Optimal operation and advanced control using decomposition and simple elements

Sigurd Skogestad

Department of Chemical Engineering

Norwegian University of Science and Technology (NTNU)

Trondheim

Tutorial workshop at NPC
Trondheim, 16 Aug. 2023

Thanks to Cristina Zotica for preparing most of the figures

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review article

Advanced control using decomposition and simple elements

Sigurd Skogestad

Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

- Still possibe to make corrections
- Please tell me about errors and misprints!

Paper is available on my home page: Just search for “skogestad”

https://folk.ntnu.no/skoge/

Chemical Engineering

Sigurd Skogestad Professor

Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), N7491 Trondheim, Norway

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"News"...

- July 2023: Tutorial review paper on "Advanced control using decomposition and simple elements". Published in Annual reviews in Control (2023). [paper] [tutorial workshop]
- 05 Jan. 2023: Tutorial paper on "Transformed inputs for linearization, decoupling and feedforward control" published in JPC. [paper]
- 13 June 2022: Plenary talk on "Putting optimization into the control layer using the magic of feedback control", at ESCAPE-32 conference, Toulouse, France [slides]
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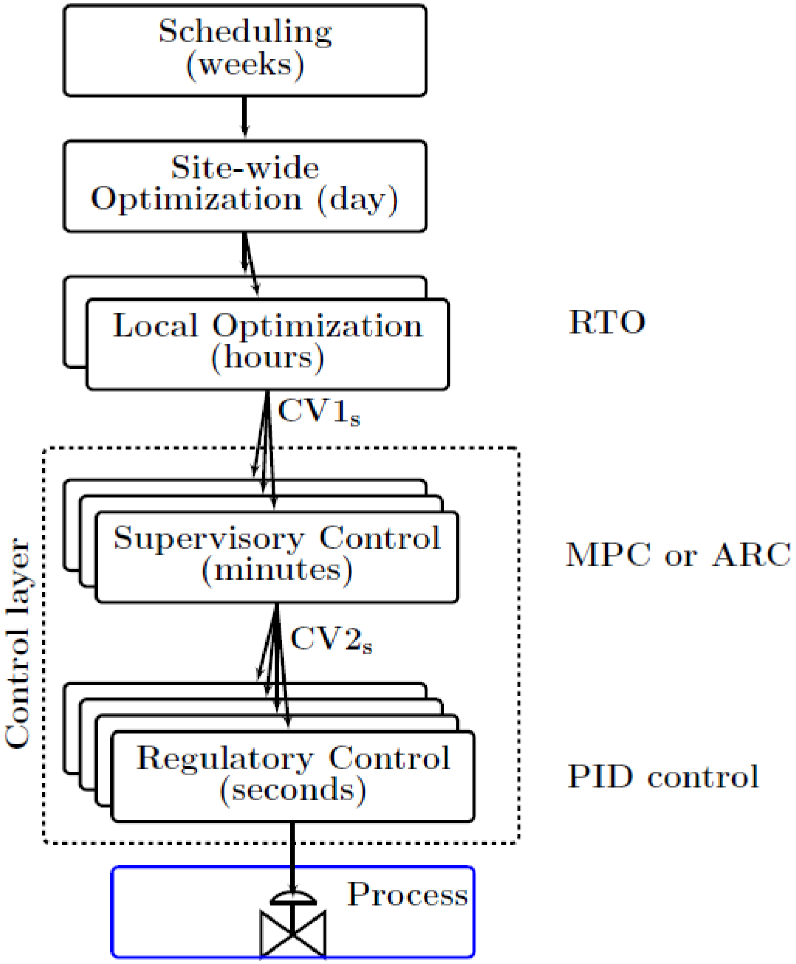


Figure 4: Decomposition of “overall control system” for optimal operation in typical process plant. This involves a vertical (hierarchical) decomposition Richalet et al. (1978) into decision layers based on time scale separation, and a horizontal decomposition into decentralized blocks/controllers, often based on physical distance. There is also feedback of measurements (y, w, CV1, CV2) (possibly estimates) from the process to the various layers and blocks but this is not shown in the figure. This paper considers the three lowest layers, with focus on the supervisory control layer.

CV1 = Economic controlled variables
CV2 = Regulatory/stabilizing controlled variables
RTO = Real-time optimization
MPC = Model predictive control
ARC = Advanced regulatory control
PID = Proportional-Integral-Derivative

Tutorial (from webpage NPC)

Optimal operation and advanced control using decomposition and simple elements

Summary.

How can you control a complex plant effectively using simple elements with a minimal amount of modelling? How can you put optimization into the control layer?
Industry has been using simple and effective as "advanced regulatory control" schemes for almost 100 years. These approaches are now finally being put into a systematic approach. There is still a need for better theory, so this is a challenging area also for new research.

Abstract:

Control engineers rely on many tools, and although some people may think that in the future there will be one general universal tool that solves all problems, like economic model predictive control (EMPC), this is not likely to happen. The main reason is that the possible benefits of using more general tools may not be worth the increased implementation costs (including modelling efforts) compared to using simpler "conventional" advanced regulatory control (ARC) solutions. In particular, this applies to process control, where each process is often unique. In addition, for a new process, a model may not be available, so at least for the initial period of operation a conventional scheme must be implemented.

Control is about implementing optimal operation in practice under varying conditions (disturbances, prices, etc.). Most people think that on-line optimization (RTO) is needed to achieve this, but in many cases, it is possible to put the optimization into the control layer using the magic of feedback.

Since its introduction in the 1940's, about 80 years ago, advanced regulatory control (ARC) has largely been overlooked by the academic community, yet it is still thriving in industrial practice, even after 60 years with model-based multivariable control (MPC). So it is safe to predict that conventional ARC (including PID control) will not be replaced by MPC, but will remain in the toolbox along with MPC.

Thus, it is time to give conventional advanced regulatory control (ARC) a "new beginning" in terms of strengthening its theoretical basis and training engineers and students on how to use it in an effective manner. Conventional ARC includes the standard control elements that industry commonly uses to enhance control when simple single-loop PID controllers do not give acceptable control performance. Examples of such control elements are cascade control, ratio control, selectors, split range control, valve position control (VPC), multiple controllers (and MVs) for the same CV, and nonlinear calculation blocks.

This workshop takes a systematic view on how to design a conventional ARC system. The starting point is usually optimal steady-state economic operation. The process may have many manipulated variables (MVs) for control (typically valves), but usually most of these are used to control "active" constraints, which are the constraints which optimally should be kept at their limits at steady state. For the remaining unconstrained degrees of freedom, we should look for self-optimizing variables, which are measured variables for which the optimal values depend weakly on the disturbances.

In terms of control system design, we usually start by designing a good control system for the normal (nominal) operating point, preferably based on single-loop PID controllers where each manipulated variable (MV), which is not optimally at a constraint, is paired with a controlled variable (CV). To handle interactions, disturbances and nonlinearity, one may add cascade control, ratio control, feedforward control, decoupling and more general calculation blocks.

However, during operation one may reach new (active) constraints, either on MVs or CVs, which may be easily observed from measurements of the potential constraints. Since the number of control degrees of freedom does not change, we will need to give up the control of another variable, which will either be another constraint (on CV or MV) or an unconstrained CV (self-optimizing variable). The key is then to know which variable give up, and in many cases we may observed by feedback and implemented using standard ARC elements.

A key new observation is that there are only four cases of constraint switching and these may be handled by using standard ARC control elements.

- For CV-CV switching we use selectors (overrides),
- for MV-MV switching we use split range control or two other alternatives,
- for simple CV-MV switching (where the CV no longer needs to be controlled when the MV saturates) we don't need to do nothing (except for including anti-windup in the controller), and
- for "complex" CV-MV switching we need to make a "repairing of loops" by combining CV-CV and MV-MV switching.

The main disadvantage with conventional ARC compared to MPC is that it is based on single-loop controllers, so one needs to pair outputs (CVs) with inputs (MVs). For most processes this works well, but for more complex cases with many constraint switches one may get significant benefits and simplifications with MPC. Other cases where MPC may offer significant benefits compared to conventional ARC are for interactive processes and for cases with known future disturbances.

In summary, optimal economic operation may in many cases be achieved by use of simple conventional ARC elements, but there is a lack of understanding, both in industry and academia, on how such control systems should be designed. The workshop offers a new beginning in terms of providing a systematic approach.

Main reference: S. Skogestad, "Advanced control using decomposition and simple elements - An important and challenging research area". Annual Reviews in Control (2023).

About the presenters

Sigurd Skogestad received his Ph.D. degree from the California Institute of Technology, Pasadena, USA in 1987. He has been a full professor at Norwegian University of Science and Technology (NTNU), Trondheim, Norway since 1987. He is the principal author, together with Prof. Ian Postlethwaite, of the book "Multivariable feedback control" published by Wiley in 1996 (first edition) and 2005 (second edition). His research interests include the use of feedback as a tool to make the system well-behaved (including self-optimizing control and stabilization), limitations on performance in linear systems, control structure design and plantwide control, interactions between process design and control, and distillation column design, control and dynamics. His other main interests are mountain skiing (cross country), orienteering (running around with a map) and grouse hunting.
He has received several awards and is a Fellow of the American Institute of Chemical Engineers (2012) and IFAC (2014).

Lucas Ferreira Bernardino received his M.Sc. degree from the Federal University of Rio de Janeiro (UFRJ), Brazil in 2019 and is now working on his Ph.D. degree on the topic of this workshop. His other interests are music (singing and playing the keyboard) and downhill skiing

About Sigurd Skogestad

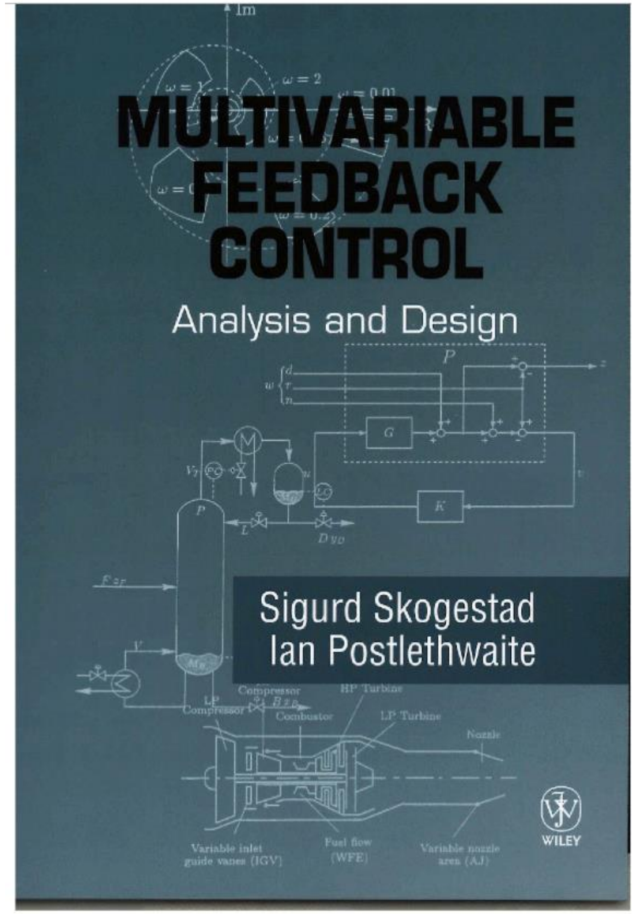
- 1955: Born in Flekkefjord, Norway
- 1956-1961: Lived in South Africa
- 1974-1978: MS (Siv.ing.) studies in chemical engineering at NTNU
- 1979-1983: Worked at Norsk Hydro co. (process simulation)
- 1983-1987: PhD student at Caltech (supervisor: Manfred Morari)
- 1987-present: Professor of chemical engineering at NTNU
- 1994-95: Visiting Professor UC Berkeley
- 2001-02: Visiting Professor UC Santa Barbara
- 1999-2009: Head of ChE Department, NTNU
- 2015-..: Director SUBPRO (Subsea research center at NTNU)

Non-professional interests:

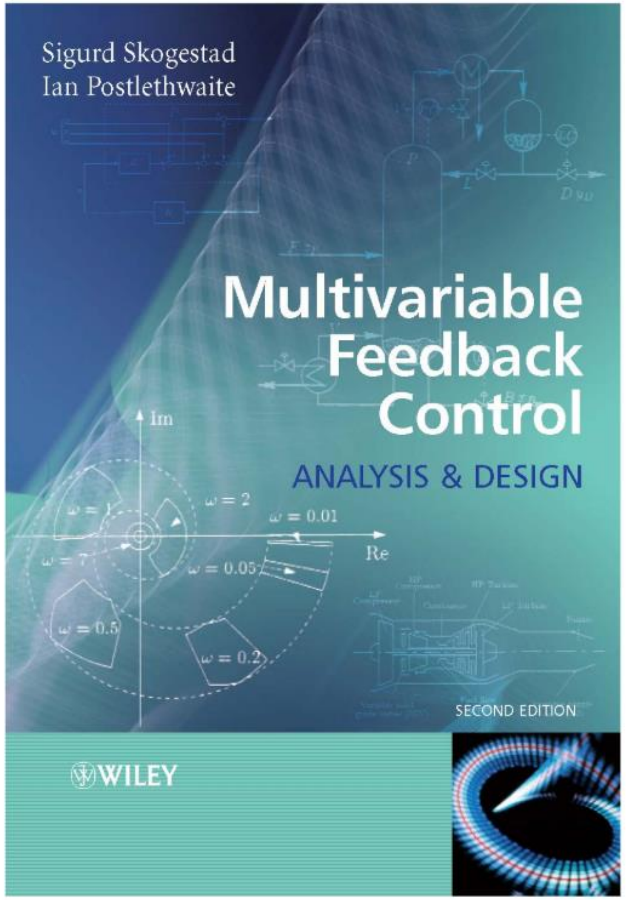
- **mountain skiing (cross country)**
- **orienteering (running around with a map)**
- **grouse hunting**

Robust multivariable control

Berkeley, Dec. 1994



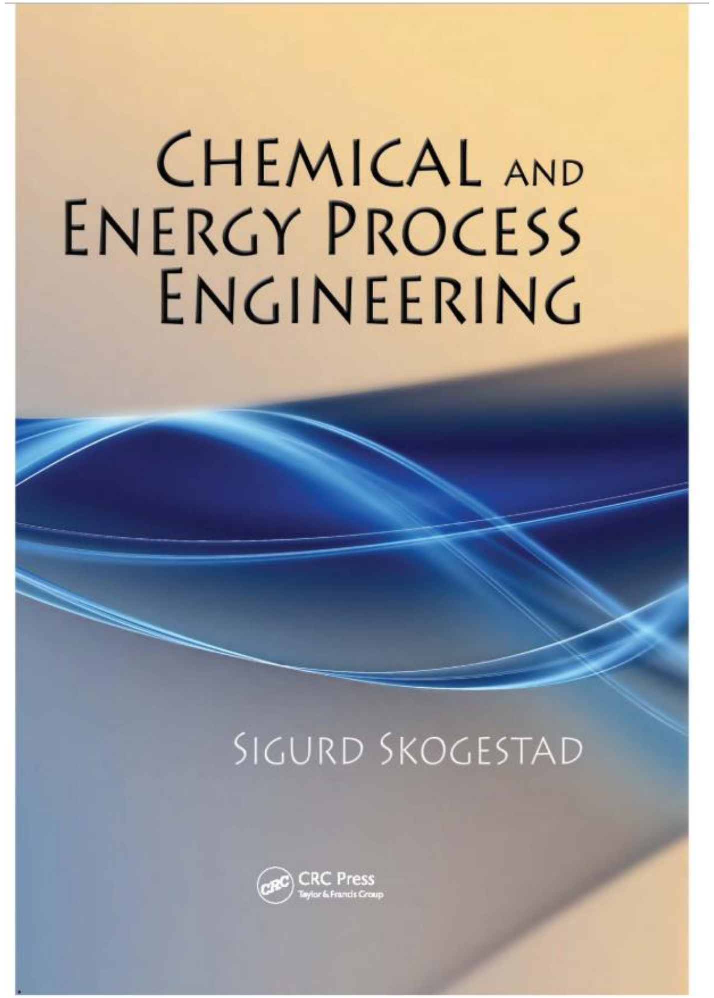
1996



2005

Process engineering

2000, 2003, 2009



2009

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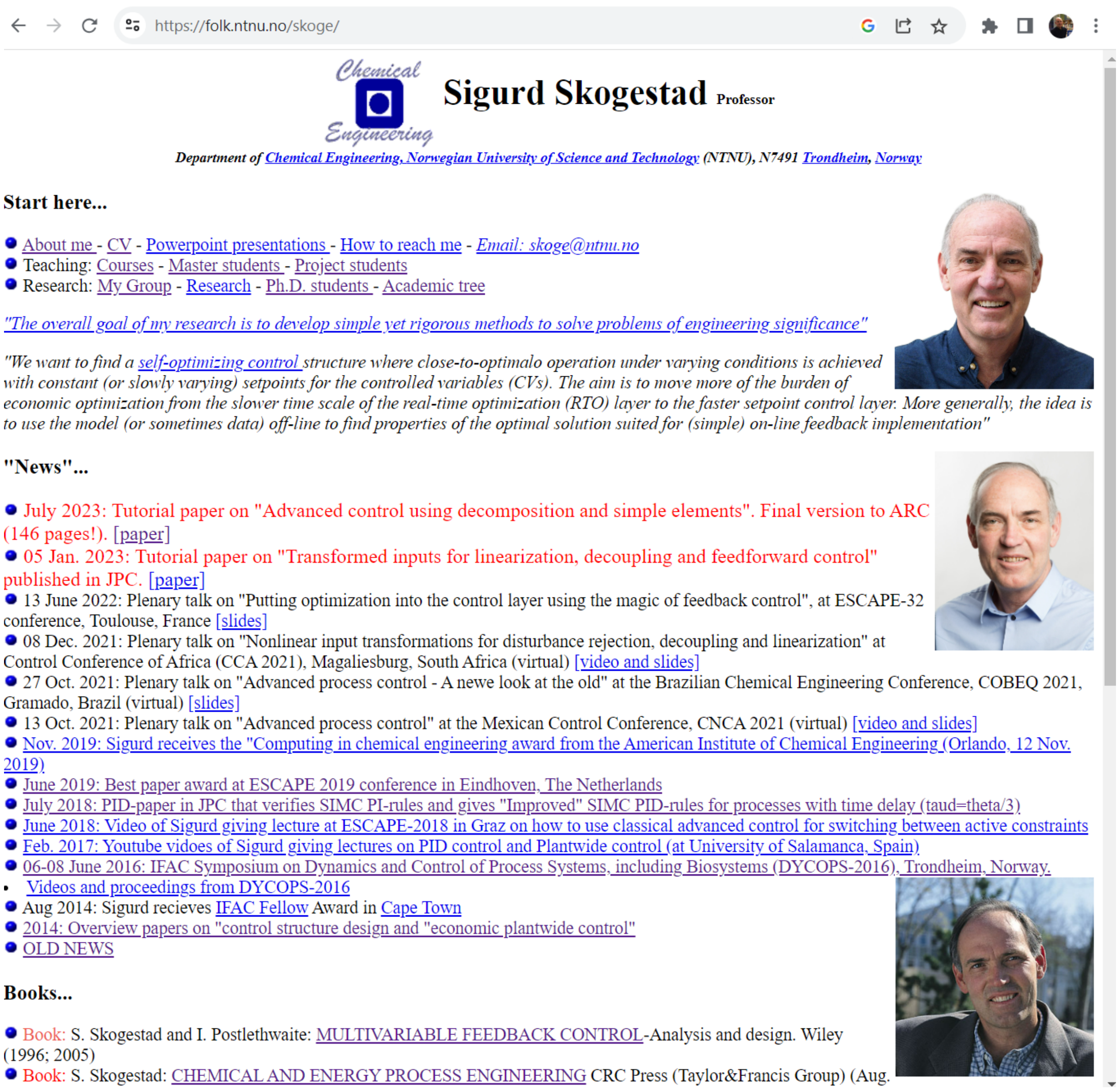

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- 08 Dec. 2021: Plenary talk on "Nonlinear input transformations for disturbance rejection, decoupling and linearization" at Control Conference of Africa (CCA 2021), Magaliesburg, South Africa (virtual) [video and slides]
- 27 Oct. 2021: Plenary talk on "Advanced process control - A newe look at the old" at the Brazilian Chemical Engineering Conference, COBEQ 2021, Gramado, Brazil (virtual) [slides]
- 13 Oct. 2021: Plenary talk on "Advanced process control" at the Mexican Control Conference, CNCA 2021 (virtual) [video and slides]
- Nov. 2019: Sigurd receives the "Computing in chemical engineering award from the American Institute of Chemical Engineering (Orlando, 12 Nov. 2019)
- June 2019: Best paper award at ESCAPE 2019 conference in Eindhoven, The Netherlands
- July 2018: PID-paper in JPC that verifies SIMC PI-rules and gives "Improved" SIMC PID-rules for processes with time delay (taud=theta/3)
- June 2018: Video of Sigurd giving lecture at ESCAPE-2018 in Graz on how to use classical advanced control for switching between active constraints
- Feb. 2017: Youtube vidoes of Sigurd giving lectures on PID control and Plantwide control (at University of Salamanca, Spain)
- 06-08 June 2016: IFAC Symposium on Dynamics and Control of Process Systems, including Biosystems (DYCOPS-2016), Trondheim, Norway.
- Videos and proceedings from DYCOPS-2016
- Aug 2014: Sigurd recieves IFAC Fellow Award in Cape Town
- 2014: Overview papers on "control structure design and "economic plantwide control"
- OLD NEWS

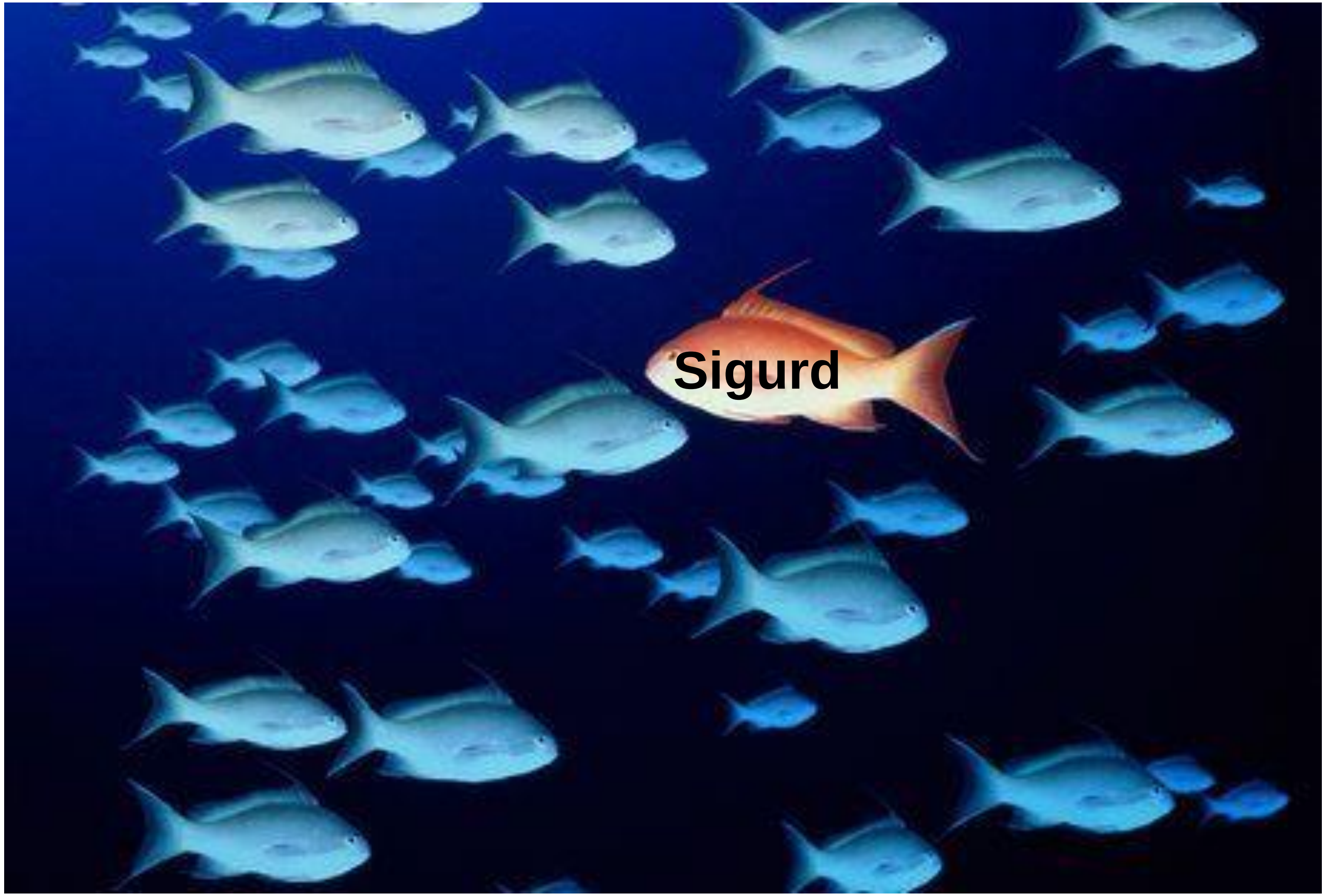
Books...

- Book: S. Skogestad and I. Postlethwaite: MULTIVARIABLE FEEDBACK CONTROL-Analysis and design. Wiley (1996; 2005)
- Book: S. Skogestad: CHEMICAL AND ENERGY PROCESS ENGINEERING CRC Press (Taylor&Francis Group) (Aug.

Academic control community fish pond

Complex optimal centralized Solution (**EMPC, FL**)

Simple solutions that work (ARC, PID)



09:40	Coffee/tea and registration
10:00 10:10 11:05 11:15	Introduction Part 1: Introduction to APC. The three main inventions of process control Break (10 min) Part 2: Typical hierarchy, Decomposition approaches, CV selection, cascade, time scale separation
12:10	Lunch (40 min)
12:50 13:45 13:55	Part 3: Constraint switching, standard control elements Break (10 min) Part 4 : More elements
14:50	Coffee/tea (20 min)
15:10 16:05 16:15 17:10	Part 5: More examples, Inventory control Break (10 min) Part 6: ESC. RTO. Model-based methods (non-MPC). Input transformations, Dual . EMPC? Summary
17:20	End of tutorial
18:30	American pizza at Peppe’s restaurant (all participants at the tutorial and NPCW are welcome)