Comparison of Feedback Controller for Link Stabilizing Units of the Laser Based Synchronization System used at the European XFEL

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MOCZB3

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Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

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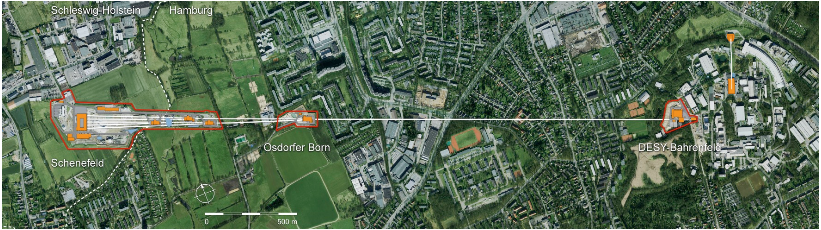
European X-ray Free Electron Laser (XFEL)



Idea

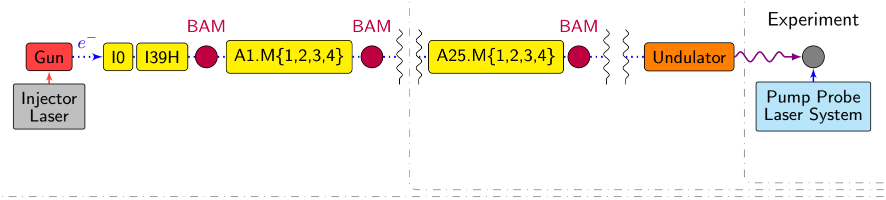
- Build a Camera to capture ultrafast processes in an atomic scale
- E.g.: Make a movie of the folding process of biomolecules

Some Numbers

- Wavelength of 0.05 to $6\,\mathrm{nm}$, Pulse duration of less than $100\,\mathrm{fs}$ (10^{-15})
- Total facility length of $3.4\,\mathrm{km}$ with 101 accelerator modules

Courtesy of http://www.xfel.eu

Laser Based Synchronization System (LbSynch)



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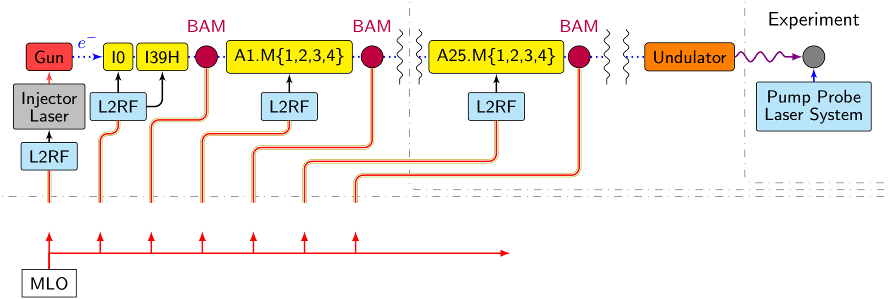

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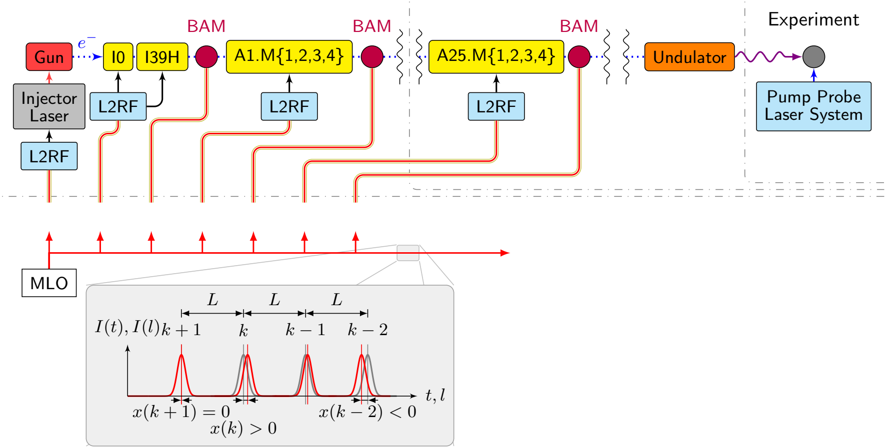

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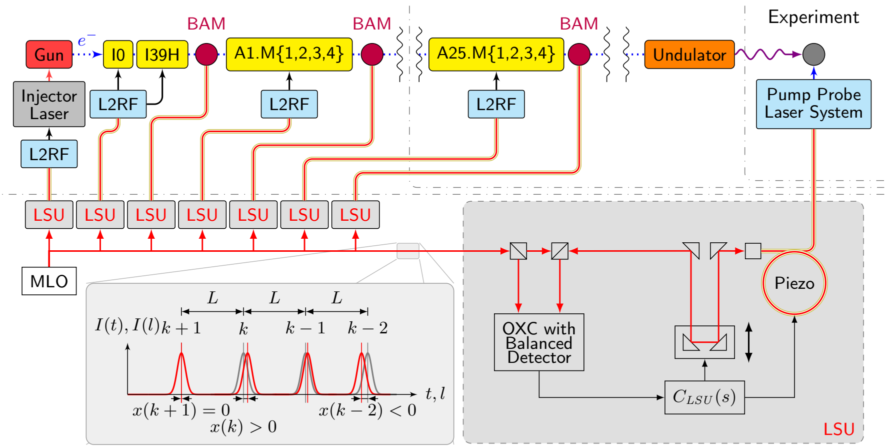

n x LSU-Control

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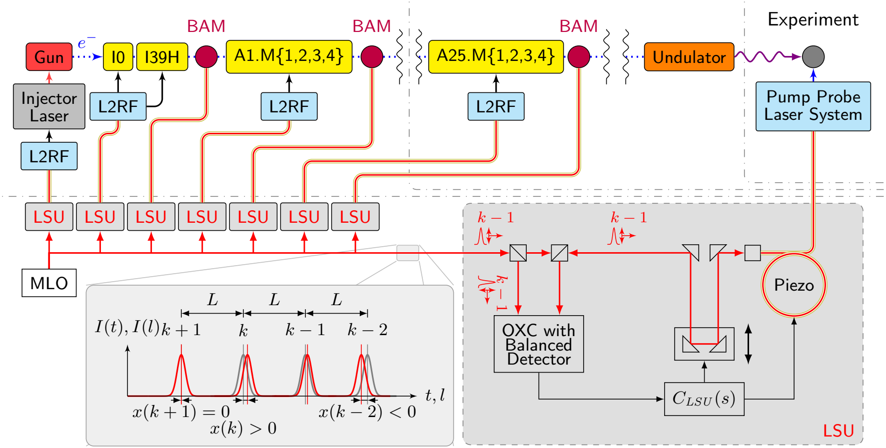

n x LSU-Control

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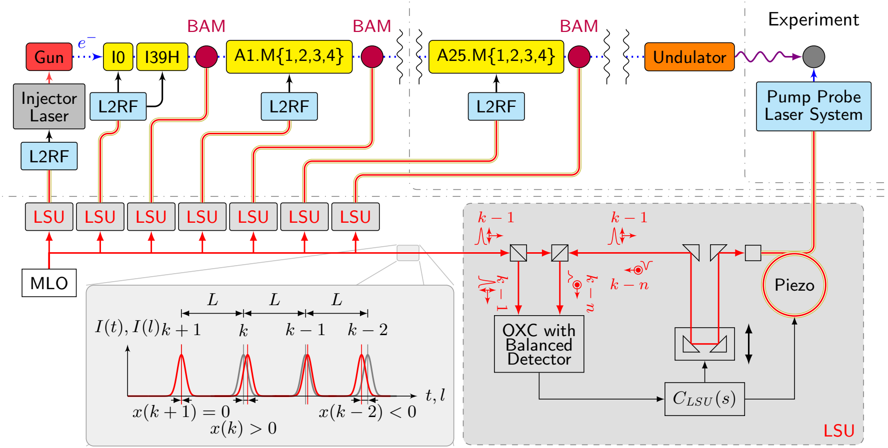

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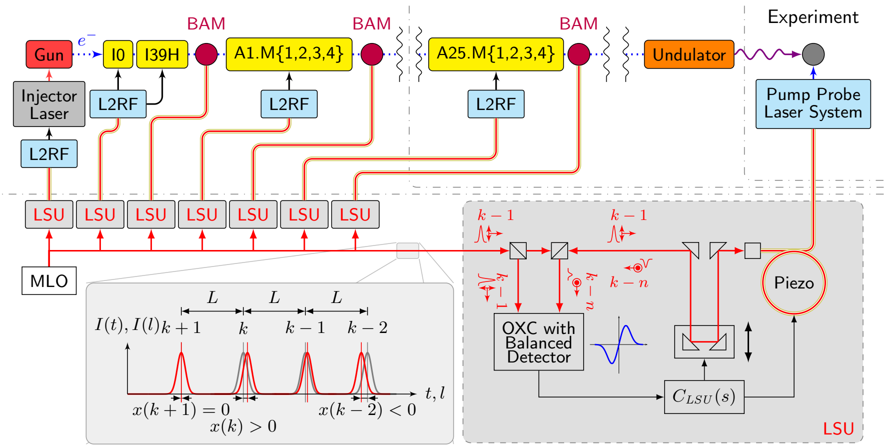

n x LSU-Control

Laser Based Synchronization System (LbSynch)

Requirements

- The relative jitter between all link ends should be less as possible

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Current State

- Heuristically tuned PI controller

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New Approach

Model based control

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New Approach

Model based control

1. Model the dynamics of the system

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New Approach

Model based control

1. Model the dynamics of the system
2. Synthesis a suitable controller with this model

Laser Based Synchronization System (LbSynch)

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- The relative jitter between all link ends should be less as possible

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- Heuristically tuned PI controller

New Approach

Model based control

1. Model the dynamics of the system
2. Synthesis a suitable controller with this model
3. Verify the controller performance in an experiment

Problem Statement

Problem Statement

- How to synthesis a model based controller?
- Has a model based controller a better performance?

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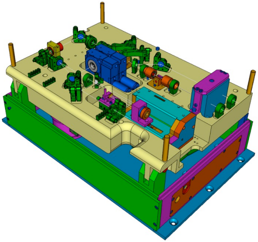
Setup of the Link Stabilizing Unit



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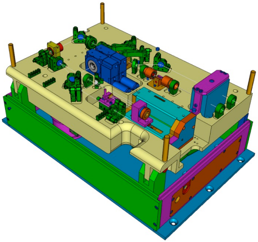

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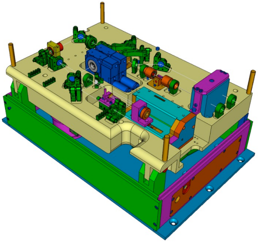

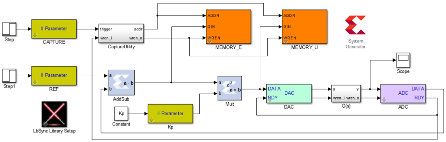

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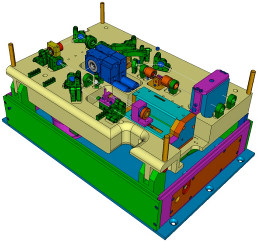

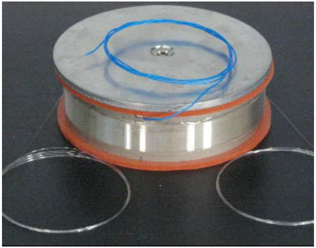

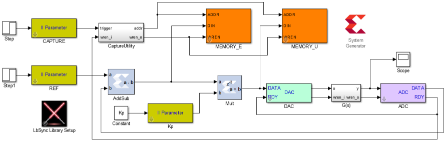

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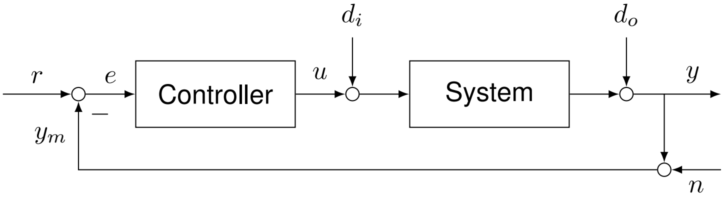
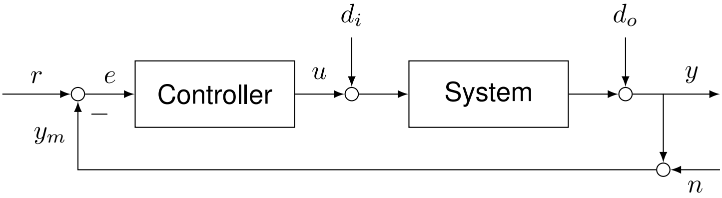
General Control Loop



- $u(t)$ output voltage applied to the piezo amplifier

based on Skogestad and Postlethwaite (2005)

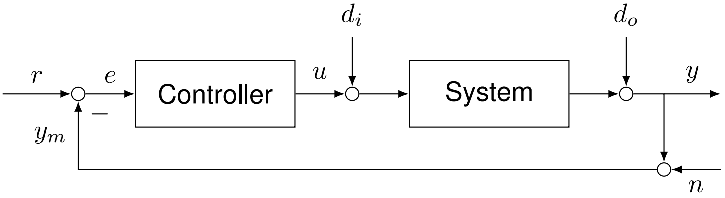
General Control Loop



- $u(t)$ output voltage applied to the piezo amplifier
- $y(t)$ the real timing difference

based on Skogestad and Postlethwaite (2005)

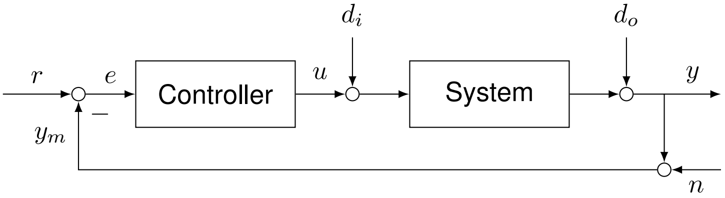
General Control Loop



- $u(t)$ output voltage applied to the piezo amplifier
- $y(t)$ the real timing difference
- $y_m(t) = y(t) + n(t)$ timing difference measured by the OXC

based on Skogestad and Postlethwaite (2005)

General Control Loop



- $u(t)$ output voltage applied to the piezo amplifier
- $y(t)$ the real timing difference
- $y_m(t) = y(t) + n(t)$ timing difference measured by the OXC
- $n(t)$ noise of the balanced detector

based on Skogestad and Postlethwaite (2005)

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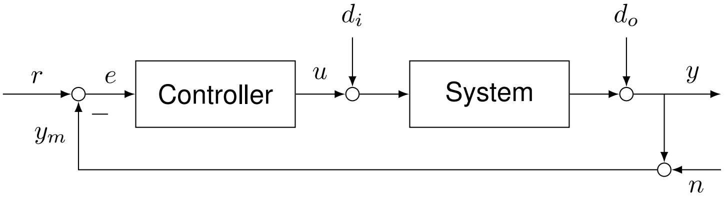

- $u(t)$ output voltage applied to the piezo amplifier
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- $d_i(t)$ input disturbances, e.g. ripple of the piezo amplifier supply

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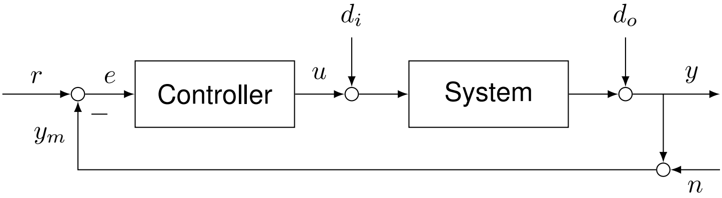
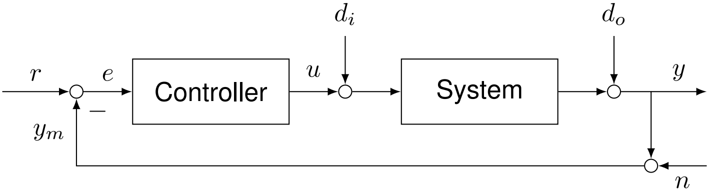


- $u(t)$ output voltage applied to the piezo amplifier
- $y(t)$ the real timing difference
- $y_m(t) = y(t) + n(t)$ timing difference measured by the OXC
- $n(t)$ noise of the balanced detector
- $d_i(t)$ input disturbances, e.g. ripple of the piezo amplifier supply
- $d_o(t)$ output disturbances, e.g. vibrations of the setup

based on Skogestad and Postlethwaite (2005)

General Control Loop



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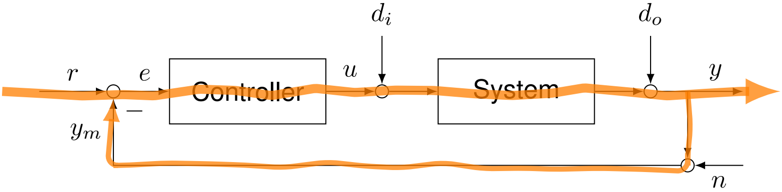
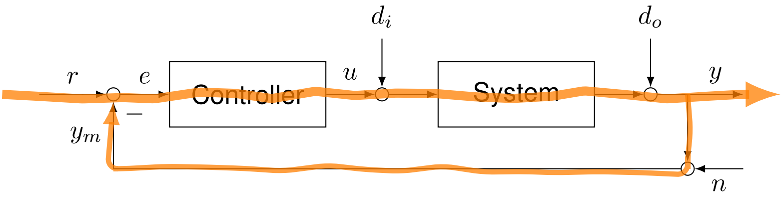


$T(s) = \frac{P(s)C(s)}{1+P(s)C(s)}$

based on Skogestad and Postlethwaite (2005)

General Control Loop

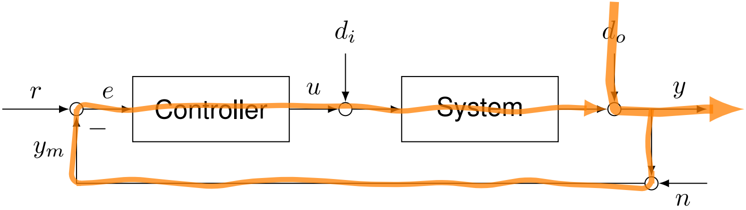


$T(s) = \frac{P(s)C(s)}{1+P(s)C(s)}$

high bandwidth controller

- Tracking of a reference $T(s) \to 1$

General Control Loop



$T(s) = \frac{P(s)C(s)}{1+P(s)C(s)}$

$S(s) = 1 - T(s) = \frac{1}{1+P(s)C(s)}$

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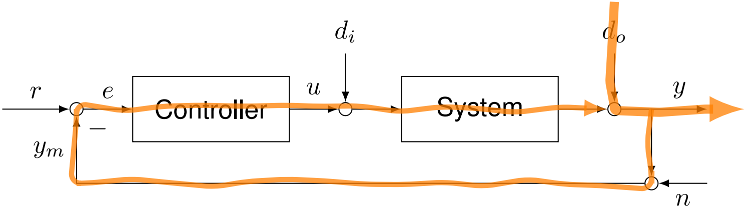

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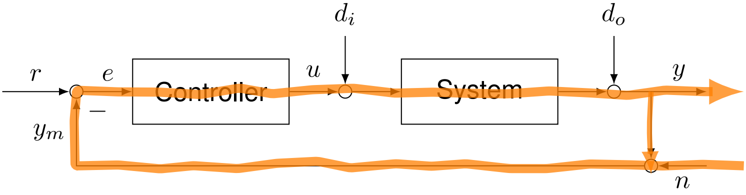
high bandwidth controller

- Tracking of a reference $T(s) \to 1$
- Output Disturbance rejection $S(s) \to 0 \Rightarrow T(s) \to 1$

based on Skogestad and Postlethwaite (2005)

General Control Loop



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high bandwidth controller

- Tracking of a reference $T(s) \to 1$
- Output Disturbance rejection $S(s) \to 0 \Rightarrow T(s) \to 1$

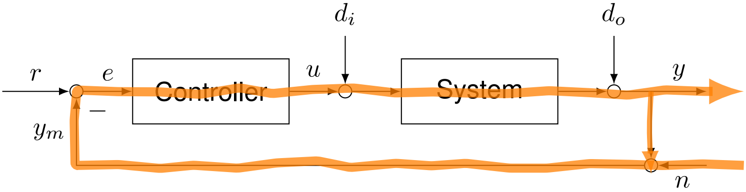
$S(s) = 1 - T(s) = \frac{1}{1+P(s)C(s)}$

high bandwidth controller

- System output due to noisy measurements $T(s) \to 0$

based on Skogestad and Postlethwaite (2005)

General Control Loop



$T(s) = \frac{P(s)C(s)}{1+P(s)C(s)}$

high bandwidth controller

- Tracking of a reference $T(s) \rightarrow 1$
- Output Disturbance rejection $S(s) \rightarrow 0 \Rightarrow T(s) \rightarrow 1$

$S(s) = 1 - T(s) = \frac{1}{1+P(s)C(s)}$

high bandwidth controller

- System output due to noisy measurements $T(s) \rightarrow 0$
- Very large controller outputs $u(t)$

based on Skogestad and Postlethwaite (2005)

State Space Model

$$\dot{x}(t) = Ax(t) + Bu(t)\,,$$
$$y(t) = Cx(t) + Du(t)\,,$$

based on Skogestad and Postlethwaite (2005)

State Space Model

$$\dot{x}(t) = Ax(t) + Bu(t)\,,$$
$$y(t) = Cx(t) + Du(t)\,,$$

- $x(t)$ states of the system (energy storages)
- $u(t)$ input to the system
- $y(t)$ output of the system

based on Skogestad and Postlethwaite (2005)

State Space Model

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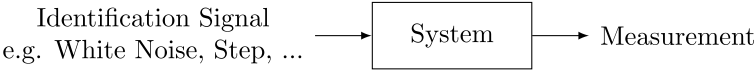
- $x(t)$ states of the system (energy storages)
- $u(t)$ input to the system
- $y(t)$ output of the system
- A describes the dynamic behavior of the system
- B describes how the input acts on the state
- C describes how the state are combined to the output
- D describes which inputs have a direct influence on the output

based on Skogestad and Postlethwaite (2005)

Model Identification



- $P(s) = \frac{\text{Measurement}}{\text{Identification Signal}}$
- Matlab System Identification Toolbox

based on Ljung (1987)

State Feedback Controller

$$
\begin{aligned}
\dot{x}(t) =& Ax(t) + Bu(t)\,, \\
y(t) =& Cx(t) + Du(t)\,,
\end{aligned}
$$

based on Zhou et al. (1996)

State Feedback Controller

$$\dot{x}(t) = Ax(t) + Bu(t)\,,$$
$$y(t) = Cx(t) + Du(t)\,,$$

$$u(t) = -Fx(t)\,,$$

based on Zhou et al. (1996)

State Feedback Controller

$$\dot{x}(t) = Ax(t) + Bu(t)\,,$$
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$$\min V = \int_0^\infty x(t)^T Q x(t) + u(t)^T R u(t)\, dt\,,$$

based on Zhou et al. (1996)

State Feedback Controller

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- Q and R are tuning parameter. e.g. $Q = C^T \cdot C$ and tune the response speed with R

based on Zhou et al. (1996)

State Feedback Controller

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- Q and R are tuning parameter. e.g. $Q = C^T \cdot C$ and tune the response speed with R
- `F = -lqr(A,B,C'*C,R);`

based on Zhou et al. (1996)

State Feedback Controller

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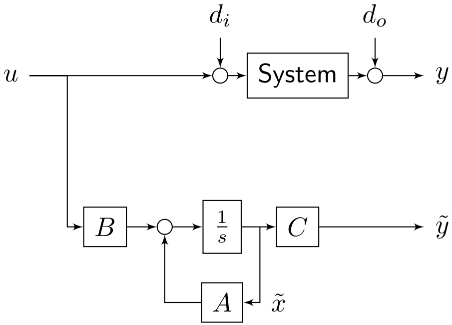
- Q and R are tuning parameter. e.g. $Q = C^T \cdot C$ and tune the response speed with R
- `F = -lqr(A,B,C'*C,R);`
- $x(t)$ is not measured in most cases.

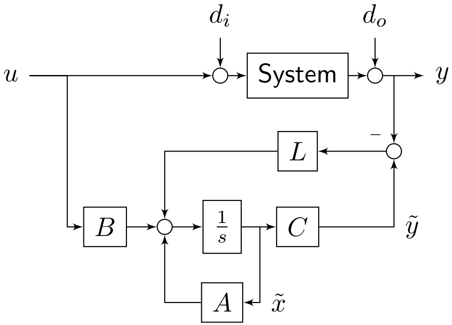
based on Zhou et al. (1996)

State Estimation



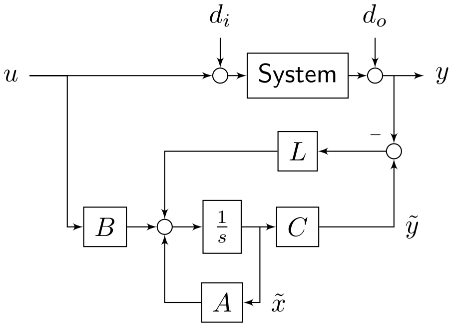
based on Zhou et al. (1996)

State Estimation



based on Zhou et al. (1996)

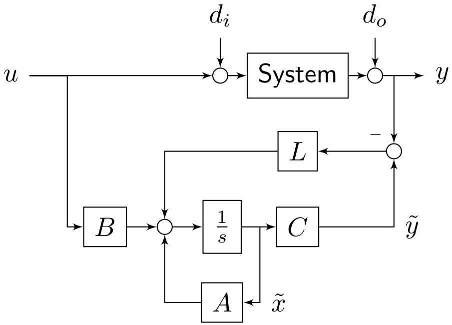
State Estimation



- The dual problem to state feedback

based on Zhou et al. (1996)

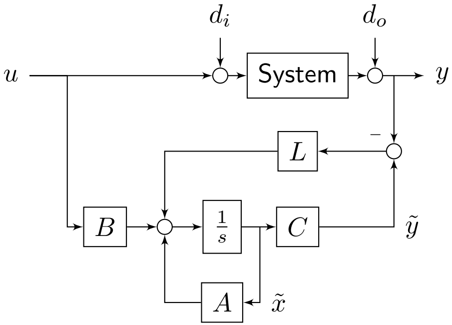
State Estimation



- The dual problem to state feedback
- Q_{obsv} and R_{obsv} are again tuning parameter. e.g. $Q_{obsv} = B \cdot B^T$ and tune the filtering of the noise with R_{obsv}

based on Zhou et al. (1996)

State Estimation



- The dual problem to state feedback
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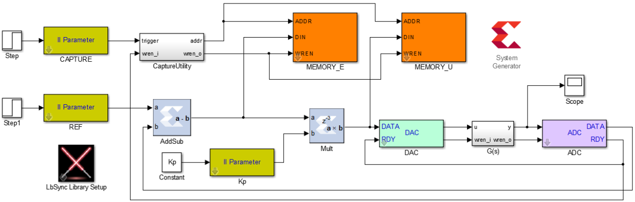
- `L = -lqr(A',C',B*B',Robsv);`

based on Zhou et al. (1996)

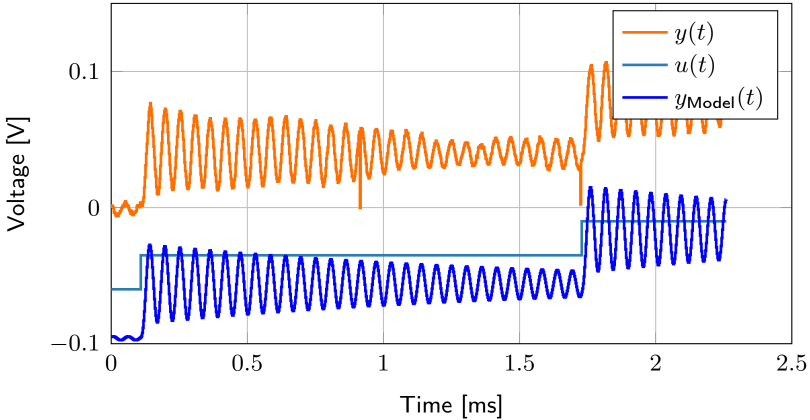
Contents

Matlab VHDL Toolbox

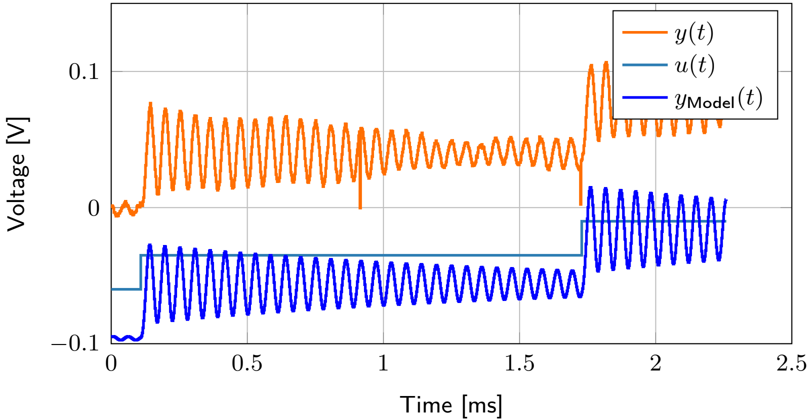


- Extends the Xilinx System Generator Toolbox
- Automatic code generation from a Simulink model (no VHDL knowledge required)
- Simulation of the real behavior (saturation, overflow, fixed point precision, etc.)

Model Identification



Model Identification



The model fits well to the dynamic behavior of the real plant.

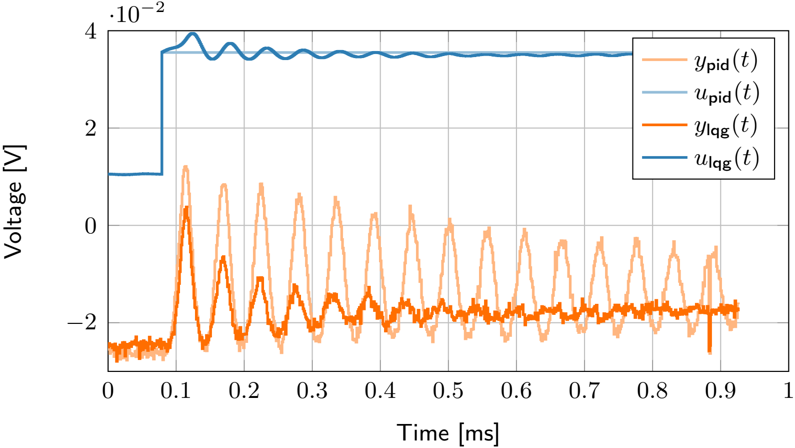
Identification

$$A = \begin{bmatrix} -253.8 & 1.133 \cdot 10^5 & 935.9 \\ -1.133 \cdot 10^5 & -1138 & -2017 \\ 935.9 & -4035 & -1.346 \cdot 10^5 \end{bmatrix},$$

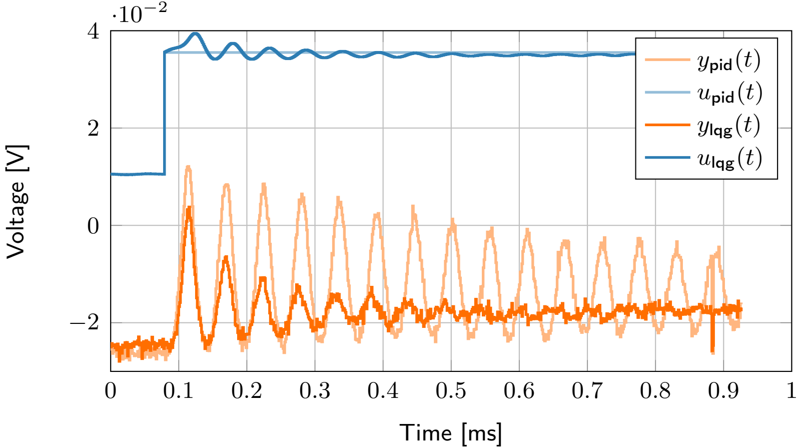
$$B = \begin{bmatrix} 112.9 & 237.9 & -209.5 \end{bmatrix},$$

$$C = \begin{bmatrix} 225.8 & -475.9 & -418.9 \end{bmatrix}$$

Effect of State Feedback

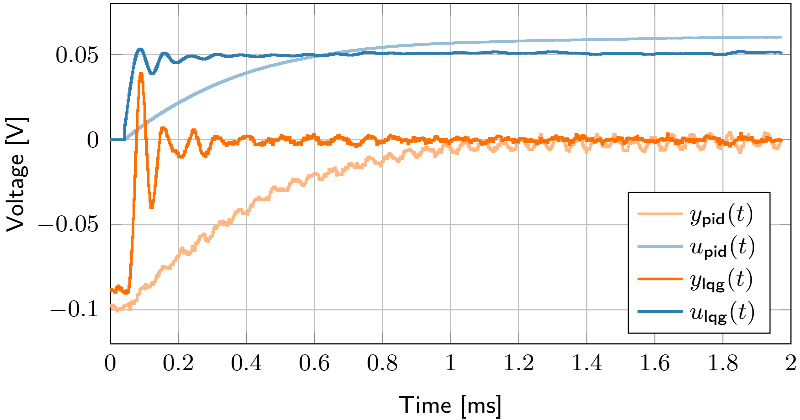


Effect of State Feedback

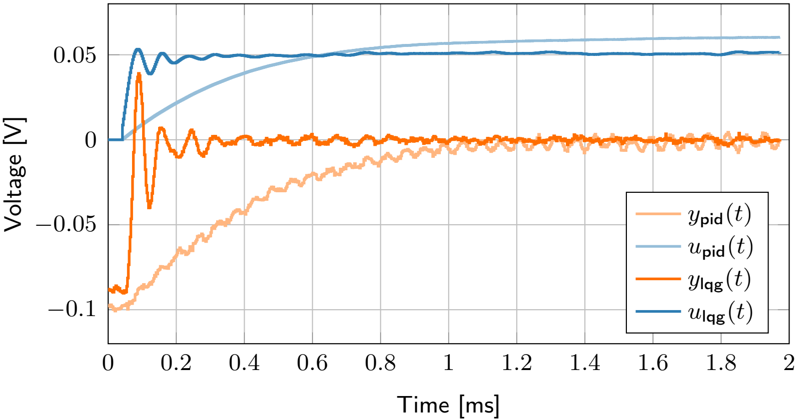


Its possible to change the dynamic behavior e.g. increase the damping.

Control Startup

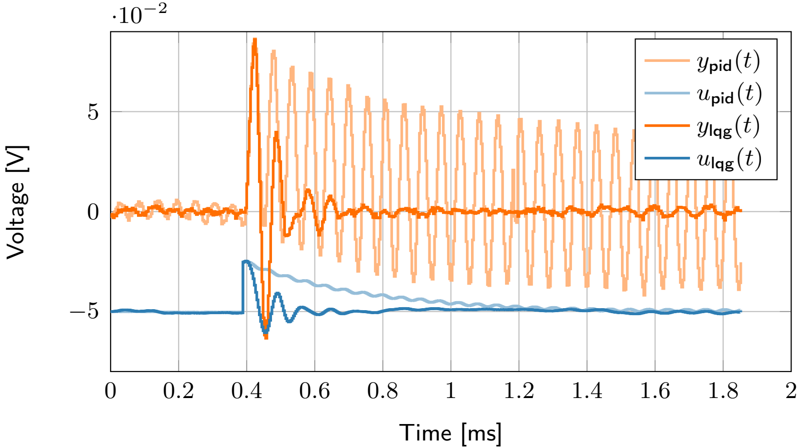


Control Startup

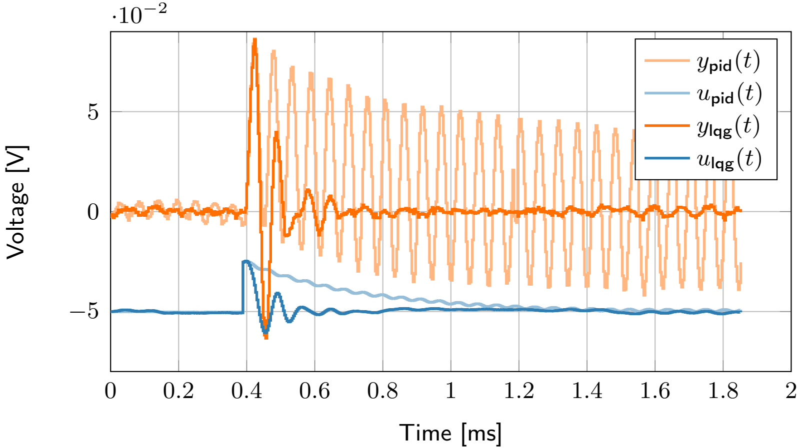


The model based controller reaches the steady state faster ...

Dynamic behavior of an input disturbances

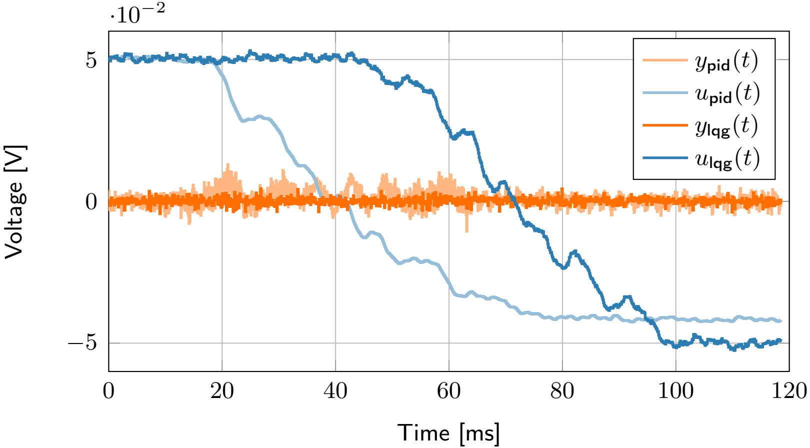


Dynamic behavior of an input disturbances

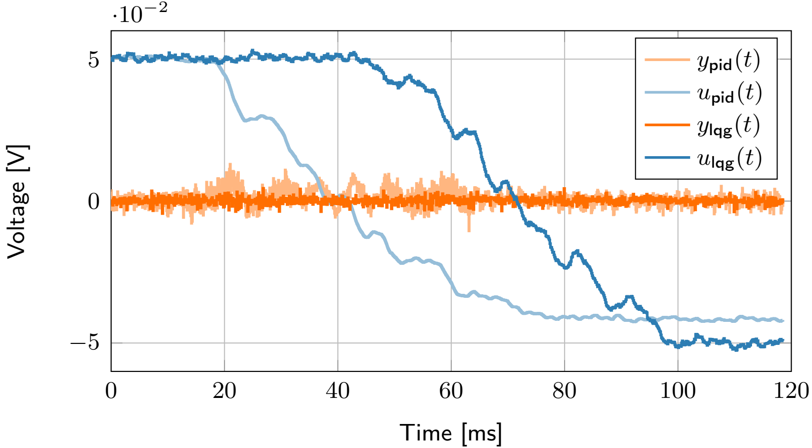


... and rejects disturbances much better than the PID controller.

Dynamic behavior of a coarse tuning step



Dynamic behavior of a coarse tuning step



Effects measurable with PID controller but not with LQG.

Contents

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- Use model based control approaches to a better performance

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- It is possible to achieve good control results for the LSU with a LQG controller

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- Test other model based controller types

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- It was shown how to synthesis a LQG controller
- The design controller was tested in an experimental setup

Outlook

- Test other model based controller types
- Include new MicroTCA boards and the final configuration

The End

Thank you very much for your attention

Further Reading

L. Ljung. *System identification: theory for the user*. Prentice-Hall information and system sciences series. Prentice-Hall, 1987. ISBN 9780138816407. URL http://books.google.com/books?id=gpVRAAAAMAAJ.

S. Skogestad and I. Postlethwaite. *Multivariable Feedback Control - Analysis and Design*. John Wiley & Sons, Ltd, 2nd edition, 2005. ISBN 978-0-470-01168-3.

K. Zhou, J.C. Doyle, and K. Glover. *Robust and Optimal Control*. Feher/Prentice Hall Digital and. Prentice Hall, 1996. ISBN 9780134565675. URL http://books.google.com/books?id=RPSOQgAACAAJ.

LQR via algebraic riccati equation

$$\dot{x}(t) = Ax(t) + Bu(t)\,,$$
$$y(t) = Cx(t) + Du(t)\,,$$

$$u(t) = -Fx(t)\,,$$
$$\min V = \int_0^\infty x(t)^T Q x(t) + u(t)^T R u(t)\, dt\,,$$
$$F = R^{-1} B^T P$$
$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$