Lecture 4

Discretisation of Continuous Time (CT) systems

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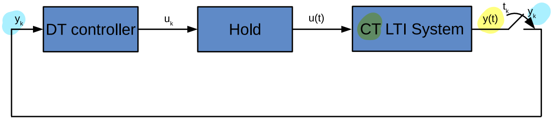
Motivation: digital control of CT systems



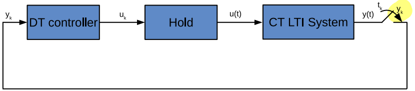
- $y(t)$: plant measurements
- y_k: input to controller

- Plant dynamics

$$\dot{x} = Ax + Bu \qquad x(t) \in \mathbb{R}^n$$
$$y = Cx + Du \qquad u(t) \in \mathbb{R}^p$$
$$x(0) = x_0 \qquad y(t) \in \mathbb{R}^m$$

Model of sample and hold

- System CT output $y(t)$ sampled at $\{t_k, k \in \mathbb{N}\}$
  - $y_k = y(t_k)$, $T_k \triangleq t_{k+1} - t_k$

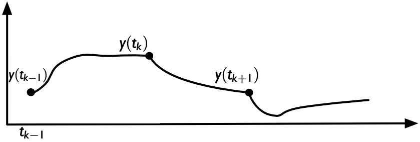


- Hold

$$u(t) = u_k \quad t \in [t_k, t_{k+1})$$

- **Problem**: obtain DT models representing the cascade Hold + (CT system) + Sampler

- **Next**: popular discretisation methods
  - exact
  - approximate

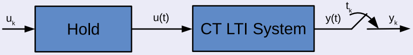


Exact discretisation

Goal: compute the discrete-time dynamics for x_k

LTI system

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$



- Set $x_k = x(t_k)$, $y_k = y(t_k)$ etc.
- Recall the Lagrange formula for the above system with $x(t_k) = x_k$

$$x(t) = e^{A(t-t_k)}x_k + \underbrace{\int_{t_k}^{t} e^{A(t-\tau)}Bu(\tau)d\tau}_{(b)}$$

State transition operator e^{As}: pushes x_k ahead by s seconds

Exact discretisation

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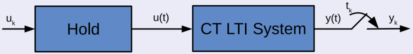

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Constant-input transmission operator $\Gamma(s) \triangleq \int_0^s e^{Az}dz$

- (b)$=\Gamma(t-t_k)Bu_k$ if $u(.) = u_k$ on $[t_k, t]$. → $t_k \leq t \leq t_{k+1}$

  Proof: (b)$=\int_{t_k}^{t} e^{A(t-\tau)}d\tau Bu_k = -\int_{t-t_k}^{0} e^{Az}dzBu_k = \int_0^{t-t_k} e^{Az}dzBu_k$, where we have set $z = t - \tau$.
- $\Gamma(t-t_k)B$ pushes u_k ahead by $t - t_k$ seconds

Exact discretisation

- Sample at times $t_0 = 0, t_1, t_2, \ldots$ and set $T_k = t_{k+1} - t_k$.
- We have

$$x_{k+1} = x(t_{k+1}) = e^{A(t_{k+1}-t_k)}x(t_k) + \int_{t_k}^{t_{k+1}} e^{A(t_{k+1}-s)}Bu(s)\,ds$$

$$= \underbrace{e^{AT_k}}_{\hat{A}_k} x_k + \underbrace{\Gamma(T_k)B}_{\hat{B}_k} u_k \qquad (1)$$

$$y_k = \hat{C}x_k + \hat{D}u_k \quad \text{for} \quad \hat{C} = C, \hat{D} = D \qquad (2)$$

- (1) - (2) : linear time-varying system

Under uniform sampling (i.e, $T_k = T$, $k = 0, 1, \ldots$)

$$\hat{A} = e^{AT}, \quad \hat{B} = \Gamma(T)B \rightarrow \text{ invariant system}$$

$$x^+ = \hat{A}x + \hat{B}u$$

$$y = \hat{C}x + \hat{D}u$$

Eigenvalues under exact sampling (1/2)

$$\hat{A} = e^{AT}$$

Properties

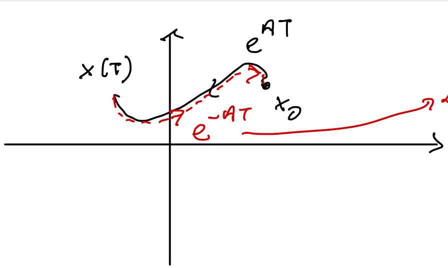
One can show that

- (a) $\lambda \in \text{Spec}(A) \Rightarrow z = e^{\lambda T} \in \text{Spec}(\hat{A})$

  $A = 0 \quad e^{AT} = e^{0} = 1$

- (b) $\det(\hat{A}) \neq 0$ always (even if $\det(A) = 0$)

  Moreover $(e^{AT})^{-1} = e^{-AT} = e^{A(-T)}$ (inverse = "backward in time")



$e^{-AT}x(T) = e^{-AT}e^{AT}x_0 = \underbrace{e^{-AT}e^{AT}}_{I}x_0 = x_0$

Eigenvalues under exact sampling (1/2)

$$\hat{A} = e^{AT}$$

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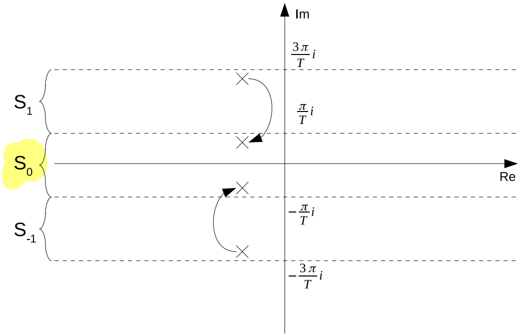
- Implications of (b) :
  reachability and controllability coincide for DT systems obtained through exact sampling
- Implications of (a) :
  $\lambda_1 \neq \lambda_2$ does not imply that $z_1 \neq z_2$
  Check : take $\lambda_2 = \lambda_1 + j\frac{2\pi}{T}N,\ N = \pm 1, \pm 2, \pm 3, \dots$ → $N \neq 0$

$$\text{We have } z_2 = \underbrace{e^{\lambda_1 T}}_{z_1} \underbrace{e^{j\frac{2\pi}{T}NT}}_{1}$$

Interpretation in the complex plane



- S_i = Strips of width $2\pi/T$
- Due to sampling, all strips "collapse" into S_0
  Sampling ⇒ loss of information: can not reconstruct eigenvalues of the CT system from those of the DT one.

Eigenvalues under exact sampling (2/2)

Map of regions in the λ-plane (continuous time) into regions of the z-plane (discrete-time).

λ-plane	z-plane
0	1
real negative	$[0, 1)$
real positive	$(1, +\infty)$
constant imaginary part	$(-1, 0]$
constant damping	log spirals

$\frac{s^2}{\omega_n^2} + \frac{2\xi s}{\omega_n} + 1$

$\omega_n > 0$ "natural frequency"

$\xi \in (0, 1]$ damping

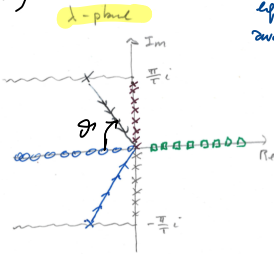
↳ $\xi = \cos(\vartheta)$

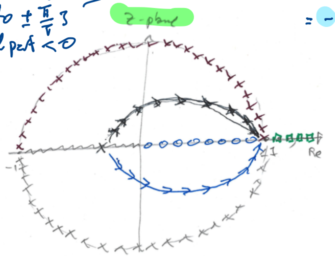
$z = e^{\lambda T}$

$\lambda = -a + j\left(\pm\frac{\pi}{T}\right),\ a>0$

$z = e^{-aT} \cdot e^{j(\pm\frac{\pi}{T})T} = -e^{-aT}$

equal to $\pm\frac{\pi}{T}j$ and real part < 0





- Remark: asymptotically stable eigenvalues λ (i.e. $\mathrm{Re}(\lambda) < 0$) are mapped into asymptotically stable eigenvalue z (i.e. $|z| < 1$).

Exact sampling: conclusions

- Pros
  - x_k and y_k represent $x(t_k)$ and $y(t_k)$ with no approximations
  - Stability, AS and instability are preserved
- Cons
  - $\hat{A} = e^{AT} = I + AT + \frac{(AT)^2}{2} + \dots$
  - can be difficult to compute for large systems !
    In Matlab, `hA=expm(A*T)`
  - does not preserve the pattern of zeros in A

Example

$$A = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix}, \quad T = 0.1$$

$$\rightarrow \quad \hat{A} = e^{AT} = \begin{bmatrix} 0.905 & 0.0905 & 0.0045 \\ 0.0045 & 0.905 & 0.0905 \\ 0.0905 & 0.0045 & 0.905 \end{bmatrix}$$

Exact sampling: conclusions

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Generalisations

What happens if $u(t)$ or $x(t)$ are affected by delays ? $\rightarrow$ see the class "Networked Control Systems"

Approximate discretisation methods

- Goal: avoid the computation of e^{AT} and preserve the structure of A

CT LTI System

$$\dot{x} = Ax + Bu \quad (1)$$
$$y = Cx + Du \quad (2)$$

Assumption

Uniform sampling period T

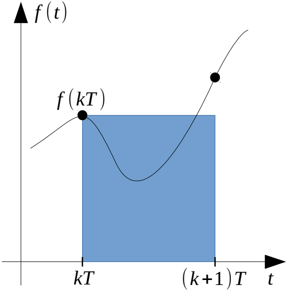
- Integrating (1) on $[kT, (k+1)T]$ and setting $x_k = x(kT)$ gives

$$x_{k+1} - x_k = A \int_{kT}^{(k+1)T} x(t)\,dt + B \int_{kT}^{(k+1)T} u(t)\,dt$$

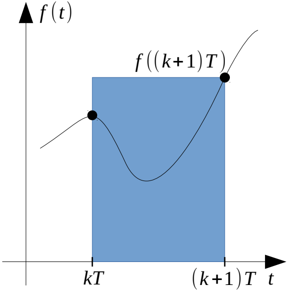
Approximate discretisation methods

- To make $u(kT)$ and $x(kT)$ appear in the right hand side, we use the following numerical integration scheme, written for a generic function $f(t)\ :\ \mathbb{R} \to \mathbb{R}^n$

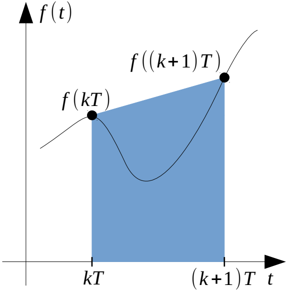
$$\int_{kT}^{(k+1)T} f(t)\,dt \simeq [(1-\alpha)f(kT) + \alpha f((k+1)T)]\,T, \quad 0 \le \alpha \le 1$$



Forward Euler (α=0)



Backward Euler (α=1)



Tustin (α=0.5)

DT Models

$\alpha = 0$: Forward Euler (FE)

$\alpha = 1$: Backward Euler (BE)

$\alpha = 0.5$: Trapezoidal method or Tustin method

In all cases, loss of information. Is stability preserved ?

Resulting DT system

$$x_{k+1} - x_k = A\left[(1-\alpha)x_k + \alpha x_{k+1}\right] T + BT\left[(1-\alpha)u_k + \alpha u_{k+1}\right]$$

- $\alpha = 0$ (FE)

$$x_{k+1} = (AT + I)x_k + BTu_k$$

- $\alpha = 1$ (BE)

$$x_{k+1} = ATx_{k+1} + x_k + BTu_{k+1}$$

- $\alpha = 0.5$ (Tustin)

$$x_{k+1} = (\frac{1}{2}AT + I)x_k + \frac{1}{2}ATx_{k+1} + BT\frac{1}{2}\left[u_k + u_{k+1}\right]$$

↓ 2h44

Analysis of FE ($\alpha = 0$)

Remark

FE provides a causal DT system with $\hat{A} = AT + I$, $\hat{B} = BT$

Lemma (properties of FE)

(a) The off-diagonal zero entries of A and $AT + I$ are in the same positions

$\lambda \in Spec(A) \Rightarrow Re(\lambda) < 0$ $\qquad$ $\lambda \in Spec(A) \Rightarrow |\lambda| < 1$

(b) if A is Hurwitz stable, then $AT + I$ is Schur stable if and only if

$$0 < T < T^* = \min_{i=1,\dots,n} \frac{-2\,\mathrm{Re}(\lambda_i)}{|\lambda_i|^2} \tag{1}$$

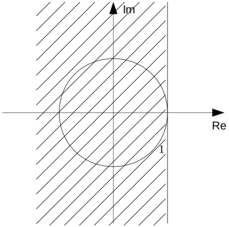
where λ_i are the eigenvalues of A. $\qquad \dot{x} = -x$

$\hat{A} = (-1)T + 1$ $\qquad \min \frac{-2Re(\lambda_i)}{\lambda_i^2} \to \frac{-2(-1)}{1} = 2$

$Av = \lambda v \qquad (AT + I)v = AvT + v = (\lambda T + 1)v$

Remark

If λ is an eigenvalue of A, then $\lambda T + 1$ is an eigenvalue of $AT + I$. The function $\lambda \mapsto \lambda T + 1$ maps the set $\{\lambda \in \mathbb{C} : \text{Re}(\lambda) < 0\}$ in the shaded region below



Remark

$$e^{AT} = I + AT + \frac{(AT)^2}{2} + \cdots$$

Therefore FE can be seen as a first order Taylor approximation of e^{AT}

Effect of discretization on reachability and observability

- Discretisation $\Rightarrow$ loss of information
- We expect that sampling may impair reachability/observability...

CT LTI System

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

Theorem

Assume that $(*)$ is controllable (or reachable) and observable. The DT system obtained through exact discretisation is controllable (or reachable) and observable if and only if, for any pair of eigenvalues λ_i, λ_j of A

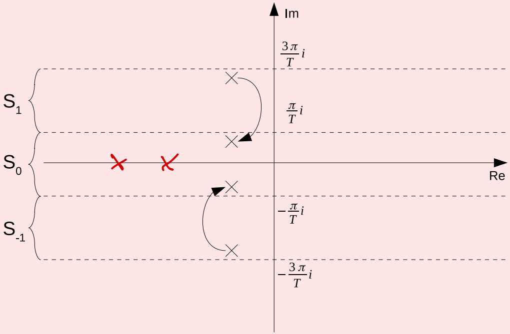
$$\text{Re}(\lambda_i) = \text{Re}(\lambda_j) \Rightarrow \text{Im}(\lambda_i - \lambda_j) \neq \frac{2n\pi}{T} \quad n = \pm 1, \pm 2, \ldots \quad (n \neq 0)$$

where T is the sampling period.

Effect of discretization on reachability and observability

Remarks

- Recall the relations between eigenvalues under exact sampling



- The CT system has real eigenvalues only $\Rightarrow$ no loss of reachability/observability
- Always possible to avoid losses of reachability/observability by choosing $T > 0$ small enough

Example

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \qquad (**)$$

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

- Check at home that $(**)$ is reachable and observable (the tests are the same for CT and DT systems)
- System eigenvalues $\lambda_1 = j, \quad \lambda_2 = -j$

DT system (sampling time $T > 0$)

$$\begin{bmatrix} x_1^+ \\ x_2^+ \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(T) & \sin(T) \\ -\sin(T) & \cos(T) \end{bmatrix}}_{\hat{A}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 1 - \cos(T) \\ \sin(T) \end{bmatrix}}_{\hat{B}} u$$

$$y = \underbrace{\begin{bmatrix} 1 & 0 \end{bmatrix}}_{\hat{C}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Reachability of the DT system

$$M_r = \left[\begin{array}{cc} \hat{B} & \hat{A}\hat{B} \end{array}\right] = \left[\begin{array}{cc} 1-\cos(T) & \cos(T)+1-2\cos^2(T) \\ \sin(T) & -\sin(T)+2\cos(T)\sin(T) \end{array}\right]$$

0 for $T = n\pi$

$$\text{Rank}(M_r) = 2 \quad \Leftrightarrow \quad T \neq n\pi \quad n = 1, 2, 3 \ldots$$

- By applying the Theorem $\text{Re}(\lambda_1) = \text{Re}(\lambda_2) = 0$. Then, the system is reachable if and only if

$$\underbrace{\text{Im}(\lambda_1 - \lambda_2)}_{\text{Im}(2j)=2} \neq \frac{2n\pi}{T} \quad \Leftrightarrow \quad T \neq n\pi$$

Conclusions

- Time-discretization $\Rightarrow$ loss of information
- Exact sampling : best possible choice but it does not
  - preserve structure
  - apply to nonlinear systems

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$\rightarrow$ What about the simultaneous presence of sampling and time delays?
Master course "Networked Control Systems"