NTNU

Norwegian University of Science and Technology

The Thinking Man and MPC

BobFest, June 8, 2024

My first observation of Bob in action

- IFAC World Congress in Sydney
- Conference best paper award
- Presentation style

Sabbatical at UCSD

- Academic year 2002-03
- Returned to academia from industry a few years earlier
- Learned a lot from Bob and Miroslav
- Vital for my academic carreer

Typical academic MPC formulation

$$\min_{\boldsymbol{u}} x_{k+N}^T P_N x_{k+N} + \sum_{i=0}^{N-1} x_{k+i}^T Q_i x_{k+i} + u_{k+i}^T R_i u_{k+i}$$

$$\text{s.t. } x_{k+i+1} = f(x_{k+i}, u_{k+i}, d_{k+i})$$

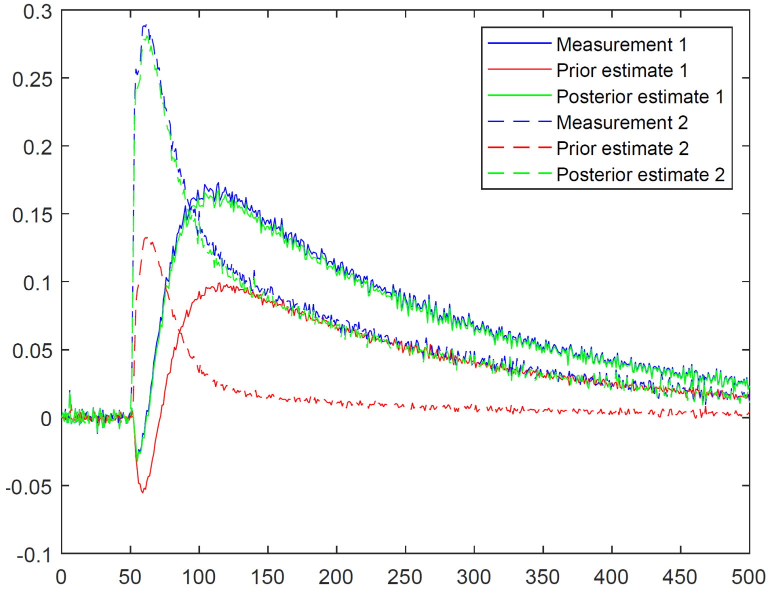
$$x_{k+i} \in \mathcal{X} \quad i = 1, \cdots, N$$

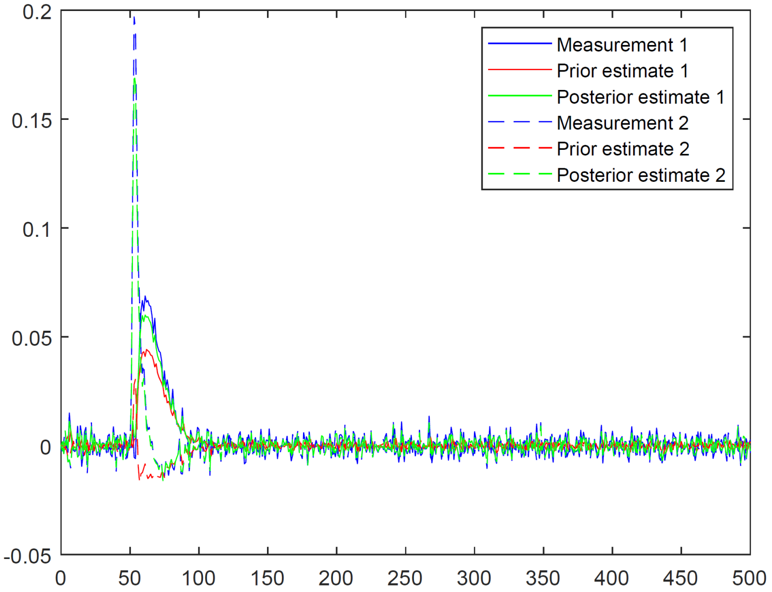
$$u_{k+i} \in \mathcal{U} \quad i = 0, \cdots, N-1$$

$$\boldsymbol{u}^T = \left[u_k^T, \cdots, u_{k+N-1}^T\right]^T$$

- x_k ‘known’ at time k.
- Must ‘guess’ future disturbances
- Hope for certainty equivalence
  - Interactions between control and estimation not made clear

Two simulations with the same MPC





Identical MPC, same disturbance

Identically tuned augmented Kalman filter (same noise variances)

Different disturbance modeling – left: common industrial practice

State estimation and Stochastic MPC

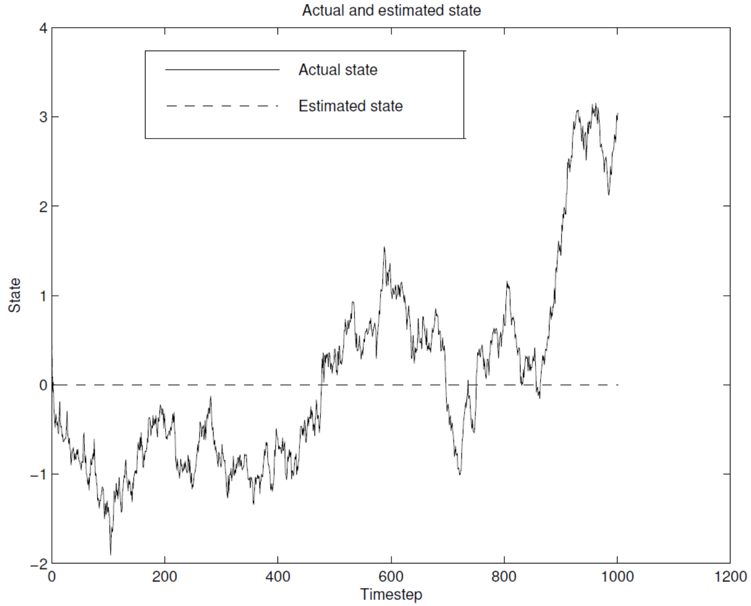
- Yan & Bitmead: Incorporating State Estimation in Predictive Control and its application to network traffic control, (Automatica, 2005)
- Use deterministic MPC, but ‘back off’ from constraint depending on predicted Kalman filter covariance.
- Avoid exaggerating predicted covariance in the far future.

Dual Adaptive MPC

- Dual control: control input used both for regulation and for learning about the system.
  - The two objectives often in conflict – at least in the short term
- Interaction between Control and State Estimation in Nonlinear MPC
  - IFAC DYCOPS 2004
- System: marginally stable and weakly unobservable at the reference
  - Certainty equivalence does not apply, 'standard' MPC + EKF unstable.
  - Stable using MPC where the objective function includes a term depending on the predicted EKF covariance

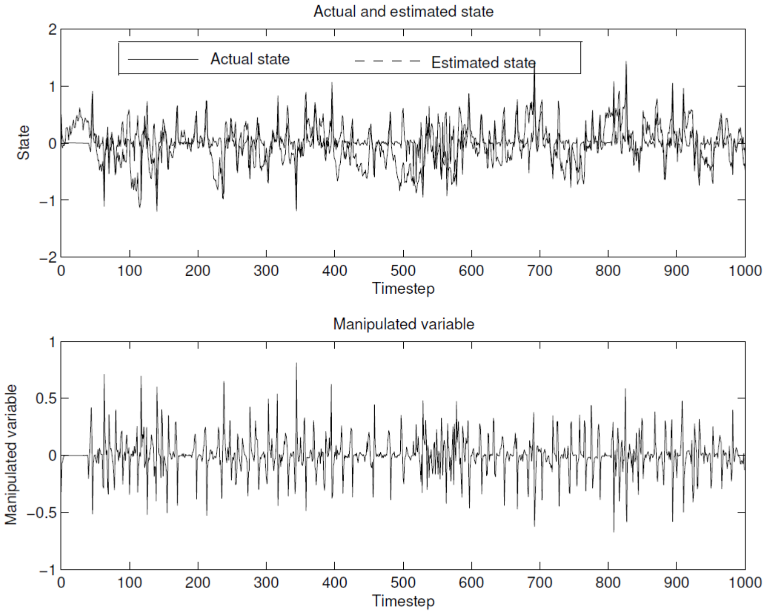
Dual Adaptive MPC

Standard MPC + EKF



Locally unobservable, state estimate does not update, no control action

Modified MPC + RHE



Input action makes estimate update possible. This enables stabilizing control

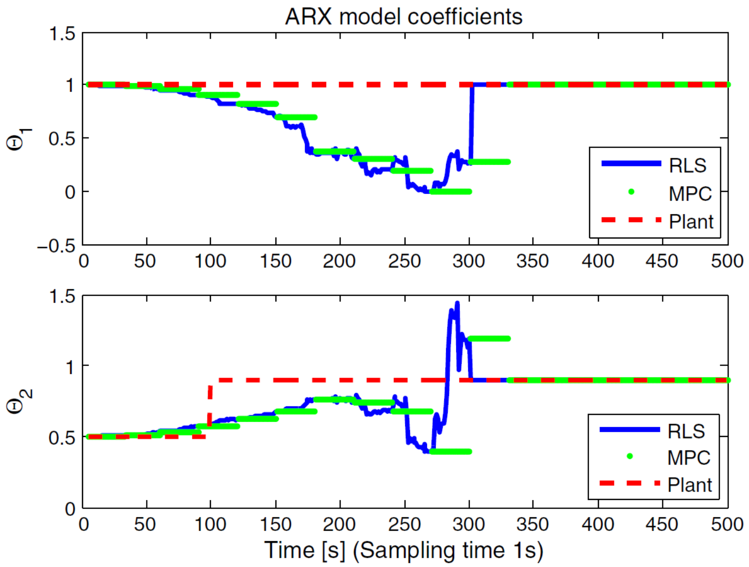
Continued cooperation

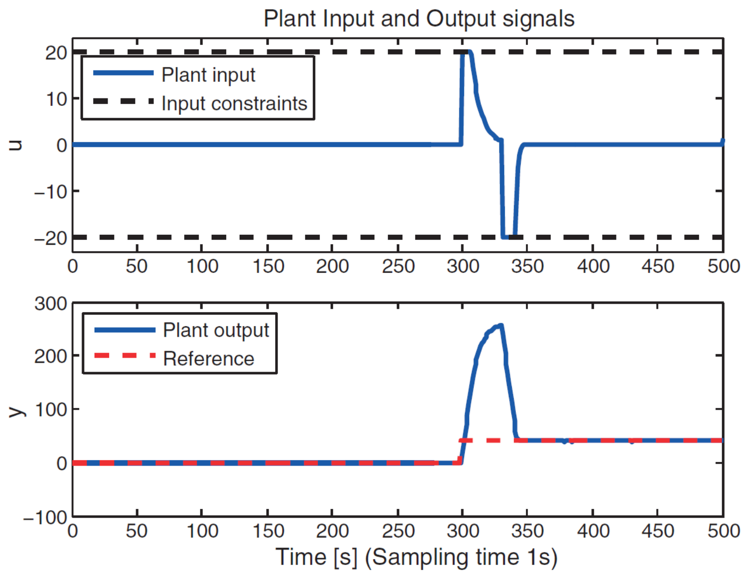
- Research project funding
- Hosting PhD students visiting UCSD
- Sabbatical at NTNU

Persistently exciting MPC

- Controlling to a fixed reference ‘ensures’ that there is not sufficient information in input/output data to update the plant model (model parameters)
- Persistently exciting model predictive control
  - Makes updating plant parameters possible
  - Marafioti, Bitmead, H., IJACSP (2013)
  - PE constraint added to MPC formulation
  - Makes optimization non-convex (input outside ellipsoid)
- Brüggeman & Bitmead: Forward-looking persistent excitation in model predictive control
  - Automatica, 2022
  - Designing reference trajectory to ensure PE

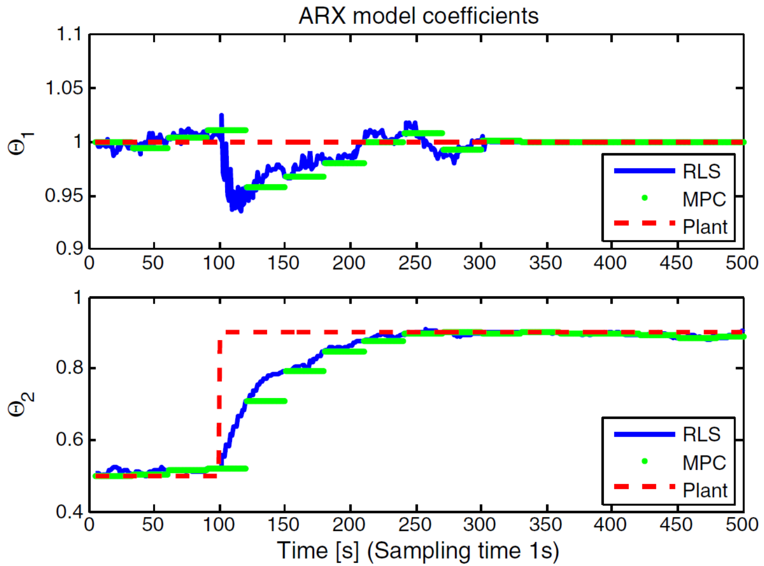
MPC without PE

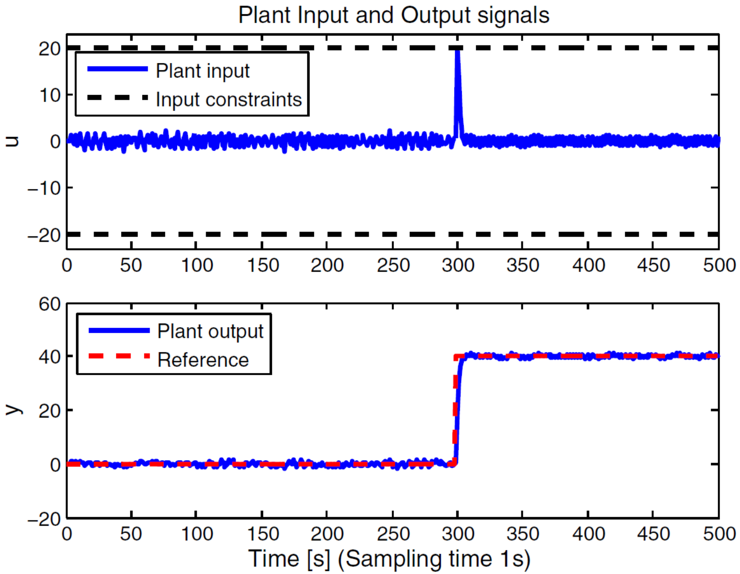




Step change in parameter 2 at t=100.
Reference change at t = 300.

MPC with PE





Small perturbations in the input keep parameter estimates from drifting. Change in parameter tracked. Reference change tracked well.

Simultaneous Input and State Estimation (SISE)

- Work initiated during Bob’s sabbatical in Trondheim shortly before COVID
- Motivated by state estimation in power systems
  - Systems may be partly unknown
  - Not full knowledge of what goes on at custormer’s sites.
- Relationship between SISE and Kalman filter clarified
- Guaranteed stable version of SISE derived
  - Also for when system is not stably invertible

- Bitmead, H., Abooshahab: A Kalman filtering derivation of simultaneous inout and state estimation. Automatica, 2019
- Abooshahab, Alyaseen, Bitmead, H.: Simultaneous input & state estimation, singular filtering and stability. Automatica, 2022.
- Abooshahab, H., Bitmead: Disturbance and state estimation in partially known power systems. IEEE CCTA 2019
- Abooshahab: PhD thesis

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Thank you Bob!

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