Automation in Complex Systems –
A systems view - methods

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Content

- Complexity issues
- Continuous vs. discrete event systems
- Uncertainty
  - In dynamical systems
  - In discrete event systems
- Modeling complex systems
- Industrial process control systems
- The human in automation

Complex Industrial Systems

- Electric power systems
- Process industry
- Complex mechanical systems
- Plant wide wastewater systems
- Discrete manufacturing
- Integrated water systems

Dynamic systems – Basic Modelling

- Creating models from first principles
  - Mass, energy, force balances
- Looking at data and creating models
  - identification

Discrete event systems

Petri nets
Seq Function Charts

Markov processes + queuing theory

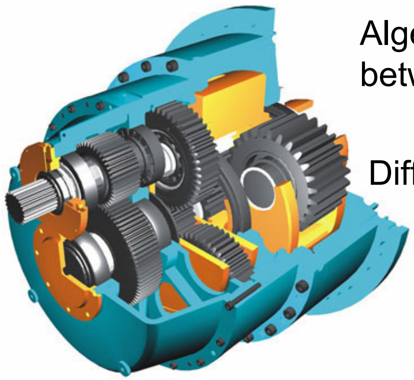
Optimization methods
Linear and nonlinear programming
Combinatorial problems

Discrete systems control
Capacity analysis
Scheduling

Complex mechanical systems

- Car body modelling
- Powertrain modelling
- Gearbox modelling
- Windmill mechanical modelling
- Astronomy telescope

Gearbox – what makes it complex?

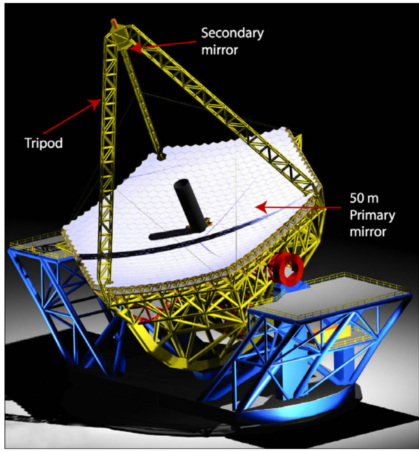


Algebraic couplings between units

Differential Algebraic Equations

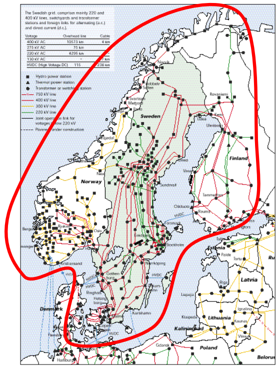
Each unit quite simple (Newtons law)

The EURO 50 Telescope



- 1854 actuators
- 3504 sensors
- Controllable but not observable
- 5 Hz bandwidth

One Physical System



- Synchronous Nordel system
  - 4 countries, 22 mill. people
  - 75000 km 110-400 kV-lines
  - 3000 generators
- Greatest coupling ≠ close
- One model!
- Everything affects everything

Källa: Nordel

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Renewable energy and automation

- Variable consumption has to be met with variable production – **storage control**!
- **Island** (decentralized) **operation** of electric power – an automation challenge
- Production has to be controlled
- Demand side management – controlling the **consumption** – a lot of automation

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Dynamic systems modelling

- Identify Inputs, Outputs and States
- Identify the Physical Laws/ Operating Principles/ How Inputs, States and Outputs are related
- Translate these into Logical / Algebraic / Differential/Difference expressions
- Convert to manipulatable form
- Analyze the system

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Definition

Complicated vs. complex

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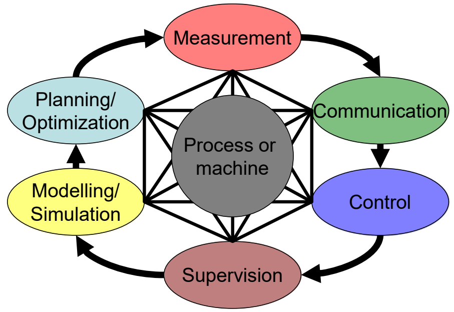
Aspects of Complexity

- Systems with
  - MANY states
  - MANY controllers
  - Widely different timescales
  - Many people involved
- Mixture of dynamical systems and discrete events (=hybrid)

Automation



- Everything connected
- Some components automatic
- Some components require human intervention

Automation (1/3)

Process or machine
- Process configuration
- Tanks, machines, lines, valves, pumps, etc.
- Actuators

Measurement
- Sensor technology
- Data screening and validation
- Calibration
- Modelling

Communication
- Networks
- Protocols
- Information flows
- Real time

Automation (2/3)

Control
- Control algorithms and structures
- Local control
- Supervisory control

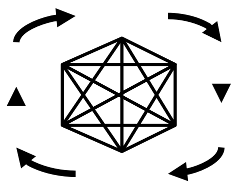
Supervision
- Data treatment
- Data analysis
- Process monitoring
- Decision support

Modelling/ Simulation
- Model building
- Steady state
- Dynamic
- Discrete
- Simulation

Automation (3/3)

Planning/ Optimization

- Production analysis
- Scheduling
- Production improvement
- Strategy



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Complex Systems

Natural Science / Engineering

- Natural science and reductionism
  - Subdivision
- Complexity of man-made systems
  - Requires a holistic view
  - Essential to consider the interactions between parts
  - System oriented disciplines

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Complexity

- Mathematics based on differential equations – good but not sufficient for complex systems
- If one person can grasp it – it is not complex!
- Biology can teach us
- In any complex system we need a network of communications
- The importance of feedback

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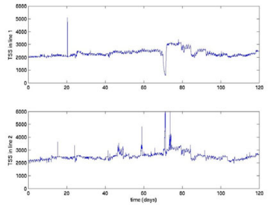
Continuous vs. Discrete Event Systems

- Continuous processes
  - Dynamical systems
  - Many PID controllers - many states
  - Interactions, nonlinearities
- Discrete manufacturing
  - Many dynamic systems on machine level
  - Discrete decisions on the cell level
  - "Complexity explosion"

Uncertainty in Dynamical Systems

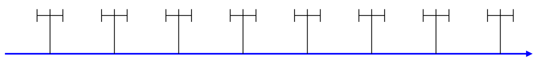
- Sensors
  - Noise – inaccuracy - aging
- Signal transmission
- Process
  - Incomplete mixing
  - Poor actuators (motors, pumps, valves)
  - Noisy variables
- External disturbances



Noise in a discrete event system

Average time for event:

Events:



time

Uncertainty in Event Driven Systems

- Machine break-down
- Operator missing
- Starving
- Blocking
- New model variants
- New customer order

An event at an unknown time

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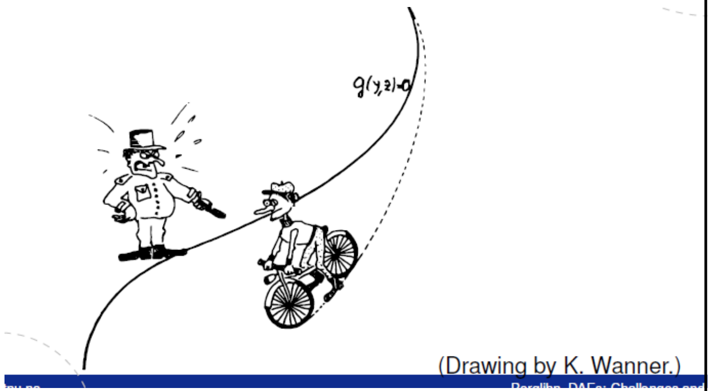
Differential Algebraic Equations

- Mixture of differential and algebraic equations
- Model libraries typically result in DAEs
  - Connecting two rotating masses
  - Connecting two pipes
  - Connecting power lines
- Stiff ODEs are related to DAEs

DAE – ODE with algebraic constraints



(Drawing by K. Wanner.)

DAE Model approach 1

$$\frac{dx}{dt} = f(x,u,t), \quad x(t_0) = x_0$$

$$G(x,u,t) = 0$$

Given x_n, t_n solve $G(x_n,u,t_n) = 0$ and evolve x_{n+1} using ODE methods

- Explicit method must be available, e.g. Runge-Kutta
- Can be expensive due to inner iterations

DAE Model approach 2

$$F\left(\frac{dx}{dt}, x, u, t\right) = 0$$

Solution:
Solve the implicit or semi-explicit form simultaneously using an implicit solver and evolve both *x* and *u* in time.

- Requires an implicit solver
- Is much more efficient
- Provides for more flexible problem specification.

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Typical models using DAE-formulation

- Chemical engineering processes with equilibrium conditions
- Constrained mechanical systems, robots
- Electrical circuits and power grids
- Heating, ventilating and air-conditioning of buildings

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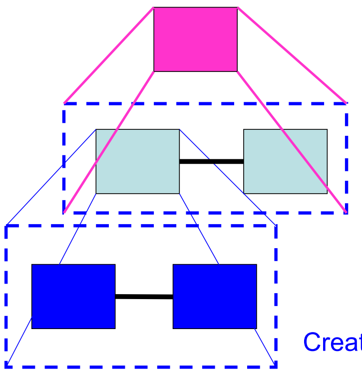
Building Models – the Hierarchical View



Connecting systems:

Through variables like elecrical currents, liquid or gas flows

Cut variables, like voltage, pressure

Creates often algebraic conditions

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Model Library

- Modelica – a modelling language for hierarchical physical modeling
- Object oriented constructs to facilitate modelling
- Exchange model modules

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Modelica - features

- Typical programming language statement:
  x := 2 + y
  x is assigned a value from the right-hand side.
- In Modelica: an equation may have expressions on both sides:
  x + y = 3 * z
- Equations do not describe assignment but *equality*.

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Modelica – features

- Initiated by Hilding Elmqvist in 1996
- Since 2000 a non-profit organization
- Modeling large (>10^6 equations), complex and heterogeneous physical systems
- Multiple domains
  - Mechanical , electrical, hydraulic, control
  - Differential, algebraic, discrete equations
  - No variable needs to be solved for manually
- www.modelica.org

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Modelica libraries

- Modelica.org/libraries
- A collection of free & commercial libraries (1600 model components, 1350 functions).
- Libraries for:
  - Electric, electronic and magnetic components
  - Mechanical components
  - Fluid components
  - Control systems
  - Functions

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Reuse of models

- A key issue to handle complexity
- The ability to reuse and exchange models depends on a standardized format

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Modelica development

Research projects within Europe spend 75 M€ in the years 2007-2015 to develop Modelica and Modelica related technology

Key contact in Lund:

Modelon AB www.modelon.com

Connect Submodels

```
model MotorDrive
      PID          controller;
      Motor        motor;
      Gearbox      gear  (n=100);
      Inertia      inertia  (J=10);
equation
      connect(controller.outPort, motor.inPort);
      connect(controller.inPort2, motor.outPort);
      connect(gear.flange_a, motor.flange_b);
      connect(gear.flange_b), inertia.flange_a);
end MotorDrive
```

modelclass

represented by a line

connection class

Simulator requirements

- Original set of equations is large
- Taking care of DAE - automatically
- Logical conditions
- Good graphical representation of model
- Numerics
  - Stiff DE
  - Automatic elimination of algebraic conditions
- Dymola from Dynasim (www.dynasim.se)

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Challenges in Complex Systems (1)

- Event and continuous processing are tightly integrated (hybrid systems)
- Two different programming constructs:
  - cyclical-data processing (such as feedback control loops)
  - event-driven logic (such as error handling and start-up sequences)

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Challenges in Complex Systems (2)

- Software system must easily break down into recognizable subsystems
- Must encourage a hierarchical, object-oriented design with well-defined interfaces
- Breaking complex systems into reusable subsystems

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Two Different Developments

- The process industry
  - Replace the analog PID controller with a computer
  - The instrumentation people
- The manufacturing industry
  - Replace the electromechanical relays with a computer (PLC)
  - The electricians
  - IEC standard 61131-3

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The human in automation

- Automation can never be successful without the acceptance of the users → *ALWAYS involve the end user*
- What makes people perform better?
- Wicked problems - too many people and opinions involved, or the economy is a major obstacle. VUCA (volatile, uncertain, complex, and ambiguous)

Complex systems….

…often means complex organisations

- You can never explore all outcomes of changes
- Chess: 10^{120} possible chess strategies (No of protons in the universe = 10^{75})
- The lesson: you can never plan for the whole game. You have to become a skilled player.

Conventional vs wicked problems (1)

	Conventional	Wicked
Problems	Clear definition of problem. Unknown solutions.	No clear definition of problem. Unknown and changing solutions.
Thought processes	Linear	Complex systems
Time dimension	Task completed when task solved	No time solution. Politically determinate
Nature of knowledge - expertise	Scientific solutions by experts	Problem definition is function of stakeholder views and perspectives

Conventional vs wicked problems (2)

	Conventional	Wicked
Outcomes	Outcome is either true or false, successful or unsuccessful	Unknown outcome – may be better, worse, or acceptable. No “correct” solution.
Problem approach	Scientific, knowledge protocols	Solutions depending on stakeholder views
Problem characteristic	Loose coupling	Tight coupling
Solutions characteristic	Cause and effect analysis	Multiple feedback analyses
Value system	Shared values of outcomes	Values are in dispute, or in conflict

Incentives for people

- Money?
  Does money make work more meaningful?
- Self-fulfillment?
- Loyalty?
- What makes people take responsibility?
- Prestige?
- We have never done this before?
- The end user, the customer, …..

Dealing with Complexity

- Brute force (i.e. supercomputing) using conventional tools.
  Combinatorial explosion.
- Approximation (i.e. linearization)
- Divide and conquer (e.g. modularization)
- Change of view – new tools

Challenges for tomorrow

- To understand complexity
- To handle complexity
  - Thousands of control loops
  - The integrated production
  - Couplings between various production units
- To upgrade control systems – during operation
- Always remember the man in the loop

Release in Summer 2022

Interactions – a systemic view

Why we need to comprehend the water-climate-energy-food-economics-lifestyle connections

Open access
IWA Publication, London