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WP 3 – LEAST COSTLY CLOSED-LOOP TESTING

WORK PACKAGE OBJECTIVES

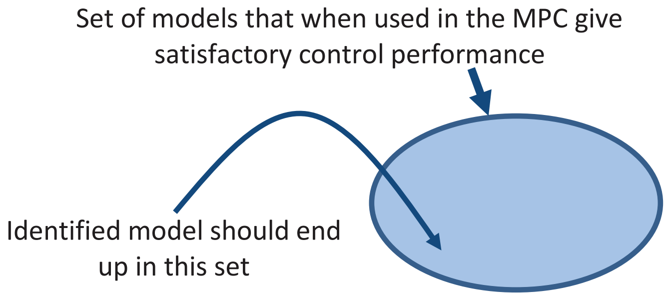
- Develop methodology and tools for autonomous and low cost closed loop testing.
- Methods adapted to constrained control, such as MPC, and MIMO system requirements.
- Link experimental costs to actual economic costs.

WORKPACKAGE OUTCOMES

- Experiment design methods for MPC:
  - Constrained open loop signal generation
  - MPC-X - MPC with eXperiment design
  - Stealthy MPC – MPC with open loop excitation
- MOOSE – A toolbox for optimal input design in MATLAB

APPLICATIONS ORIENTED EXPERIMENT DESIGN

- Identification experiments with precisely the information necessary for models giving satisfactory performance.
- Least costly experiment design.
- Information matrix requirements.



PROBLEMS WITH EXPERIMENT DESIGN UNDER MPC

- Current closed loop experiment design methods based on designing the signal spectra.
- Methods developed for linear controllers.
- MPC is nonlinear. The map from reference to input is non-linear.

SOLUTIONS FOR EXPERIMENT DESIGN UNDER MPC

- **Stealthy MPC** – by hiding the excitation from the controller the identification becomes an open loop problem.
- **MPC-X –** including constraint on experiment design in the MPC so that the excitation is generated by the controller.

CONSTRAINED SIGNAL GENERATION

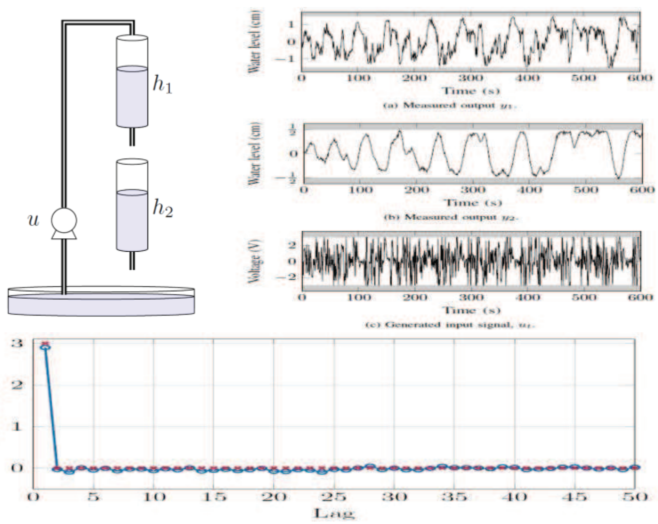
- Generation of signal with prescribed autocorrelation while satisfying input and output constraints.

$$\begin{aligned} \underset{u(1),\ldots,u(N)}{\text{minimize}} \quad & \left\| r_N - r^d \right\|_2^2 \\ \text{subject to} \quad & x_{t+1} = F x_t + G u_t \\ & y_t = H x_t \\ & u_{min} \le u_t \le u_{max} \\ & y_{min} \le y_t \le y_{max} \end{aligned}$$

- Difficult optimization can be simplified using receding horizon control ideas.
- Extended to robust MPC to satisfy constraints under model uncertainties

EXAMPLE – DOUBLE TANK SYSTEM

- Parameters re-identified online



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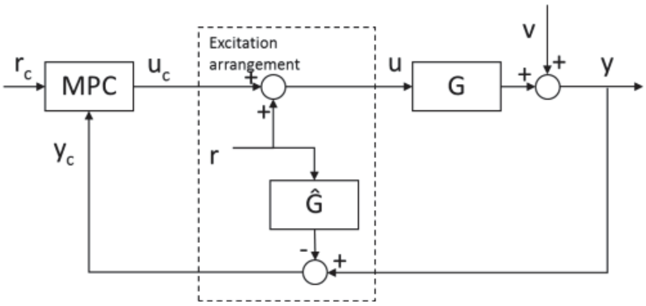
WP 3 – LEAST COSTLY CLOSED-LOOP TESTING

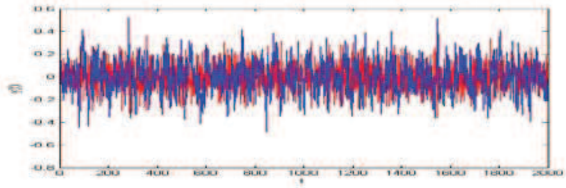
STEALTHY MPC

- **Idea –** Hide excitation from MPC – open loop identification!
- Patent pending.



EXAMPLE

- **Experiments**
  - Least costly experiment design
  - White noise signal with same power
- **Results**
  - Output with (blue) and without (red) excitation.



  - White noise does not give satisfactory model.
- **Conclusion –** Stealthy MPC works even if $\hat{G}$ is not exactly G.

MPC-X – MPC with eXperiment design

- Challenges:
  - Which constraint should be added?
  - Computational tractability.

Standard MPC:

$$\begin{aligned}\underset{\{u(k)\}_{k=1}^{N_u}}{\text{minimize}} \quad & \sum_{k=1}^{N_y} \|\hat{y}(k) - r(k)\|_Q^2 + \sum_{k=1}^{N_u} \|\Delta u(k)\|_{Q_u}^2 \\ \text{subject to} \quad & x(k+1) = Ax(k) + Bu(k) \\ & y(k) = Cx(k),\ k = 1, \dots, N_y \\ & x(1) = \hat{x}(t) \\ & u_{min} \leq u(k) \leq u_{max},\ k = 1, \dots, N_u \\ & y_{min} \leq y(k) \leq y_{max},\ k = 1, \dots, N_y \\ & \mathcal{I}_1^t + \mathcal{I}_{t+1}^{t+N_y} \succcurlyeq \kappa(t) \frac{\gamma \chi_\alpha^2(n_\theta)}{2} V''_{app}(\theta_0)\end{aligned}$$

Past Information matrix — Predicted Information matrix — Performance specification

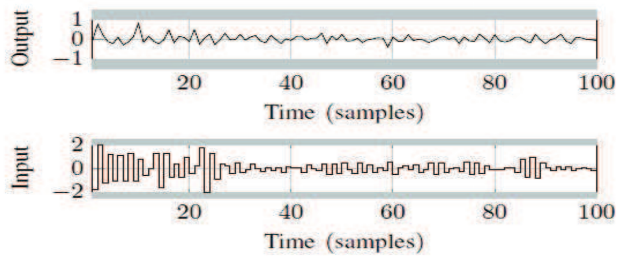
Different methods to achieve same closed loop performance

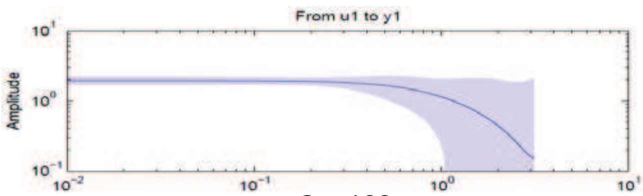
Method	Simulation time	Output variance
MPC-X	100	0.12
White ref.	100	0.20
White ref.	520	0.12

EXAMPLE – DOUBLE TANK SYSTEM

- N = 100 samples
- Umax = 2, Ymax = 1

MPC-X: Input variance 0.36 (0.28 minimum possible)





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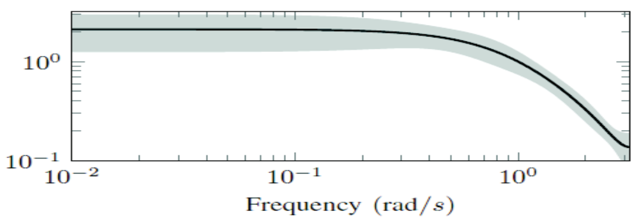

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