Prospects for model based plasma control in nuclear fusion reactors

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Special Thanks to TEXTOR, Asdex Upgrade, West and TCV teams
Feed Back control system

Integrated optimisation of all Control System’s elements taking plant dynamics into account
DEMO Actuator usage

Distributed
Task shared
Close to \textbf{variable} constraints
Operated close to **varying** performance, operational and machine integrity limits

ODEs to non-linear, coupled PDEs

Off-normal events

Repetitive
Generic control system

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Y_r → C → A → P → Y_m
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Limited scope for sensing
Bandwidth, Latency
Degradation
Sacrificial diagnostics
Plasma control in an ill-sensed reactor?
Developments in Systems and Control Theory

- < 1960 classical control engineering (SISO)
- 1960-1980 state space, large scale systems, Kalman observation
- 1980-1990 robust control, system identification
- 1990-2000 model based predictive control
- 2000-2010 hybrid (event-driven) system theory
- > 2010 network control, distributed control, Iterative Learning Control
- 1 Thesis: Control close to phase transitions
Detailed knowledge of state is key in these methods.
Rutherford equation

\[0.82 \frac{\tau_r}{r_s} \frac{dw}{dt} = r_s \Delta'_0 + r_s \Delta'_\text{des} + r_s \Delta'_{CD}\]

Modified, Generalized Rutherford eq.

Nonlinear 1st order Ordinary Differential Equation

Local linearization of the (non-linear) ODE

Reformulate in state-space description around multiple operating points

Compute transfer functions for different operating points

Conceive Control structure

Ensure performance and stability

Carry-out closed loop simulations
Simulation NTM control

Below \( w_c \)

Low power
State observers

Plant

Model
Kalman filter for plasma profiles: RAPTOR
MPC using the repetitiveness of the plant
MPC for j-distribution

- Unconstrained EC power (fb)
- Saturated EC power (ff)
- Constrained EC power (fb)

Graphs showing time evolution of various parameters, including EC power, NBI power, and other related quantities.
Non-linear observation and linear model predictive control of current distribution
Unsented Kalman filter for mode frequency and phase
Diagnostics vs. Sensors

Diagnostic
• High spatio-temporal resolution
• High latency acceptable
• Should work often in various configurations

Sensor
• Spatio-temporal resolution optimal for control problem
• Latency ruins bandwidth
• Should work always for limited set of predefined configurations

Can high-end physics analysis be used for control?
Doing by Learning:
Iterative Learning Control on TCV
Things we will / could / should be doing

• Use trajectories as early warning systems (GOT Blanken)
• Incorporation of NTM dynamics in RAPTOR
  – Realistic evolution of jboot with island width
  – Hybrid plant control
    (Maljaars en van de Brand)
• Observer + MPC for
  – plasma position and current control
  – density distribution, Blanken et al.
  – operation in vicinity of transitions: e.g. H-mode and detachment
• Combined observer for shielded and non-shielded coils?
Conclusions

Control in nuclear fusion reactor complicated due to plant, actuator and sensor limitations.

Reactor is going to be run repetitively along known trajectories: non-linear state observation and linear prediction models.

Variety of developments in RTC that are highly relevant for our community.

Control oriented models required for controller derivation (off-line), state observation, prediction, experiment improvement.
Sawtooth locking
Non-ideal sensor

\[ Y_m = \frac{Y_r CP}{1 + SCP} + \frac{dP}{1 + SCP} - \frac{SCP}{1 + SCP} \]
Plasma control not sufficient for plant integrity. The plant will have dedicated safety systems. The controllers need to interact with these
Extract plasma edges, solve the geometry problem...

- ...and we can measure the plasma boundary directly!
Vision in control loop!

$t = 1.297$ s

Vertical position

- Measured position
- Desired position

Vision in the Loop

Desired Position → Compare → Control → Optical Measurement

Measured position
Engineering approach: Control of MHD using CO-LOCATED actuator-sensor
Closed loop control of MHD in TEXTOR
Modelling for control (2)

1. Define objective
   - Purpose of model?
   - Required accuracy?
   - Control goals

2. Prepare information
   - Identify variables of interest?
   - State assumptions?
   - Input/output structures

3. Formulate model
   - Conservation laws
   - Constitutive equations
   - Transfer functions

4. Model-based control design
   - Model representations
   - Control configurations
   - Improve performances

5. Determine solution
   - Analytical solutions
   - Numerical solutions

6. Analyze results
   - Results correct?
   - Interpret the results

7. Validate model
   - Select key variables
   - Compare with experiments
Mattei et al. propose the Command Governor approach to avoid constraints violations in ITER shape control. It makes use of the time-varying linearized plasma model and requires the online solution of an optimization problem. See

MIMO Sawtooth control