Automation in Complex Systems – part 2

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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
  - Integrated water systems
- Discrete manufacturing
  - Integrated water systems

Complex mechanical systems
- Car body modelling
- Powertrain modelling
- Gearbox modelling
- Windmill mechanical modelling
- Astronomy telescope
Basic Modelling

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

Gearbox

What makes it complex?

- Algebraic couplings between units
  - Differential Algebraic Equations
- Each unit quite simple (Newton's law)

Definition

Complicated vs. complex
Aspects of Complexity

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

Automation (1/3)

- 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
- Supervision
- Modelling/Simulation
- Control algorithms and structures
- Local control
- Supervisory control
- Data treatment
- Data analysis
- Process monitoring
- Decision support
- Model building
- Steady state
- Dynamic
- Discrete
- Simulation
**Automation (3/3)**

- Production analysis
- Scheduling
- Production improvement
- Strategy
- Everything connected
  - Some components automatic
  - Some components require human intervention

**Key Challenges (1)**

- The key challenge is to contribute positively to process profitability.
- For more mature applications: control can improve plant economy by decreasing energy use, increasing throughput, reducing off-specification products etc.
- For new applications, such as drugs, electronic materials: control can be a key to getting a process up and running

**Key Challenges (2)**

- To maintain safe, economical and reliable plant operation.
- Environmental considerations will take on increasing importance
- Benchmarking becomes more important

**Complex Systems**

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

- Mathematics based on differential equations – good but not sufficient for complex systems
- Mathematical controllers can be understood by a single person
- If you can grasp it – it is not complex!
- Biology can teach us

Key Disciplines

- Control
- Communication
- Computing
- Software Engineering

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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 dynamical system

Noise in a discrete event system

Average time for event:

Events:

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

Differential Algebraic Equations

\[ \frac{dx}{dt} = f(x,u,t), \quad x(t_0) = x_0 \]
\[ G(x,u,t) = 0 \]

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.

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

Papers published containing “DAE”

(Source: Scopus)

Building Models – the Hierarchical View

Connecting systems:
- Through variables like electrical currents, liquid or gas flows
- Cut variables, like voltage, pressure

Creates often algebraic conditions
Model Library

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

Modelica – important 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

Reuse of models

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

Modelica development

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

Key contacts in Lund:
Hilding Elmqvist, Dassault Systèmes AB, hilding.elmqvist@3ds.com
Modelon AB www.modelon.com
Modelica - characteristics

- Modelica Standard Library
  - open source contains about 1280 model components and 910 functions from many domains. Continuous and discrete blocks
- 1-dim and 3-dim mechanical components
- Electrical, hydraulic, thermo-fluid, power system, power train components
- Class parameters
- Multiple inheritance

Connect Submodels

```model MotorDrive
  PID controller;
  Motor motor;
  Gearbox gear (n=100);
  Inertia inertia (J=10);
end MotorDrive
```

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)

Simulator platforms Modelica

- CATIA Systems, CyModelica, Dymola, LMS AMESim, JModelica.org, MapleSim, OpenModelica, SCICOS, SimulationX, Vertex and Wolfram SystemModeler.
- Modelica models can be imported into Simulink using export features of Dymola, MapleSim, SimulationX and Vertex.
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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)

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

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 operators
• What makes people perform better?
• Are we like (PI)D controllers?

Incentives for people

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

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.
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