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

M. Heuer¹ G. Lichtenberg² S. Pfeiffer¹ H. Schlarb¹

¹Deutsches Elektronen-Synchrotron Hamburg, Germany
²Hamburg University of Applied Sciences, Germany

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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 nm, Pulse duration of less than $100 \text{ fs} \left(10^{-15}\right)$
- Total facility length of 3.4 km with 101 accelerator modules

 Courtesy of http://www.xfel.eu
Laser Based Synchronization System (LbSynch)
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\[ I(t), I(l)k + 1 \]

\[ x(k + 1) = 0 \]
\[ x(k) > 0 \]
\[ x(k - 2) < 0 \]
Laser Based Synchronization System (LbSynch)

\[ I(t), I(l) \]
\[ x(k + 1) = 0 \quad x(k) > 0 \quad x(k - 2) < 0 \]
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\[ I(t), I(l)_{k+1} \quad k \quad k-1 \quad k-2 \]

\[ x(k+1) = 0 \quad x(k) > 0 \quad x(k-2) < 0 \]

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Laser Based Synchronization System (LbSynch)

Requirements

▶ The relative jitter between all link ends should be less as possible
Laser Based Synchronization System (LbSynch)

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Current State

- Heuristically tuned PI controller
Laser Based Synchronization System (LbSynch)

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New Approach

Model based control
Laser Based Synchronization System (LbSynch)

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New Approach

Model based control
1. Model the dynamics of the system
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- The relative jitter between all link ends should be less as possible

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New Approach

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

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

Current State

▶ 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?
Introduction

2 Link Stabilizing Unit

3 Introduction to Control

4 Implementation and Experimental Results

5 Conclusion and Outlook
Setup of the Link Stabilizing Unit
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Setup of the Link Stabilizing Unit
$u(t)$ output voltage applied to the piezo amplifier

based on Skogestad and Postlethwaite (2005)
**General Control Loop**

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- $y(t)$ the real timing difference

Based on Skogestad and Postlethwaite (2005)
General Control Loop

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- $y(t)$ the real timing difference
- $y_m(t) = y(t) + n(t)$ timing difference measured by the OXC

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▶ $n(t)$ noise of the balanced detector

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- $n(t)$ 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

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

- Tracking of a reference
- Output Disturbance rejection
- System output due to noisy measurements
- Very large controller outputs

Based on Skogestad and Postlethwaite (2005)
General Control Loop

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

high bandwidth controller

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

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

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

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

- **High bandwidth controller**

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**high bandwidth controller**

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

based on Skogestad and Postlethwaite (2005)
General Control Loop

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

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- **high bandwidth controller**
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  - Output Disturbance rejection $S(s) \to 0 \Rightarrow T(s) \to 1$

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

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- **high bandwidth controller**
  - Tracking of a reference \( T(s) \to 1 \)
  - Output Disturbance rejection
  - System output due to noisy measurements \( T(s) \to 0 \)
  - Very large controller outputs \( u(t) \)

- \( r \) to \( e \)
- \( y_m \)
- \( e \) to \( u \)
- \( u \) to \( y \)
- \( d_i \)
- \( d_o \)
- \( n \)

Based on Skogestad and Postlethwaite (2005)
State Space Model

\[ \dot{x}(t) = Ax(t) + Bu(t), \]
\[ y(t) = Cx(t) + Du(t), \]
State Space Model

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\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

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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

Identification Signal
e.g. White Noise, Step, ...

\[ P(s) = \frac{\text{Measurement}}{\text{Identification Signal}} \]

- Matlab System Identification Toolbox

Based on Ljung (1987)
State Feedback Controller

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

based on Zhou et al. (1996)
State Feedback Controller

\[ \dot{x}(t) = Ax(t) + Bu(t), \]
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\[ u(t) = -Fx(t), \]

based on Zhou et al. (1996)
State Feedback Controller

\[ \dot{x}(t) = Ax(t) + Bu(t), \]
\[ y(t) = Cx(t) + Du(t), \]
\[ u(t) = -Fx(t), \]
\[ \min V = \int_{0}^{\infty} x(t)^{T}Qx(t) + u(t)^{T}Ru(t) \, dt, \]

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

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- \( Q \) and \( R \) are tuning parameters. E.g. \( Q = C^T \cdot C \) and tune the response speed with \( R \)
- \( F = -\text{lqr}(A,B,C^*C,R); \)

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State Feedback Controller

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

Based on Zhou et al. (1996)
State Estimation

\[
\begin{align*}
  &u \\
  &\downarrow \\
  &\text{System} \\
  &\downarrow \\
  &y \\
  &\downarrow \\
  &\tilde{y} \\
  &\downarrow \\
  &\tilde{x} \\
  &\downarrow \\
  &A \\
  &\downarrow \\
  &\frac{1}{s} \\
  &\downarrow \\
  &B \\
  &\downarrow \\
  &di \quad d_o
\end{align*}
\]

\[
\tilde{y} = \frac{1}{s} \cdot \frac{1}{s} + \frac{1}{s} \cdot \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s} + \frac{1}{s}
\]

Based on Zhou et al. (1996)
The dual problem to state feedback

\[ \begin{align*}
Q_{\text{obsv}} \text{ and } R_{\text{obsv}} \text{ are again tuning parameters. e.g. } Q_{\text{obsv}} &= B \cdot B^T \\
L &= -\text{lqr}(A', C', B \cdot B', R_{\text{obsv}})
\end{align*} \]

based on Zhou et al. (1996)
State Estimation

The dual problem to state feedback

Based on Zhou et al. (1996)
The dual problem to state feedback

\( Q_{\text{obs}} \) and \( R_{\text{obs}} \) are again tuning parameter. e.g. \( Q_{\text{obs}} = B \cdot B^T \) and tune the filtering of the noise with \( R_{\text{obs}} \)

based on Zhou et al. (1996)
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 \[ R_{obsv} \]

\[ L = -lqr(A',C',B*B',R_{obsv}); \]

based on Zhou et al. (1996)
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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.)
The model fits well to the dynamic behavior of the real plant.
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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

It's possible to change the dynamic behavior, e.g., increase the damping.
It's possible to change the dynamic behavior e.g. increase the damping.
Control Startup

The model based controller reaches the steady state faster...
The model based controller reaches the steady state faster ...
Dynamic behavior of an input disturbances

The graph shows the dynamic behavior of an input disturbance over time. The voltage [V] is plotted against time [ms]. The graph includes two sets of data: $y_{\text{pid}}(t)$ and $u_{\text{pid}}(t)$, which represent the PID controller's output and input, respectively. Additionally, $y_{\text{lqg}}(t)$ and $u_{\text{lqg}}(t)$ represent the output and input of the LQG controller. The LQG controller rejects disturbances much better than the PID controller.
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.
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Statements

Use model based control approaches to a better performance
It is possible to achieve good control results for the LSU with a LQG controller
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- It is possible to achieve good control results for the LSU with a LQG controller
An overview of the LbSynch System was given

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
Conclusion

▶ An overview of the LbSynch System was given
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The End

Thank you very much for your attention
Further Reading


LQR via algebraic riccati equation

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