Multivariable Control

Lecture 3: Observability, Observers, and Observer Based Control

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The slides are authored by Jakob Stoustrup, and only edited by me.

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Contents

Observability (1)

A continuous time system

$$\dot{x}(t) = Ax(t)\,, \quad y(t) = Cx(t)$$

is said to be *observable* iff $y(t) \equiv 0 \Rightarrow x(t) \equiv 0$.

A discrete time system

$$x(k+1) = Ax(k)\,, \quad y(k) = Cx(k)$$

is said to be *observable* iff $y(k) \equiv 0 \Rightarrow x(k) \equiv 0$.

Observability (2)

We consider the discrete time system

$$x(k+1) = Ax(k)\,, \quad y(k) = Cx(k)\,, \quad x(0) = x_0$$

and iterate:

$$\begin{aligned} x(0) &= x_0 & \qquad y(0) &= Cx_0 \end{aligned}$$

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We consider the discrete time system

$$x(k+1) = Ax(k)\,, \quad y(k) = Cx(k)\,, \quad x(0) = x_0$$

and iterate:

$$\begin{array}{rclcrcl} x(0) & = & x_0 & \qquad & y(0) & = & Cx_0 \\ x(1) & = & Ax(0) & & & & \end{array}$$

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We consider the discrete time system

$$x(k+1) = Ax(k)\,, \quad y(k) = Cx(k)\,, \quad x(0) = x_0$$

and iterate:

$$\begin{aligned} x(0) &= x_0 & y(0) &= Cx_0 \\ x(1) &= Ax_0 & y(1) &= CAx_0 \\ x(2) &= Ax(1) \end{aligned}$$

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$$x(k+1) = Ax(k)\,, \quad y(k) = Cx(k)\,, \quad x(0) = x_0$$

and iterate:

$$\begin{aligned} x(0) &= x_0 & y(0) &= Cx_0 \\ x(1) &= Ax_0 & y(1) &= CAx_0 \\ x(2) &= A^2x_0 & y(2) &= CA^2x_0 \\ &\vdots \\ x(n-1) &= Ax(n-2) \end{aligned}$$

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Observability (3)

Writing the equations

$$y(k) = CA^k x_0\,,\; k = 0, \ldots, n-1$$

in matrix form we obtain:

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in matrix form we obtain:

$$\underbrace{\begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{pmatrix}}_{\text{Observability matrix}} x_0 = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

Observability (3)

Writing the equations

$$y(k) = CA^k x_0\,,\; k = 0, \ldots, n-1$$

in matrix form we obtain:

$$\begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{pmatrix} x_0 = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

When is this equation solvable for some $x_0 \neq 0$?

Observability (4)

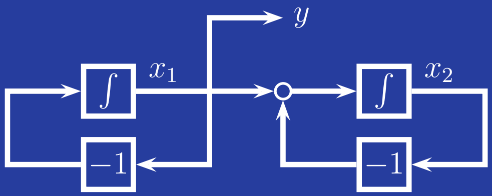
THEOREM. A system

continuous time	discrete time
$\Sigma : \begin{cases} \dot{x}(t) = Ax(t) \\ y(t) = Cx(t) \end{cases}$	$\Sigma : \begin{cases} x(k+1) = Ax(k) \\ y(k) = Cx(k) \end{cases}$

where $x \in \mathbb{R}^n$, $y \in \mathbb{R}^p$, is observable if and only if

$$\operatorname{rank} \mathcal{O} = \operatorname{rank} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{pmatrix} = n$$

Example: series connection (1)



State and output equations:

$$\left\{ \begin{array}{rcl} \dot{x}_1 & = & -x_1 \\ \dot{x}_2 & = & -x_2 + x_1 \\ y & = & x_1 \end{array} \right\}$$

State space model:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

$$y = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

Example: series connection (2)

For the state space matrices:

$$A = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

the observability matrix $\mathcal{O}$ becomes:

$$\mathcal{O} = \begin{pmatrix} C \\ CA \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1 & 0 \end{pmatrix}$$

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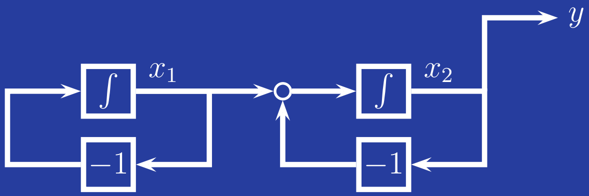
$$A = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

the observability matrix $\mathcal{O}$ becomes:

$$\mathcal{O} = \begin{pmatrix} C \\ CA \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1 & 0 \end{pmatrix}$$

$\det \mathcal{O} = 0 \implies$ system is unobservable.

Example: series connection (3)



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$$y = \begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

Example: series connection (4)

For the state space matrices:

$$A = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix}, \quad C = \begin{pmatrix} 0 & 1 \end{pmatrix}$$

the observability matrix $\mathcal{O}$ becomes:

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For the state space matrices:

$$A = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix}, \quad C = \begin{pmatrix} 0 & 1 \end{pmatrix}$$

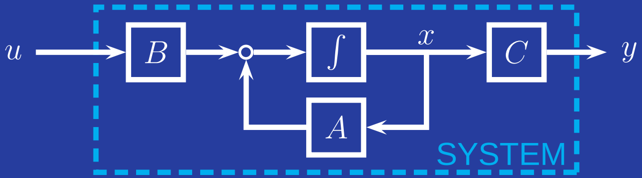
the observability matrix $\mathcal{O}$ becomes:

$$\mathcal{O} = \begin{pmatrix} C \\ CA \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & -1 \end{pmatrix}$$

$\det \mathcal{O} = -1 \neq 0 \implies$ system is observable.

Contents

The full order observer (1)



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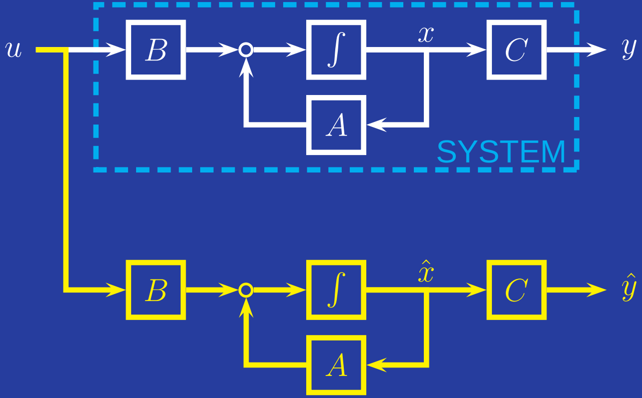
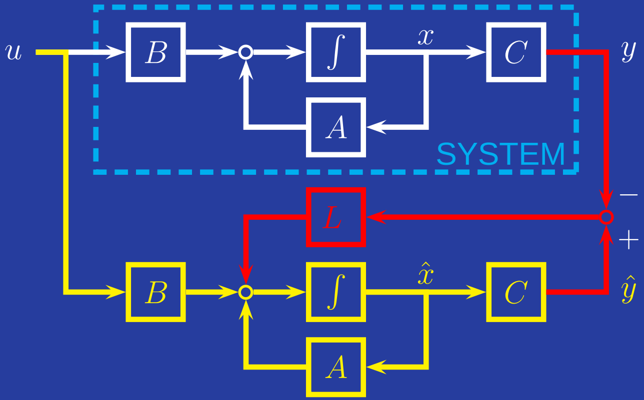


The full order observer (1)



The full order observer (2)

System:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned}$$

Observer:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L(C\hat{x} - y) \\ \hat{y} &= C\hat{x} \end{aligned}$$

The full order observer (2)

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$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned}$$

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Error, $e = \hat{x} - x$:

$$\dot{e} = \dot{\hat{x}} - \dot{x} = A\hat{x} + Bu + L(C\hat{x} - y) - (Ax + Bu)$$

The full order observer (2)

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System:
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Error, $e = \hat{x} - x$:

$$\begin{aligned} \dot{e} = \dot{\hat{x}} - \dot{x} &= A\hat{x} + Bu + L(C\hat{x} - y) - (Ax + Bu) \\ &= A(\hat{x} - x) + L(C\hat{x} - Cx) \\ &= (A + LC)(\hat{x} - x) = (A + LC)e \end{aligned}$$

The full order observer (3)

THEOREM. A full order observer for the system

$$\begin{array}{rcl} \dot{x} & = & Ax + Bu \\ y & = & Cx \end{array}$$

with observer gain L is stable, if and only if the eigenvalues of the matrix $A + LC$ all have negative real part.

Moreover, such an L always exists, if (A, C) is observable.

Observable canonical form (1)

Any observable *single output* system can be written in the form:

$$\dot{x}_o = A_o x_o\,, \quad y = C_o x_o\,, \quad x_o \in \mathbb{R}^n\,,\, y \in \mathbb{R}$$

where

$$A_o = \left(\begin{array}{c|c} a & \begin{array}{c} I_{n-1} \\ \hline 0_{1\times(n-1)} \end{array} \end{array} \right), \quad C_o = \left(\begin{array}{c|c} 1 & 0_{1\times(n-1)} \end{array} \right)$$

and where $a \in \mathbb{R}^{n\times 1}$, $a^T = \begin{pmatrix} a_1 & a_2 & \ldots & a_n \end{pmatrix}$. It can be shown that

$$\det(\lambda I - A_o) = \lambda^n - a_1\lambda^{n-1} - \ldots - a_n$$

Observable canonical form (2)

For $n = 3$ the observable canonical form becomes:

$$A_o = \left(\begin{array}{c|cc} a_1 & 1 & 0 \\ a_2 & 0 & 1 \\ \hline a_3 & 0 & 0 \end{array}\right), \; C_o = \left(\begin{array}{c|cc} 1 & 0 & 0 \end{array}\right)$$

which is indeed observable:

$$\mathcal{O}_o = \begin{pmatrix} C_o \\ C_o A_o \\ C_o A_o^2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ a_1 & 1 & 0 \\ a_1^2 + a_2 & a_1 & 1 \end{pmatrix}$$

$\det(\mathcal{O}) = 1 \neq 0 \implies$ system is observable.

Observable canonical form (3)

Consider a system:

$$\dot{x} = Ax\,, \quad y = Cx\,, \quad x \in \mathbb{R}^n\,, \quad y \in \mathbb{R}$$

For $n = 3$, the observable canonical form for this system can be found through the following procedure:

1. Compute $t_3 = \mathcal{O}^{-1}\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ where $\mathcal{O} = \begin{pmatrix} C \\ CA \\ CA^2 \end{pmatrix}$

Observable canonical form (3)

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3. Define $T = \begin{pmatrix} t_1 & t_2 & t_3 \end{pmatrix}$

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2. Compute $t_2 = At_3$, $t_1 = At_2$.
3. Define $T = \begin{pmatrix} t_1 & t_2 & t_3 \end{pmatrix}$
4. The state space matrices for the observable canonical form are now given by $A_o = T^{-1}AT$, and $C_o = CT$.

Example: observable can. form (1)

We consider the system

$$\begin{aligned} \dot{x} &= \begin{pmatrix} 2 & -3 \\ 4 & -5 \end{pmatrix} x + \begin{pmatrix} 2 \\ 3 \end{pmatrix} u \\ y &= \begin{pmatrix} -3 & 2 \end{pmatrix} x \end{aligned}$$

having the observability matrix

$$\mathcal{O} = \begin{pmatrix} C \\ CA \end{pmatrix} = \begin{pmatrix} -3 & 2 \\ 2 & -1 \end{pmatrix}, \quad \det(\mathcal{O}) = -1 \neq 0$$

Example: observable can. form (2)

We compute the columns of T by

$$t_2 = \mathcal{O}^{-1}\begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}1 & 2\\2 & 3\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}2\\3\end{pmatrix}$$

$$t_1 = At_2 = \begin{pmatrix}2 & -3\\4 & -5\end{pmatrix}\begin{pmatrix}2\\3\end{pmatrix} = \begin{pmatrix}-5\\-7\end{pmatrix}$$

Thus,

$$T = \begin{pmatrix}-5 & 2\\-7 & 3\end{pmatrix} \implies T^{-1} = \begin{pmatrix}-3 & 2\\-7 & 5\end{pmatrix}$$

Example: observable can. form (3)

Eventually, we have

$$A_o = T^{-1}AT = \begin{pmatrix} -3 & 2 \\ -7 & 5 \end{pmatrix} \begin{pmatrix} 2 & -3 \\ 4 & -5 \end{pmatrix} \begin{pmatrix} -5 & 2 \\ -7 & 3 \end{pmatrix}$$

$$= \begin{pmatrix} -3 & 1 \\ -2 & 0 \end{pmatrix}$$

and

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and

$$C_o = CT = \begin{pmatrix} -3 & 2 \end{pmatrix} \begin{pmatrix} -5 & 2 \\ -7 & 3 \end{pmatrix} = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

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$$= \left(\begin{array}{c|c} -3 & 1 \\ \hline -2 & 0 \end{array}\right) \Rightarrow \det(\lambda I - A) = \lambda^2 + 3\lambda + 2$$

and

$$C_o = CT = \begin{pmatrix} -3 & 2 \end{pmatrix} \begin{pmatrix} -5 & 2 \\ -7 & 3 \end{pmatrix} = \left(\begin{array}{c|c} 1 & 0 \end{array}\right)$$

Example: observable can. form (3)

Eventually, we have

$$A_o = T^{-1}AT = \begin{pmatrix} -3 & 2 \\ -7 & 5 \end{pmatrix} \begin{pmatrix} 2 & -3 \\ 4 & -5 \end{pmatrix} \begin{pmatrix} -5 & 2 \\ -7 & 3 \end{pmatrix}$$

$$= \left(\begin{array}{c|c} -3 & 1 \\ \hline -2 & 0 \end{array}\right) \Rightarrow \det(\lambda I - A) = (\lambda+1)(\lambda+2)$$

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Contents

Observer gain design (1)

For a single output system in observable canonical form, an observer state matrix takes a particular simple form:

$$A_o = \left(\begin{array}{c|cc} a_1 & 1 & 0 \\ a_2 & 0 & 1 \\ \hline a_3 & 0 & 0 \end{array}\right), \; C_o = \left(\begin{array}{c|cc} 1 & 0 & 0 \end{array}\right)$$

Applying the observer gain

$$L_o = \begin{pmatrix} \ell_1 \\ \ell_2 \\ \ell_3 \end{pmatrix}$$

Observer gain design (2)

we obtain:

$$A_o + L_o C_o = \left(\begin{array}{c|cc} a_1 & 1 & 0 \\ a_2 & 0 & 1 \\ \hline a_3 & 0 & 0 \end{array}\right) + \begin{pmatrix} \ell_1 \\ \ell_2 \\ \ell_3 \end{pmatrix} \left(\begin{array}{c|cc} 1 & 0 & 0 \end{array}\right)$$

$$= \left(\begin{array}{c|cc} a_1 + \ell_1 & 1 & 0 \\ a_2 + \ell_2 & 0 & 1 \\ \hline a_3 + \ell_3 & 0 & 0 \end{array}\right)$$

Observer gain design (3)

Thus, the characteristic polynomial has been changed from

$$\det(\lambda I - A_o) = \lambda^n - a_1\lambda^{n-1} - \ldots - a_n$$

to

$$\begin{aligned}\det(\lambda I - (A_o + L_o C_o)) = \\ \lambda^n - (a_1 + \ell_1)\lambda^{n-1} - \ldots - (a_n + \ell_n)\end{aligned}$$

By choosing $\ell_1, \ldots, \ell_n$ appropriately, *any* observer pole configuration can be obtained. This is known as *observer pole assignment*.

Observer pole assignment

Let $A \in \mathbb{R}^{n \times n}$, $C \in \mathbb{R}^{1 \times n}$ be given.

1. Choose desired observer polynomial
   $\det(\lambda I - (A + LC)) = \lambda^n + a_{\text{obs},1}\lambda^{n-1} + \ldots + a_{\text{obs},n}$.

Observer pole assignment

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   $\det(\lambda I - (A + LC)) = \lambda^n + a_{\text{obs},1}\lambda^{n-1} + \ldots + a_{\text{obs},n}$.
2. Determine T, such that $A_o = T^{-1}AT$ and $C_o = CT$ are in observable canonical form.

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2. Determine T, such that $A_o = T^{-1}AT$ and $C_o = CT$ are in observable canonical form.
3. Determine open loop polynomial $\det(\lambda I - A) = \lambda^n - a_1\lambda^{n-1} - \ldots - a_n$

Observer pole assignment

Let $A \in \mathbb{R}^{n \times n}$, $C \in \mathbb{R}^{1 \times n}$ be given.

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2. Determine T, such that $A_o = T^{-1}AT$ and $C_o = CT$ are in observable canonical form.
3. Determine open loop polynomial
   $\det(\lambda I - A) = \lambda^n - a_1\lambda^{n-1} - \ldots - a_n$
4. Define $L_o = -\begin{pmatrix} a_1 + a_{\text{obs},1} \\ \vdots \\ a_n + a_{\text{obs},n} \end{pmatrix}$.

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Let $A \in \mathbb{R}^{n\times n}$, $C \in \mathbb{R}^{1\times n}$ be given.

1. Choose desired observer polynomial $\det(\lambda I - (A + LC)) = \lambda^n + a_{\text{obs},1}\lambda^{n-1} + \ldots + a_{\text{obs},n}$.
2. Determine T, such that $A_o = T^{-1}AT$ and $C_o = CT$ are in observable canonical form.
3. Determine open loop polynomial $\det(\lambda I - A) = \lambda^n - a_1\lambda^{n-1} - \ldots - a_n$
4. Define $L_o = -\begin{pmatrix} a_1 + a_{\text{obs},1} \\ \vdots \\ a_n + a_{\text{obs},n} \end{pmatrix}$.
5. Compute resulting observer gain $L = TL_o$.

Example: pole assignment (1)

We consider again the system

$$\begin{aligned} \dot{x} &= \begin{pmatrix} 2 & -3 \\ 4 & -5 \end{pmatrix} x + \begin{pmatrix} 2 \\ 3 \end{pmatrix} u \\ y &= \begin{pmatrix} -3 & 2 \end{pmatrix} x \end{aligned}$$

for which we would like to assign observer poles to $\{-4, -5\}$, i.e. to design L such that $A + LC$ has eigenvalues in $\{-4, -5\}$.

Example: pole assignment (2)

1. Desired closed loop polynomial: $\lambda^2 + 9\lambda + 20$

Example: pole assignment (2)

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2. $T = \begin{pmatrix} -5 & 2 \\ -7 & 3 \end{pmatrix} \Rightarrow A_o = \left(\begin{array}{c|c} -3 & 1 \\ \hline -2 & 0 \end{array}\right), C_o = \left(\begin{array}{c|c} 1 & 0 \end{array}\right)$

Example: pole assignment (2)

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Example: pole assignment (2)

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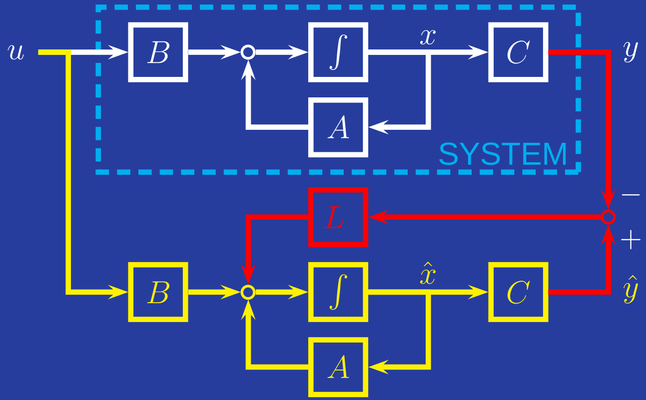
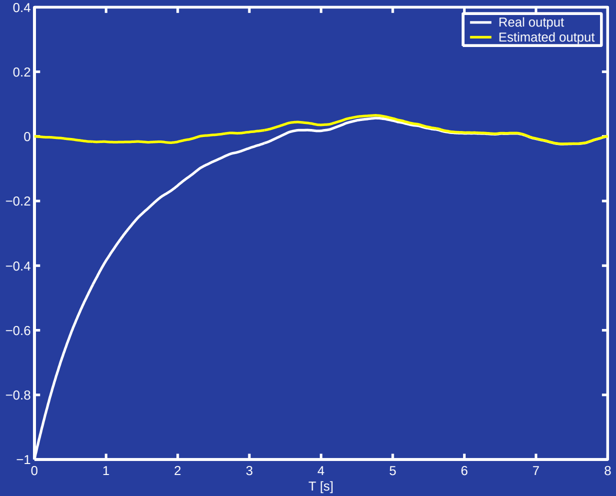
The full order observer

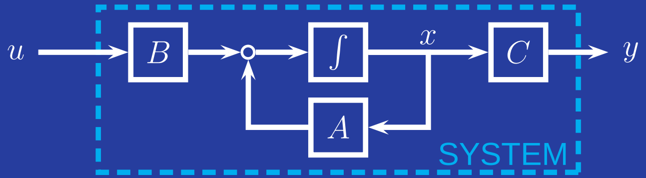


Example: obs. pole assignment



Contents

Observer Based Control (1)



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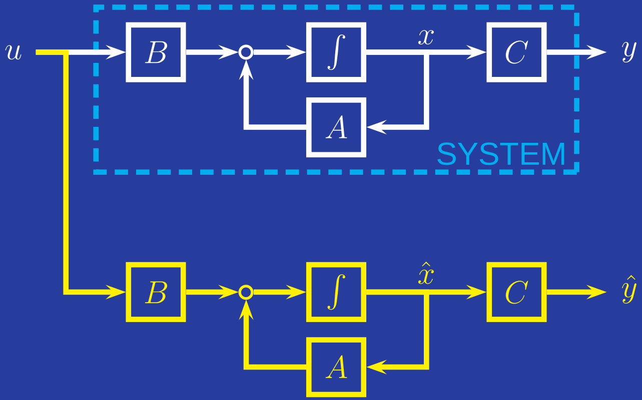

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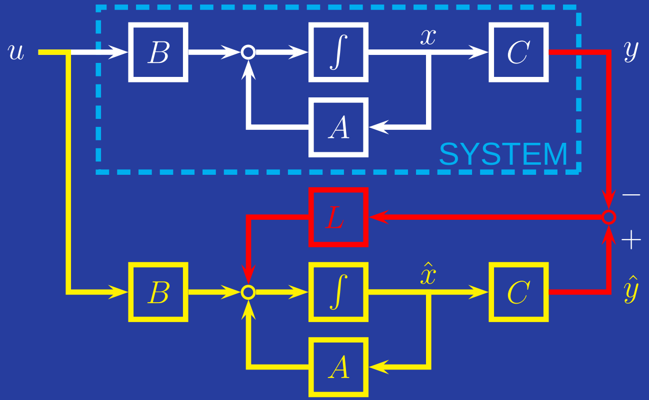

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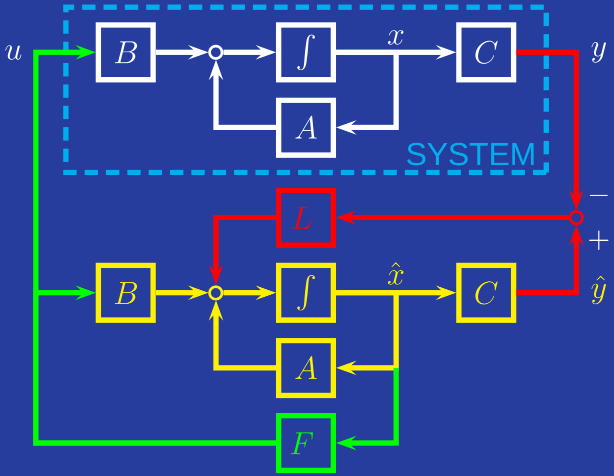

Observer based control (2)

System:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned}$$

Observer:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L(C\hat{x} - y) \\ \hat{y} &= C\hat{x} \end{aligned}$$

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The separation principle (1)

Combining the two equations:

$$\begin{aligned}\dot{x} &= Ax + Bu = Ax + BF\hat{x} = Ax + BF(e + x) \\ &= (A + BF)x + BFe\end{aligned}$$

and

$$\dot{e} = (A + LC)e$$

gives:

$$\begin{pmatrix} \dot{x} \\ \dot{e} \end{pmatrix} = \begin{pmatrix} A + BF & BF \\ 0 & A + LC \end{pmatrix} \begin{pmatrix} x \\ e \end{pmatrix}$$

The separation principle (2)

THEOREM. An observer based controller for the system

$$\begin{aligned} \dot{x} &= Ax + Bu \quad , \quad x \in \mathbb{R}^n \\ y &= Cx \end{aligned}$$

with observer gain L and feedback gain F results in $2n$ closed loop poles, coinciding with the eigenvalues of the two matrices:

$$A + BF \quad \text{and} \quad A + LC$$

Example: observer based control (1)

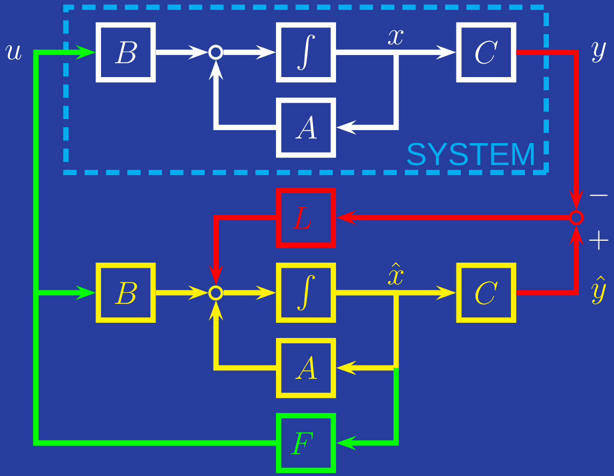
We consider again the system

$$\begin{aligned} \dot{x} &= \begin{pmatrix} 2 & -3 \\ 4 & -5 \end{pmatrix} x + \begin{pmatrix} 2 \\ 3 \end{pmatrix} u \\ y &= \begin{pmatrix} -3 & 2 \end{pmatrix} x \end{aligned}$$

for which we apply an observer based controller with

$$L = \begin{pmatrix} -6 \\ -12 \end{pmatrix} \quad \text{and} \quad F = \begin{pmatrix} 42 & -30 \end{pmatrix}$$

Observer based control



Example: observer based control (2)

The transfer function of the controller becomes:

$$\begin{aligned} K(s) &= -F\left(sI - A - BF - LC\right)^{-1} L \\ &= -108\frac{s + \frac{7}{3}}{s^2 + 15s + 74} \end{aligned}$$

The closed loop transfer function becomes:

$$G(s)\left(I - K(s)G(s)\right)^{-1} = \frac{s^2 + 15s + 74}{(s+5)^2(s+4)^2}$$

Example: observer based control (3)