Fuzzy modeling and design for a 3D Crane

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ICONS - September 2013

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Summary

Objective: Fuzzy control of a 3D crane.

- TS fuzzy model of the crane
- TS observer
- The observer is tested in simulation and on a lab setup
- The controller is tested in simulation

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Introduction

Approaches for the control of a 3D Crane

- time-optimal control
- robust control for the crane swing and an LQ controller for tracking reference
- combined feedforward, feedback control and disturbance estimation
- fuzzy-logic projection controller designed based on cart position and swing angle
- fuzzy-logic controller to reduce the load swing during positioning of the crane

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Experimental setup

- States:
  - x_1, x_3, x_9: positions on y, x and z axes
  - x_2, x_4, x_{10}: velocities
  - x_5, x_7: angles
  - x_6, x_8: angular velocities
- Inputs: acceleration
- Model alterations:
  $x_9 \to x_9 + 0.1$
- Physical constraints

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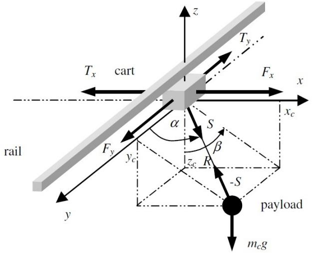
Mathematical model

Model equations

$$
\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= u_1^* + \mu_1 x_5 u_3^* - \mu_1 g x_5 \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= u_2^* - \mu_2 x_7 u_3^* + \mu_2 g x_7 \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= (u_1^* + \mu_1 x_5 u_3^* - \mu_1 g x_5 - g x_5 - 2 x_6 x_{10}) \frac{1}{x_9 + 0.1} \\
\dot{x}_7 &= x_8 \\
\dot{x}_8 &= -(u_2^* - \mu_2 x_7 u_3^* + \mu_2 g x_7 + g x_7 + 2 x_8 x_{10}) \frac{1}{x_9 + 0.1} \\
\dot{x}_9 &= x_{10} \\
\dot{x}_{10} &= u_3^*
\end{aligned}
$$

3D Crane system



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Discrete TS model

- Euler discretization
- Sampling time $T_e = 0.01\ s$ (system data acquisition rate)
- Discrete time model:

$$\begin{aligned} \mathbf{x}(k+1) &= A_d(\mathbf{x}(k))\mathbf{x}(k) + B_d(\mathbf{x}(k))\mathbf{u}(k) \\ \mathbf{y}(k) &= C\mathbf{x}(k) \end{aligned}$$

- Four nonlinear terms $\rightarrow$ fuzzy model with 16 rules:

$$\mathbf{x}(k+1) = \sum_{j=1}^{16} h_j(\mathbf{z}(k))(A_{d_j}\mathbf{x}(k) + B_{d_j}\mathbf{u}(k))$$

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TS observer

- The purpose is to apply advanced control techniques
- Five measurable states out of 10 $\rightarrow$ observer design
- TS system:

$$\mathbf{x}(k+1) = \sum_{i=1}^{r} h_i(\mathbf{z})(A_i\mathbf{x}(k) + B_i\mathbf{u}(k))$$
$$\mathbf{y}(k) = C\mathbf{x}(k)$$

- Fuzzy estimator:

$$\hat{\mathbf{x}}(k+1) = \sum_{i=1}^{r} h_i(\mathbf{z}(k))(A_i\hat{\mathbf{x}}(k) + B_i\mathbf{u}(k) + L_i(\mathbf{y}(k) - \hat{\mathbf{y}}(k)))$$
$$\hat{\mathbf{y}}(k) = C\hat{\mathbf{x}}(k)$$

where L_i, $i = 1, ..., r$, are the observer gains.

TS observer

- Design: calculate matrices P, H and M_i, $i = 1...16$, solving the LMIs:

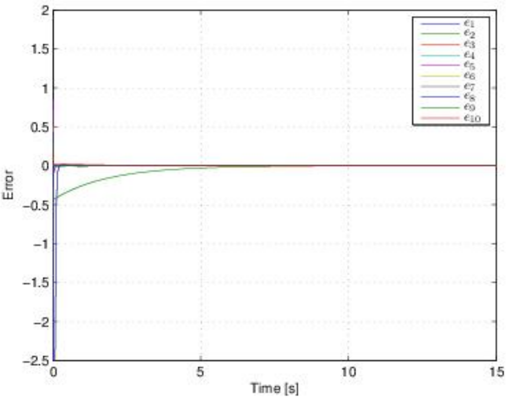
$$\begin{pmatrix} -P & (HA_i - M_iC)^T \\ HA_i - M_iC & -H - H^T + P \end{pmatrix} < 0$$

- Observer gains:

$$L_i = H^{-1} M_i, \ \ i = 1, \dots, r$$

Simulation results

- Inputs: randomly generated staircase signals
- Outputs: simulated states



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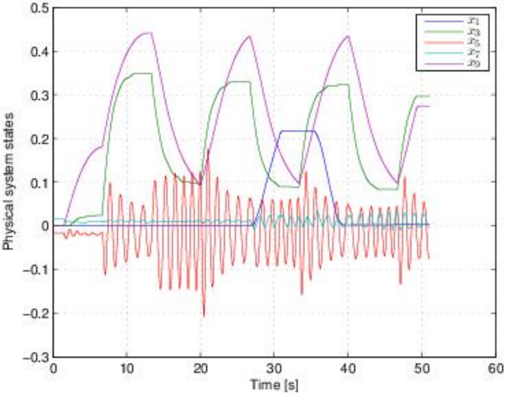
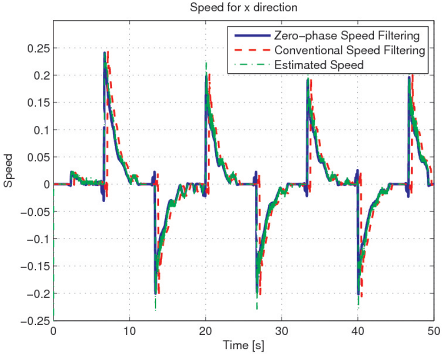
Experimental results

- Inputs: PID controller command signals
- Outputs: measured data from the plant



Experimental results

- Speed computed by differentiation and filtering
- Two filters: a zero-phase filter (used as a benchmark) and a low-pass filter



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Controller design

- PDC controller

$$\mathbf{u}(k) = -\sum_{i=1}^{r} h_i(\mathbf{z}) F_i \mathbf{x}(k)$$

- F_i - the local feedback gains - are obtained by solving :

$$G_{ii} < 0$$
$$\left(\frac{G_{ij} + G_{ji}}{2}\right)^T + \left(\frac{G_{ij} + G_{ji}}{2}\right) < 0$$

where:

$$G_{ij} = \begin{pmatrix} -H - H^T + P & (A_i H - B_i S_j)^T \\ A_i H - B_i S_j & -P \end{pmatrix}$$

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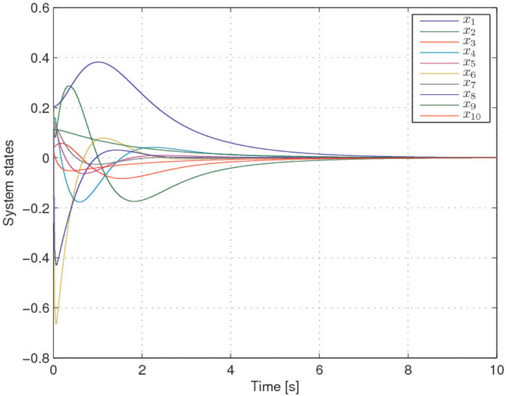
State feedback control

- The controller has been tested in simulation
- If all states are known, the closed-loop system is stabilized



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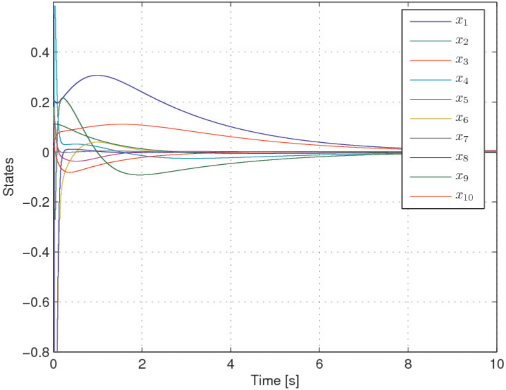
Observer-based control

- The controller was combined with the observer and tested in simulation
- Note on the separation principle



Conclusion

- The observer has been tested in a real-time experiment
- Controller: tested in simulation
- Future work: implementation of the controller

Acknowledgement:

This work was supported by a grant of the Romanian National Authority for Scientific Research, CNCS – UEFISCDI, project number PN-II-RU-TE-2011-3-0043, contract number 74/05.10.2011