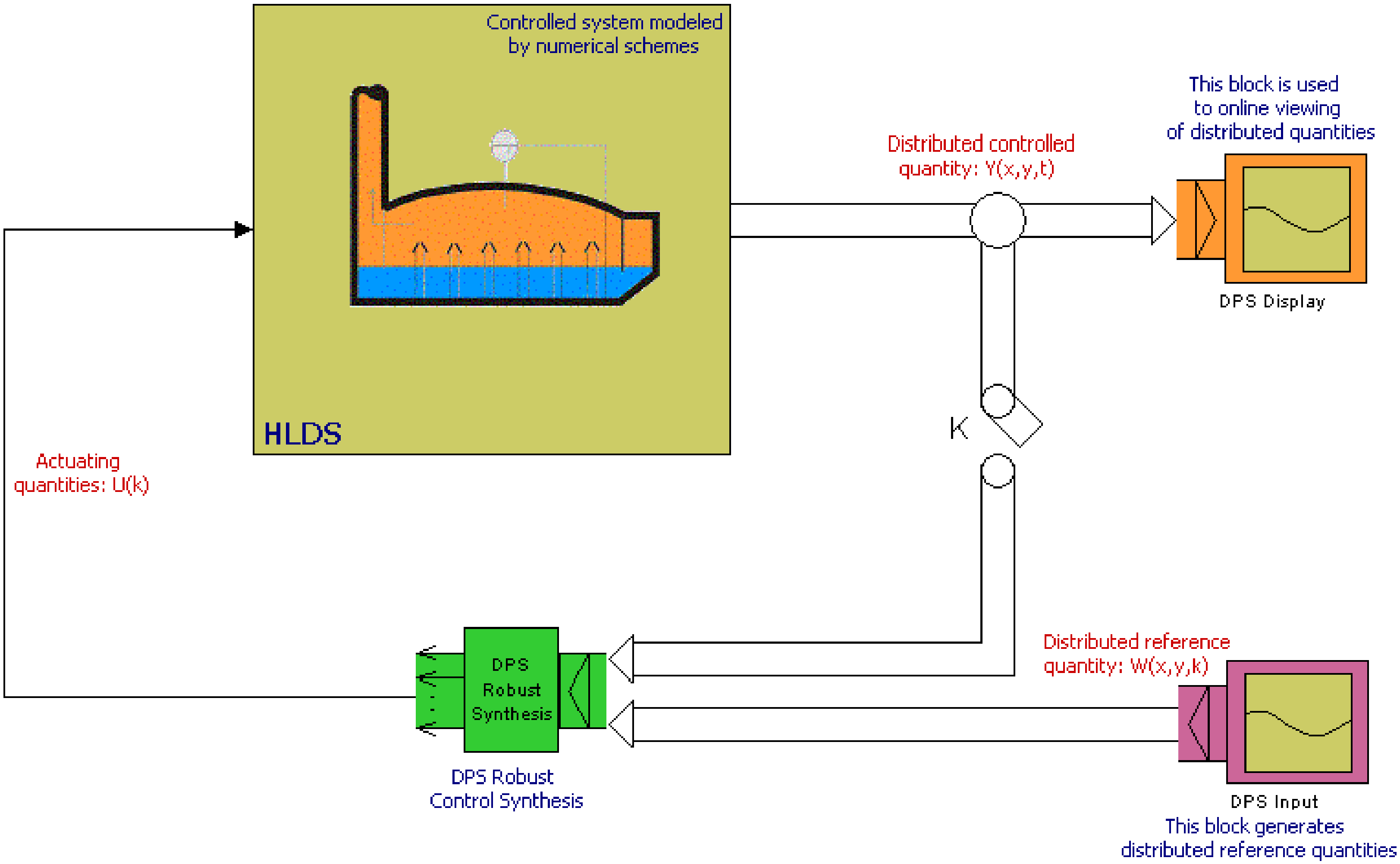
(...) similarly for all for i=1...4

- Further reduced DPS step responses in steady-state are defined

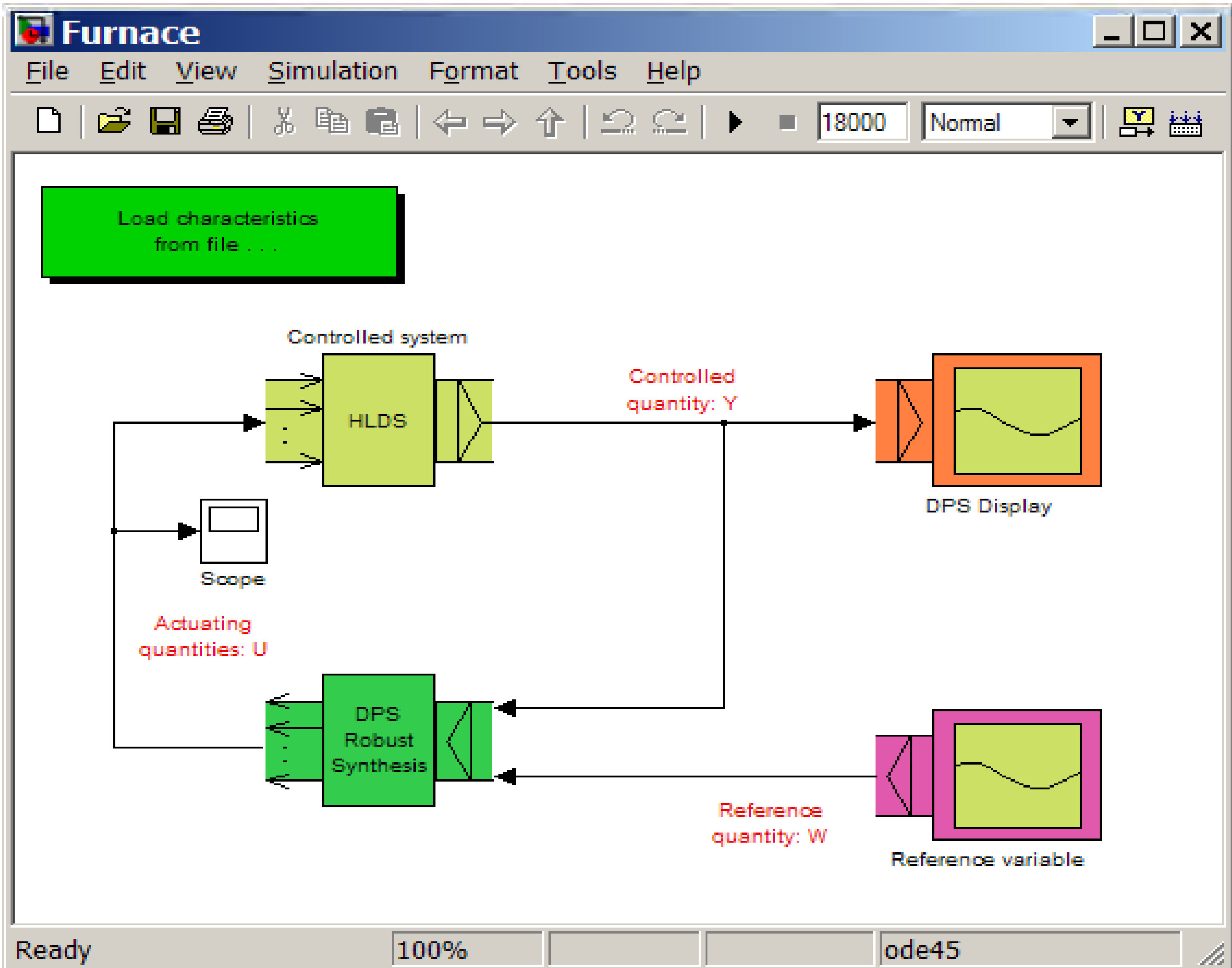
$$\left\{ \mathrm{H\ HR_i}\left(\mathbf{x},\infty\right) = \mathrm{H\ H_i}\left(\mathbf{x},\infty\right) / \mathrm{H\ H_i}\left(\mathbf{x}_\mathrm{i},\infty\right)\right\}_{\mathrm{i}=1,4}$$

as space components of investigated controlled system dynamics.

DPS control of the furnace

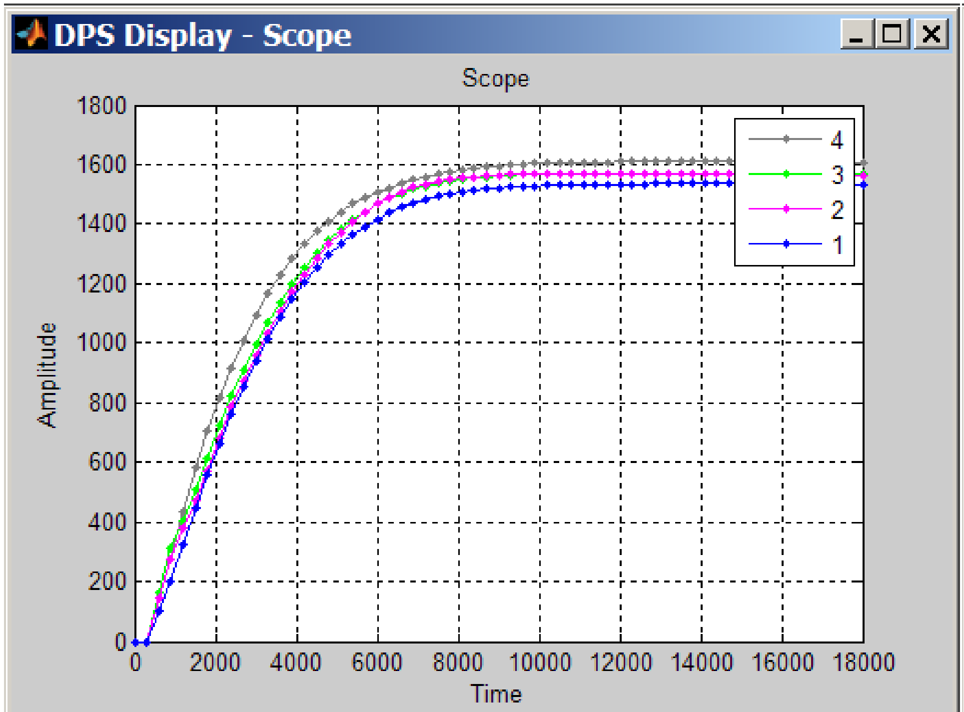


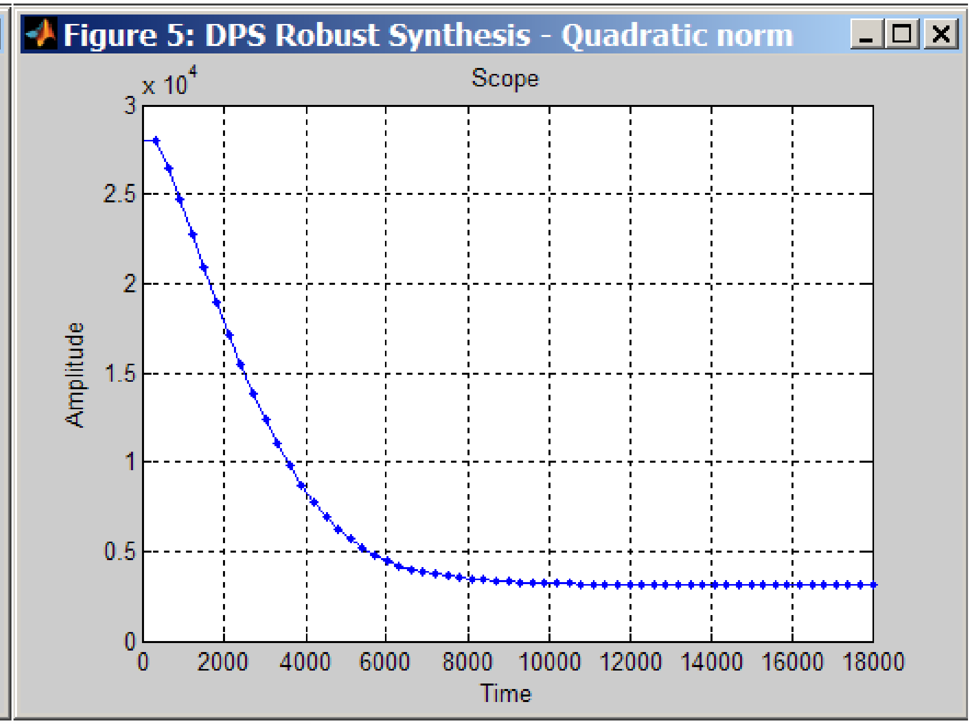
DPS Toolbox: control loop



DPS Toolbox: simulation

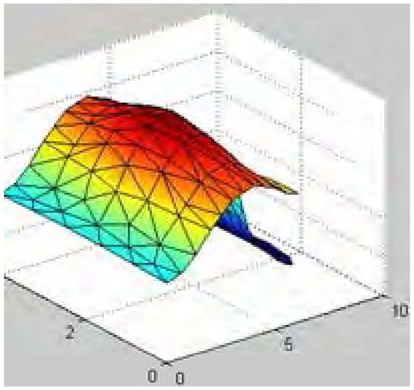
Detailed simulation and fine tuning of DPS control = ready to implement!

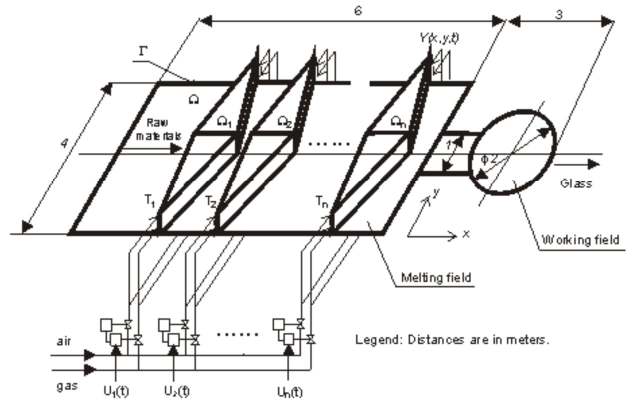




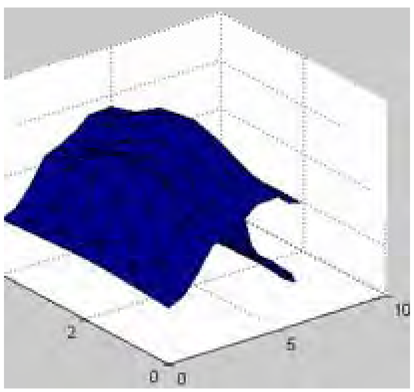
DPS Toolbox: simulation

Reference quantity:

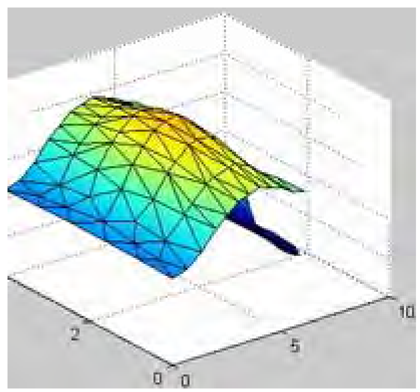




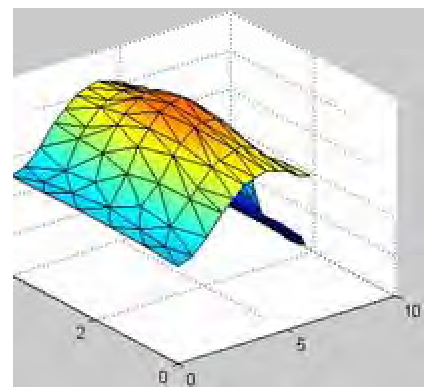
Control progress:



t=15 min



t=150 min



t=300 min

DPS Toolbox: upcoming features

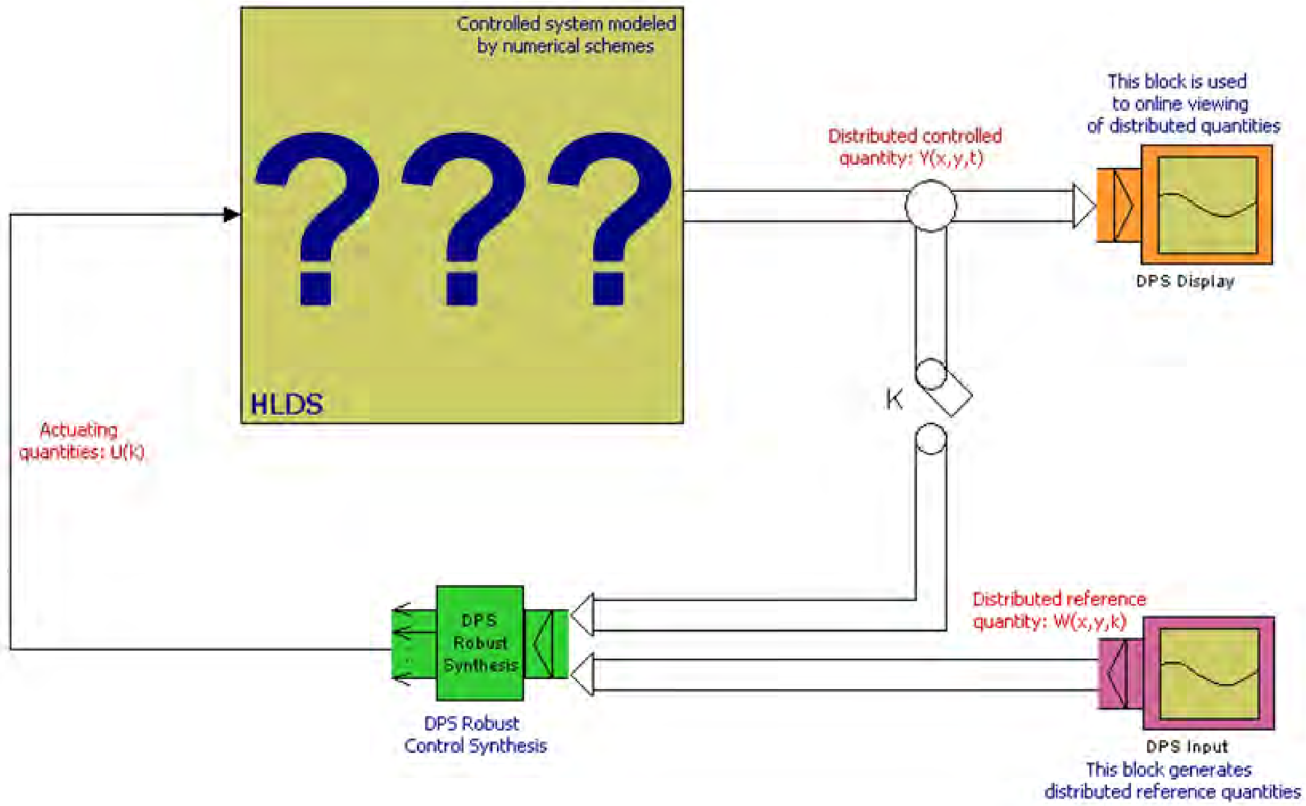
A major update of the DPS Blockset for Matlab and Simulink is coming with features including:

- Predictive DPS control systems
- Robust control systems
- Adaptive DPS control systems
- New applications and examples

and many more...

Give us some inspiration!

What distributed parameter system would **YOU** like to *control*?



Get some inspiration!

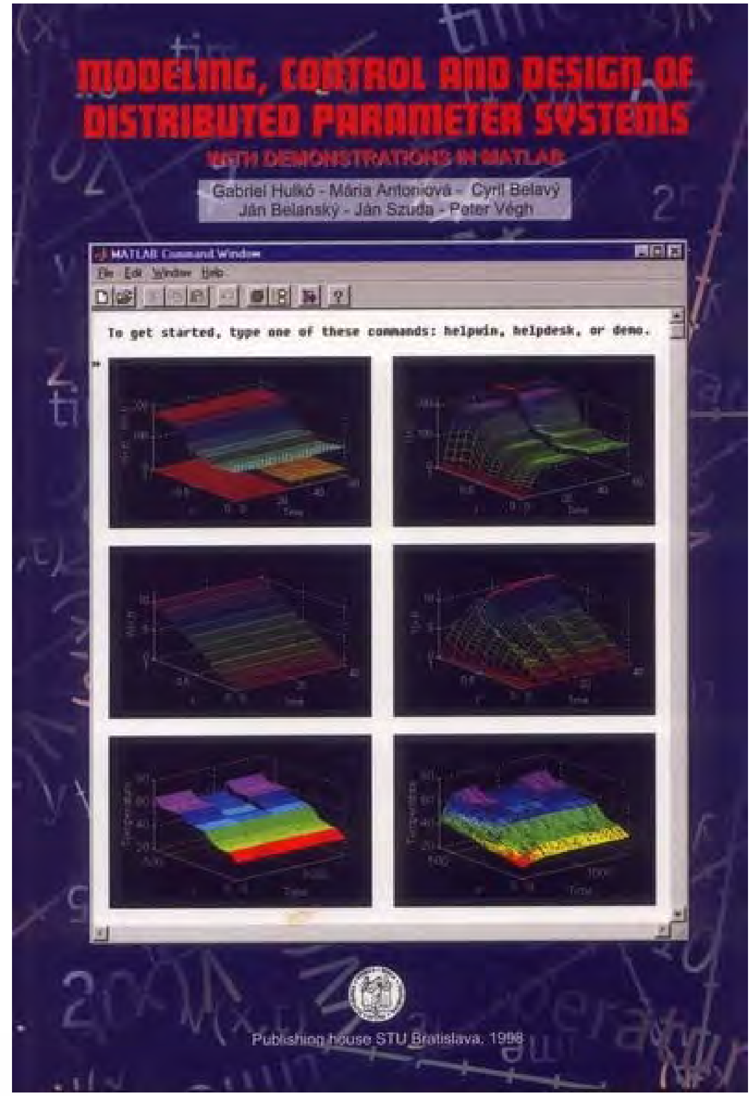
Hulkó et. al:

Modeling, Control and Design of Distributed Parameter Systems with demonstrations in MATLAB

Limited free copies available here.

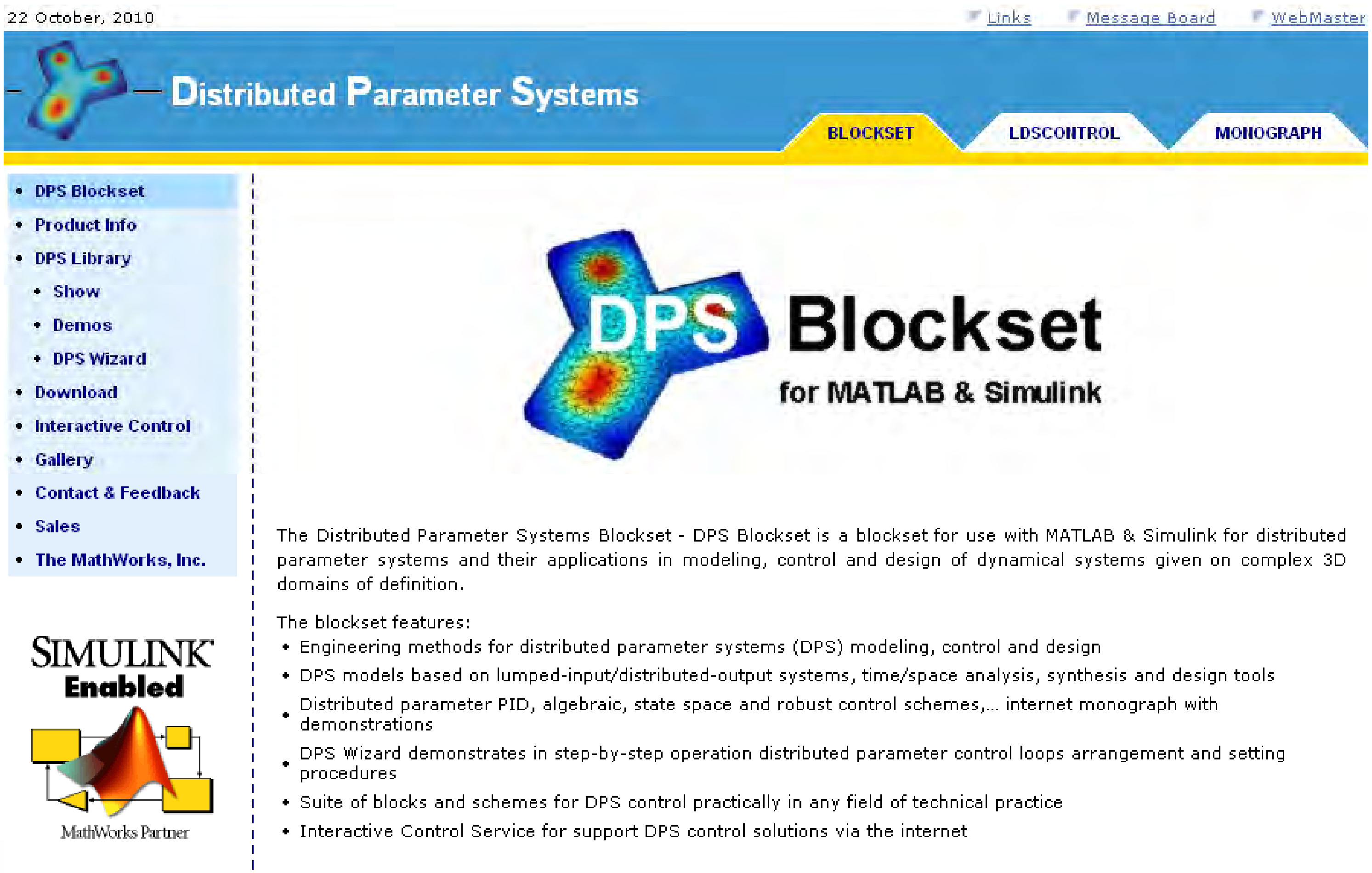
Internet version available on:

http://www.dpscontrol.sk/



Get some inspiration!

DPS Control at: **www.dpscontrol.sk**



Thank you for your attention.

http://www.dpscontrol.sk/

Ideas, proposals and collaborative projects are always welcome.

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