

Lecture 18

Controllability and state transfer

- state transfer
- reachable set, controllability matrix
- minimum norm inputs
- infinite-horizon minimum norm transfer

State transfer

consider $\dot{x} = Ax + Bu$ (or $x(t+1) = Ax(t) + Bu(t)$) over time interval $[t_i, t_f]$

we say input $u : [t_i, t_f] \rightarrow \mathbf{R}^m$ *steers* or *transfers* state from $x(t_i)$ to $x(t_f)$ (over time interval $[t_i, t_f]$)

(subscripts stand for *initial* and *final*)

questions:

- where can $x(t_i)$ be transferred to at $t = t_f$?
- how quickly can $x(t_i)$ be transferred to some x_{target} ?
- how do we find a u that transfers $x(t_i)$ to $x(t_f)$?
- how do we find a ‘small’ or ‘efficient’ u that transfers $x(t_i)$ to $x(t_f)$?

Reachability

consider state transfer from $x(0) = 0$ to $x(t)$

we say $x(t)$ is *reachable* (in t seconds or epochs)

we define $\mathcal{R}_t \subseteq \mathbf{R}^n$ as the set of points reachable in t seconds or epochs

for CT system $\dot{x} = Ax + Bu$,

$$\mathcal{R}_t = \left\{ \int_0^t e^{(t-\tau)A} B u(\tau) d\tau \mid u : [0, t] \rightarrow \mathbf{R}^m \right\}$$

and for DT system $x(t+1) = Ax(t) + Bu(t)$,

$$\mathcal{R}_t = \left\{ \sum_{\tau=0}^{t-1} A^{t-1-\tau} B u(\tau) \mid u(t) \in \mathbf{R}^m \right\}$$

- \mathcal{R}_t is a subspace of \mathbf{R}^n
- $\mathcal{R}_t \subseteq \mathcal{R}_s$ if $t \leq s$
(*i.e.*, can reach more points given more time)

we define the *reachable set* \mathcal{R} as the set of points reachable for some t :

$$\mathcal{R} = \bigcup_{t \geq 0} \mathcal{R}_t$$

Reachability for discrete-time LDS

DT system $x(t+1) = Ax(t) + Bu(t)$, $x(t) \in \mathbf{R}^n$

$$x(t) = \mathcal{C}_t \begin{bmatrix} u(t-1) \\ \vdots \\ u(0) \end{bmatrix}$$

where $\mathcal{C}_t = [B \quad AB \quad \dots \quad A^{t-1}B]$

so reachable set at t is $\mathcal{R}_t = \text{range}(\mathcal{C}_t)$

by C-H theorem, we can express each A^k for $k \geq n$ as linear combination of A^0, \dots, A^{n-1}

hence for $t \geq n$, $\text{range}(\mathcal{C}_t) = \text{range}(\mathcal{C}_n)$

thus we have

$$\mathcal{R}_t = \begin{cases} \text{range}(\mathcal{C}_t) & t < n \\ \text{range}(\mathcal{C}) & t \geq n \end{cases}$$

where $\mathcal{C} = \mathcal{C}_n$ is called the *controllability matrix*

- any state that can be reached can be reached by $t = n$
- the reachable set is $\mathcal{R} = \text{range}(\mathcal{C})$

Controllable system

system is called *reachable* or *controllable* if all states are reachable (*i.e.*, $\mathcal{R} = \mathbf{R}^n$)

system is reachable if and only if $\mathbf{Rank}(\mathcal{C}) = n$

example:
$$x(t + 1) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} u(t)$$

controllability matrix is
$$\mathcal{C} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

hence system is not controllable; reachable set is

$$\mathcal{R} = \text{range}(\mathcal{C}) = \{ x \mid x_1 = x_2 \}$$

General state transfer

with $t_f > t_i$,

$$x(t_f) = A^{t_f - t_i} x(t_i) + \mathcal{C}_{t_f - t_i} \begin{bmatrix} u(t_f - 1) \\ \vdots \\ u(t_i) \end{bmatrix}$$

hence can transfer $x(t_i)$ to $x(t_f) = x_{\text{des}}$

$$\Leftrightarrow x_{\text{des}} - A^{t_f - t_i} x(t_i) \in \mathcal{R}_{t_f - t_i}$$

- general state transfer reduces to reachability problem
- if system is controllable any state transfer can be achieved in $\leq n$ steps
- important special case: driving state to zero (sometimes called regulating or controlling state)

Least-norm input for reachability

assume system is reachable, $\text{Rank}(\mathcal{C}_t) = n$

to steer $x(0) = 0$ to $x(t) = x_{\text{des}}$, inputs $u(0), \dots, u(t-1)$ must satisfy

$$x_{\text{des}} = \mathcal{C}_t \begin{bmatrix} u(t-1) \\ \vdots \\ u(0) \end{bmatrix}$$

among all u that steer $x(0) = 0$ to $x(t) = x_{\text{des}}$, the one that minimizes

$$\sum_{\tau=0}^{t-1} \|u(\tau)\|^2$$

is given by

$$\begin{bmatrix} u_{\text{ln}}(t-1) \\ \vdots \\ u_{\text{ln}}(0) \end{bmatrix} = \mathcal{C}_t^T (\mathcal{C}_t \mathcal{C}_t^T)^{-1} x_{\text{des}}$$

u_{ln} is called *least-norm* or *minimum energy* input that effects state transfer

can express as

$$u_{\text{ln}}(\tau) = B^T (A^T)^{(t-1-\tau)} \left(\sum_{s=0}^{t-1} A^s B B^T (A^T)^s \right)^{-1} x_{\text{des}},$$

for $\tau = 0, \dots, t-1$

\mathcal{E}_{\min} , the minimum value of $\sum_{\tau=0}^{t-1} \|u(\tau)\|^2$ required to reach $x(t) = x_{\text{des}}$, is sometimes called *minimum energy* required to reach $x(t) = x_{\text{des}}$

$$\begin{aligned}
 \mathcal{E}_{\min} &= \sum_{\tau=0}^{t-1} \|u_{\text{ln}}(\tau)\|^2 \\
 &= \left(\mathcal{C}_t^T (\mathcal{C}_t \mathcal{C}_t^T)^{-1} x_{\text{des}} \right)^T \mathcal{C}_t^T (\mathcal{C}_t \mathcal{C}_t^T)^{-1} x_{\text{des}} \\
 &= x_{\text{des}}^T (\mathcal{C}_t \mathcal{C}_t^T)^{-1} x_{\text{des}} \\
 &= x_{\text{des}}^T \left(\sum_{\tau=0}^{t-1} A^\tau B B^T (A^T)^\tau \right)^{-1} x_{\text{des}}
 \end{aligned}$$

- $\mathcal{E}_{\min}(x_{\text{des}}, t)$ gives measure of how hard it is to reach $x(t) = x_{\text{des}}$ from $x(0) = 0$ (*i.e.*, how large a u is required)
- $\mathcal{E}_{\min}(x_{\text{des}}, t)$ gives practical measure of controllability/reachability (as function of x_{des}, t)
- ellipsoid $\{ z \mid \mathcal{E}_{\min}(z, t) \leq 1 \}$ shows points in state space reachable at t with one unit of energy

(shows directions that can be reached with small inputs, and directions that can be reached only with large inputs)

\mathcal{E}_{\min} as function of t :

if $t \geq s$ then

$$\sum_{\tau=0}^{t-1} A^{\tau} B B^T (A^T)^{\tau} \geq \sum_{\tau=0}^{s-1} A^{\tau} B B^T (A^T)^{\tau}$$

hence

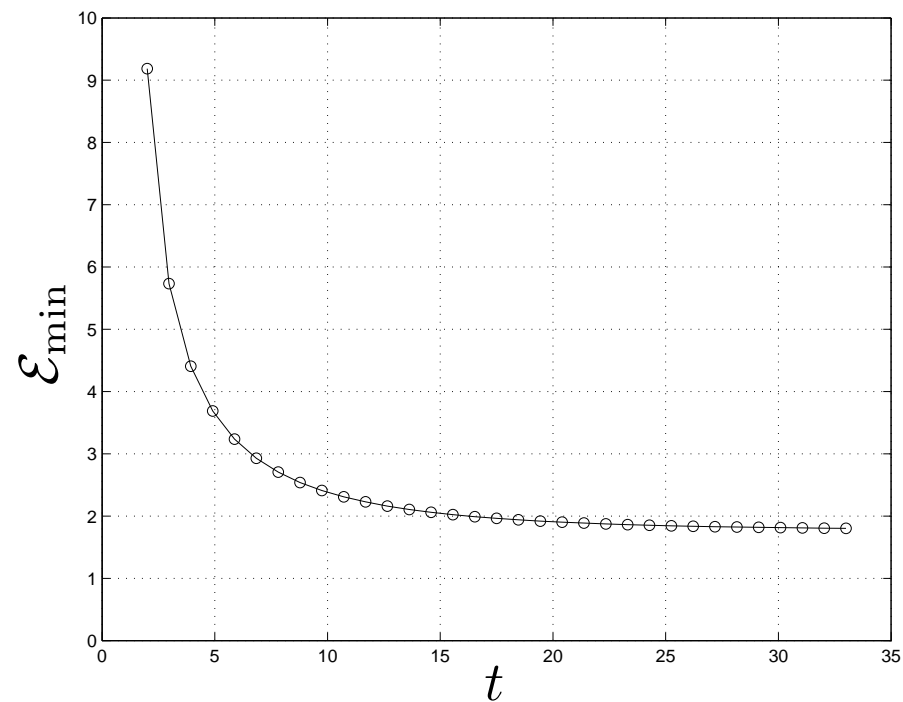
$$\left(\sum_{\tau=0}^{t-1} A^{\tau} B B^T (A^T)^{\tau} \right)^{-1} \leq \left(\sum_{\tau=0}^{s-1} A^{\tau} B B^T (A^T)^{\tau} \right)^{-1}$$

so $\mathcal{E}_{\min}(x_{\text{des}}, t) \leq \mathcal{E}_{\min}(x_{\text{des}}, s)$

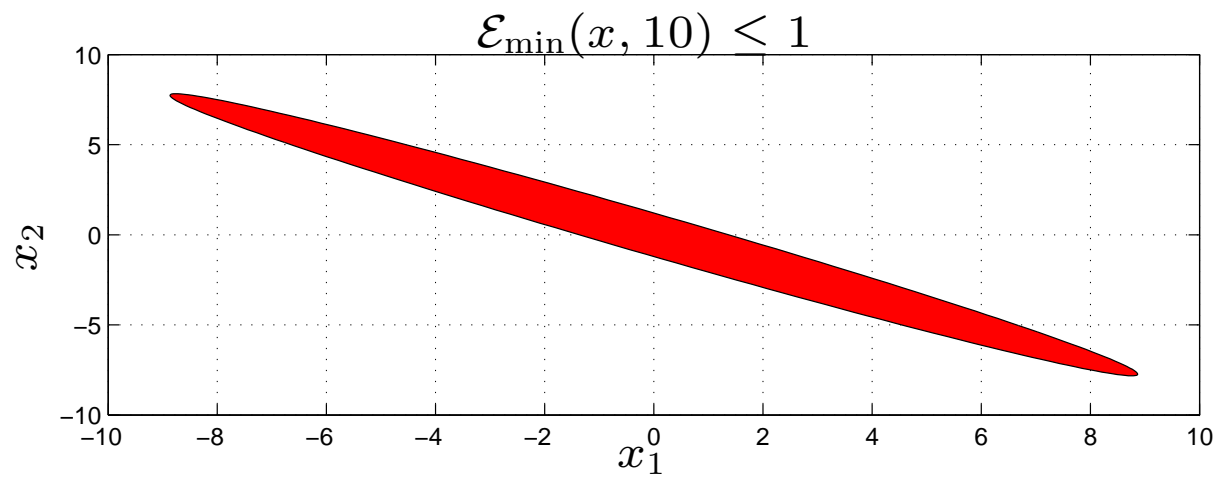
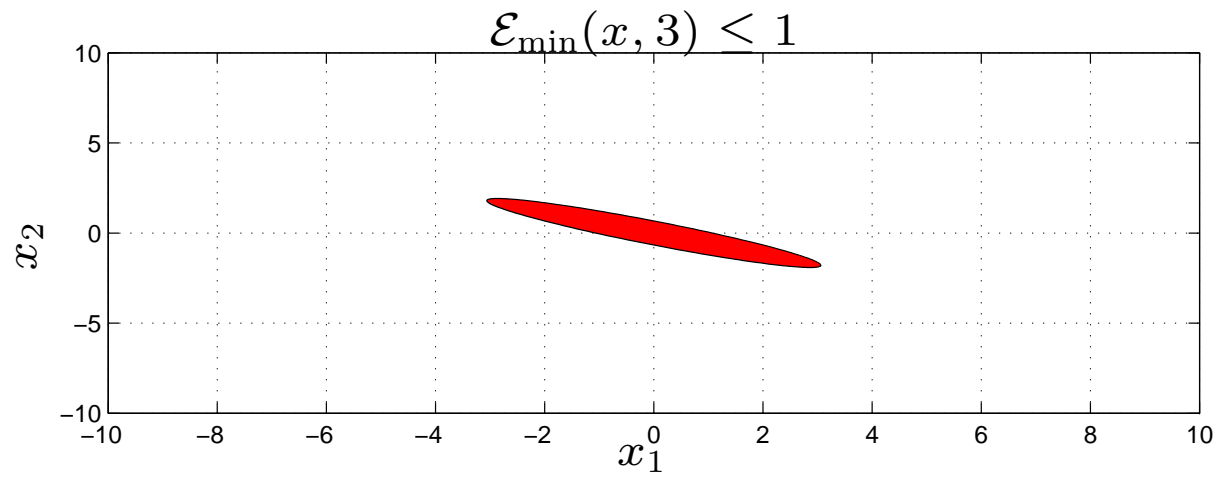
i.e.: takes less energy to get somewhere more leisurely

example: $x(t + 1) = \begin{bmatrix} 1.75 & 0.8 \\ -0.95 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u(t)$

$\mathcal{E}_{\min}(z, t)$ for $z = [1 \ 1]^T$:



ellipsoids $\mathcal{E}_{\min} \leq 1$ for $t = 3$ and $t = 10$:



Minimum energy over infinite horizon

the matrix

$$P = \lim_{t \rightarrow \infty} \left(\sum_{\tau=0}^{t-1} A^\tau B B^T (A^T)^\tau \right)^{-1}$$

always exists, and gives the minimum energy required to reach a point x_{des} (with no limit on t):

$$\min \left\{ \sum_{\tau=0}^{t-1} \|u(\tau)\|^2 \mid x(0) = 0, x(t) = x_{\text{des}} \right\} = x_{\text{des}}^T P x_{\text{des}}$$

if A is stable, $P > 0$ (*i.e.*, can't get anywhere for free)

if A is not stable, then P can have nonzero nullspace

- $Pz = 0, z \neq 0$ means can get to z using u 's with energy as small as you like

(u just gives a little kick to the state; the instability carries it out to z efficiently)
- basis of highly maneuverable, unstable aircraft

Continuous-time reachability

consider now $\dot{x} = Ax + Bu$ with $x(t) \in \mathbf{R}^n$

reachable set at time t is

$$\mathcal{R}_t = \left\{ \int_0^t e^{(t-\tau)A} B u(\tau) d\tau \mid u : [0, t] \rightarrow \mathbf{R}^m \right\}$$

fact: for $t > 0$, $\mathcal{R}_t = \mathcal{R} = \text{range}(\mathcal{C})$, where

$$\mathcal{C} = [B \quad AB \quad \dots \quad A^{n-1}B]$$

is the controllability matrix of (A, B)

- same \mathcal{R} as discrete-time system
- for continuous-time system, any reachable point can be reached as fast as you like (with large enough u)

first let's show for *any* u (and $x(0) = 0$) we have $x(t) \in \text{range}(\mathcal{C})$

write e^{tA} as power series:

$$e^{tA} = I + \frac{t}{1!}A + \frac{t^2}{2!}A^2 + \dots$$

by C-H, express A^n, A^{n+1}, \dots in terms of A^0, \dots, A^{n-1} and collect powers of A :

$$e^{tA} = \alpha_0(t)I + \alpha_1(t)A + \dots + \alpha_{n-1}(t)A^{n-1}$$

therefore

$$\begin{aligned} x(t) &= \int_0^t e^{\tau A} B u(t - \tau) d\tau \\ &= \int_0^t \left(\sum_{i=0}^{n-1} \alpha_i(\tau) A^i \right) B u(t - \tau) d\tau \end{aligned}$$

$$\begin{aligned} &= \sum_{i=0}^{n-1} A^i B \int_0^t \alpha_i(\tau) u(t - \tau) d\tau \\ &= \mathcal{C}z \end{aligned}$$

where $z_i = \int_0^t \alpha_i(\tau) u(t - \tau) d\tau$

hence, $x(t)$ is always in $\text{range}(\mathcal{C})$

need to show converse: every point in $\text{range}(\mathcal{C})$ can be reached

Impulsive inputs

suppose $x(0_-) = 0$ and we apply input $u(t) = \delta^{(k)}(t)f$, where $\delta^{(k)}$ denotes k th derivative of δ and $f \in \mathbf{R}^m$

then $U(s) = s^k f$, so

$$\begin{aligned} X(s) &= (sI - A)^{-1} B s^k f \\ &= (s^{-1}I + s^{-2}A + \dots) B s^k f \\ &= \underbrace{(s^{k-1} + \dots + sA^{k-2} + A^{k-1})}_{\text{impulsive terms}} + s^{-1}A^k + \dots) B f \end{aligned}$$

hence

$$x(t) = \text{impulsive terms} + A^k B f + A^{k+1} B f \frac{t}{1!} + A^{k+2} B f \frac{t^2}{2!} + \dots$$

in particular, $x(0_+) = A^k B f$

thus, input $u = \delta^{(k)} f$ transfers state from $x(0_-) = 0$ to $x(0_+) = A^k B f$

now consider input of form

$$u(t) = \delta(t) f_0 + \cdots + \delta^{(n-1)}(t) f_{n-1}$$

where $f_i \in \mathbf{R}^m$

by linearity we have

$$x(0_+) = B f_0 + \cdots + A^{n-1} B f_{n-1} = \mathcal{C} \begin{bmatrix} f_0 \\ \vdots \\ f_{n-1} \end{bmatrix}$$

hence we can reach any point in $\text{range}(\mathcal{C})$

(at least, using impulse inputs)

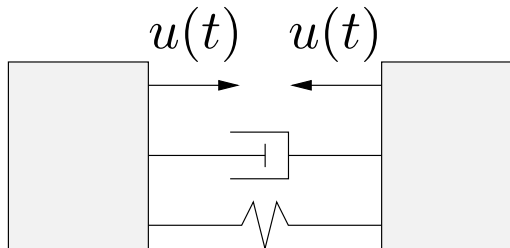
can also be shown that any point in $\text{range}(\mathcal{C})$ can be reached for any $t > 0$ using *nonimpulsive* inputs

fact: if $x(0) \in \mathcal{R}$, then $x(t) \in \mathcal{R}$ for all t (no matter what u is)

to show this, need to show $e^{tA}x(0) \in \mathcal{R}$ if $x(0) \in \mathcal{R} \dots$

Example

- unit masses at y_1, y_2 , connected by unit springs, dampers
- input is tension between masses
- state is $x = [y^T \dot{y}^T]^T$



system is

$$\dot{x} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix} u$$

- can we maneuver state anywhere, starting from $x(0) = 0$?
- if not, where can we maneuver state?

controllability matrix is

$$\mathcal{C} = [B \quad AB \quad A^2B \quad A^3B] = \begin{bmatrix} 0 & 1 & -2 & 2 \\ 0 & -1 & 2 & -2 \\ 1 & -2 & 2 & 0 \\ -1 & 2 & -2 & 0 \end{bmatrix}$$

hence reachable set is

$$\mathcal{R} = \text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix} \right\}$$

we can reach states with $y_1 = -y_2$, $\dot{y}_1 = -\dot{y}_2$, *i.e.*, precisely the differential motions

it's obvious — internal force does not affect center of mass position or total momentum!

Least-norm input for reachability

(also called *minimum energy input*)

assume that $\dot{x} = Ax + Bu$ is reachable

we seek u that steers $x(0) = 0$ to $x(t) = x_{\text{des}}$ and minimizes

$$\int_0^t \|u(\tau)\|^2 d\tau$$

let's discretize system with interval $h = t/N$

(we'll let $N \rightarrow \infty$ later)

thus u is piecewise constant:

$$u(\tau) = u_d(k) \quad \text{for } kh \leq \tau < (k+1)h, \quad k = 0, \dots, N-1$$

so

$$x(t) = \begin{bmatrix} B_d & A_d B_d & \cdots & A_d^{N-1} B_d \end{bmatrix} \begin{bmatrix} u_d(N-1) \\ \vdots \\ u_d(0) \end{bmatrix}$$

where

$$A_d = e^{hA}, \quad B_d = \int_0^h e^{\tau A} d\tau B$$

least-norm u_d that yields $x(t) = x_{\text{des}}$ is

$$u_{\text{dln}}(k) = B_d^T (A_d^T)^{(N-1-k)} \left(\sum_{i=0}^{N-1} A_d^i B_d B_d^T (A_d^T)^i \right)^{-1} x_{\text{des}}$$

let's express in terms of A :

$$B_d^T (A_d^T)^{(N-1-k)} = B_d^T e^{(t-\tau)A^T}$$

where $\tau = t(k + 1)/N$

for N large, $B_d \approx (t/N)B$, so this is approximately

$$(t/N)B^T e^{(t-\tau)A^T}$$

similarly

$$\begin{aligned} \sum_{i=0}^{N-1} A_d^i B_d B_d^T (A_d^T)^i &= \sum_{i=0}^{N-1} e^{(ti/N)A} B_d B_d^T e^{(ti/N)A^T} \\ &\approx (t/N) \int_0^t e^{\bar{t}A} B B^T e^{\bar{t}A^T} d\bar{t} \end{aligned}$$

for large N

hence least-norm discretized input is approximately

$$u_{\text{ln}}(\tau) = B^T e^{(t-\tau)A^T} \left(\int_0^t e^{\bar{t}A} B B^T e^{\bar{t}A^T} d\bar{t} \right)^{-1} x_{\text{des}}, \quad 0 \leq \tau \leq t$$

for large N

hence, this is the least-norm continuous input

- can make t small, but get larger u
- cf. DT solution: sum becomes integral

min energy is

$$\int_0^t \|u_{\text{ln}}(\tau)\|^2 d\tau = x_{\text{des}}^T Q(t)^{-1} x_{\text{des}}$$

where

$$Q(t) = \int_0^t e^{\tau A} B B^T e^{\tau A^T} d\tau$$

can show

$$\begin{aligned} (A, B) \text{ controllable} &\Leftrightarrow Q(t) > 0 \text{ for all } t > 0 \\ &\Leftrightarrow Q(s) > 0 \text{ for some } s > 0 \end{aligned}$$

in fact, $\text{range}(Q(t)) = \mathcal{R}$ for any $t > 0$

Minimum energy over infinite horizon

the matrix

$$P = \lim_{t \rightarrow \infty} \left(\int_0^t e^{\tau A} B B^T e^{\tau A^T} d\tau \right)^{-1}$$

always exists, and gives minimum energy required to reach a point x_{des} (with no limit on t):

$$\min \left\{ \int_0^t \|u(\tau)\|^2 d\tau \mid x(0) = 0, x(t) = x_{\text{des}} \right\} = x_{\text{des}}^T P x_{\text{des}}$$

- if A is stable, $P > 0$ (*i.e.*, can't get anywhere for free)
- if A is not stable, then P can have nonzero nullspace
- $Pz = 0, z \neq 0$ means can get to z using u 's with energy as small as you like (u just gives a little kick to the state; the instability carries it out to z efficiently)

General state transfer

consider state transfer from $x(t_i)$ to $x(t_f) = x_{\text{des}}$, $t_f > t_i$

since

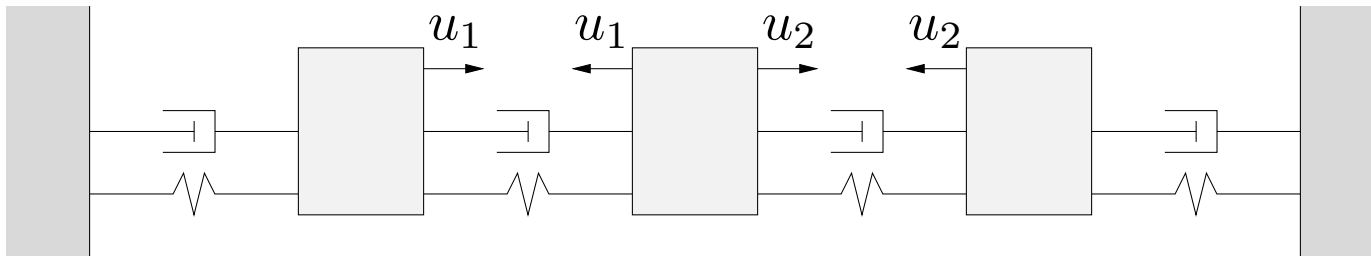
$$x(t_f) = e^{(t_f - t_i)A}x(t_i) + \int_{t_i}^{t_f} e^{(t_f - \tau)A}Bu(\tau) d\tau$$

u steers $x(t_i)$ to $x(t_f) = x_{\text{des}} \Leftrightarrow$

u (shifted by t_i) steers $x(0) = 0$ to $x(t_f - t_i) = x_{\text{des}} - e^{(t_f - t_i)A}x(t_i)$

- general state transfer reduces to reachability problem
- if system is controllable, any state transfer can be effected
 - in ‘zero’ time with impulsive inputs
 - in any positive time with non-impulsive inputs

Example



- unit masses, springs, dampers
- u_1 is force between 1st & 2nd masses
- u_2 is force between 2nd & 3rd masses
- $y \in \mathbf{R}^3$ is displacement of masses 1,2,3
- $x = \begin{bmatrix} y \\ \dot{y} \end{bmatrix}$

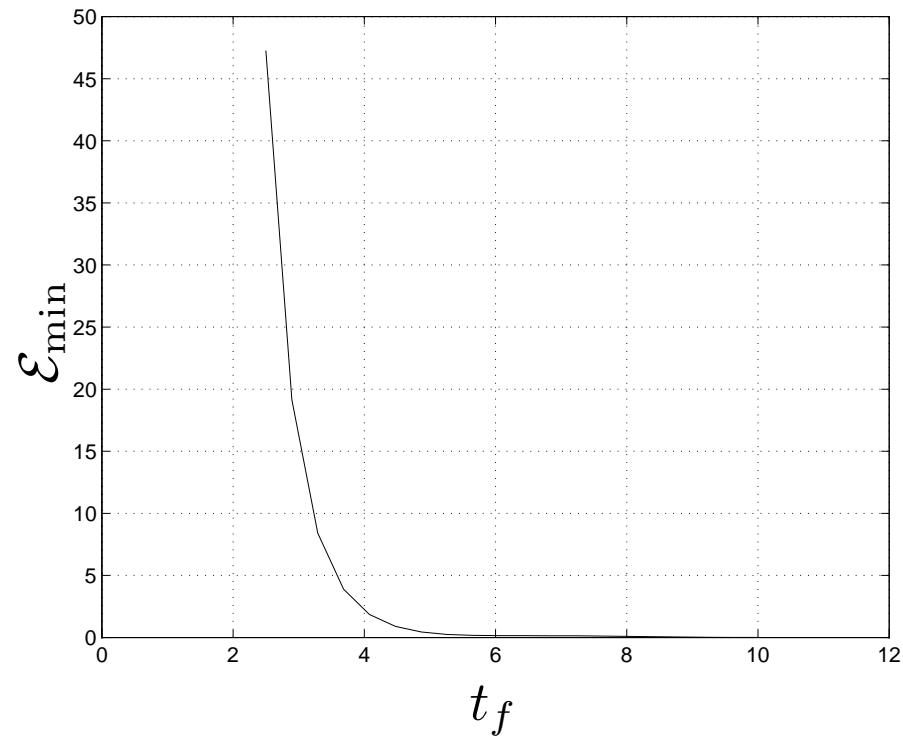
system is:

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -2 & 1 & 0 & -2 & 1 & 0 \\ 1 & -2 & 1 & 1 & -2 & 1 \\ 0 & 1 & -2 & 0 & 1 & -2 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

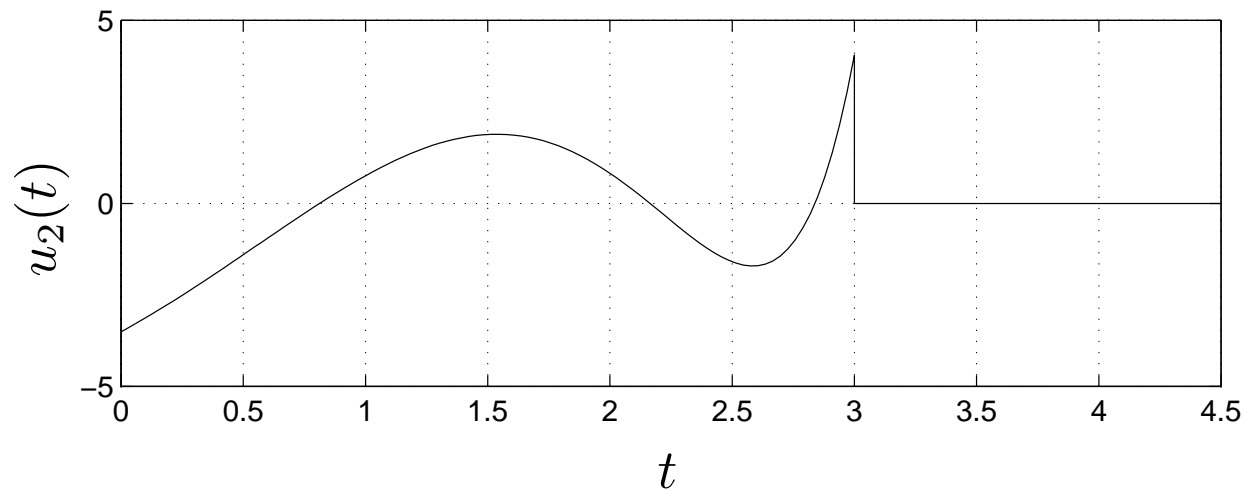
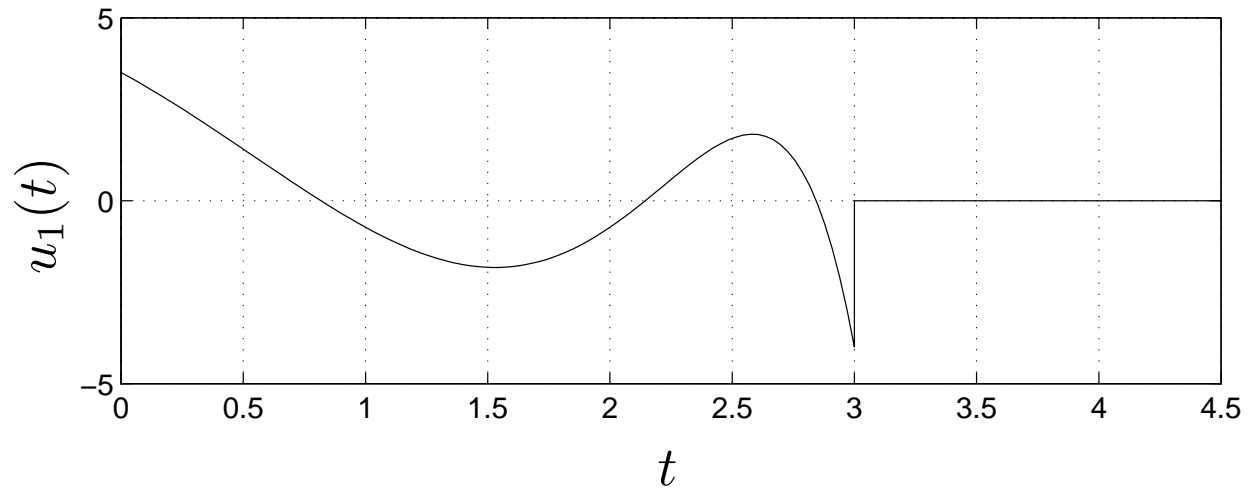
steer state from $x(0) = e_1$ to $x(t_f) = 0$

i.e., control initial state e_1 to zero at $t = t_f$

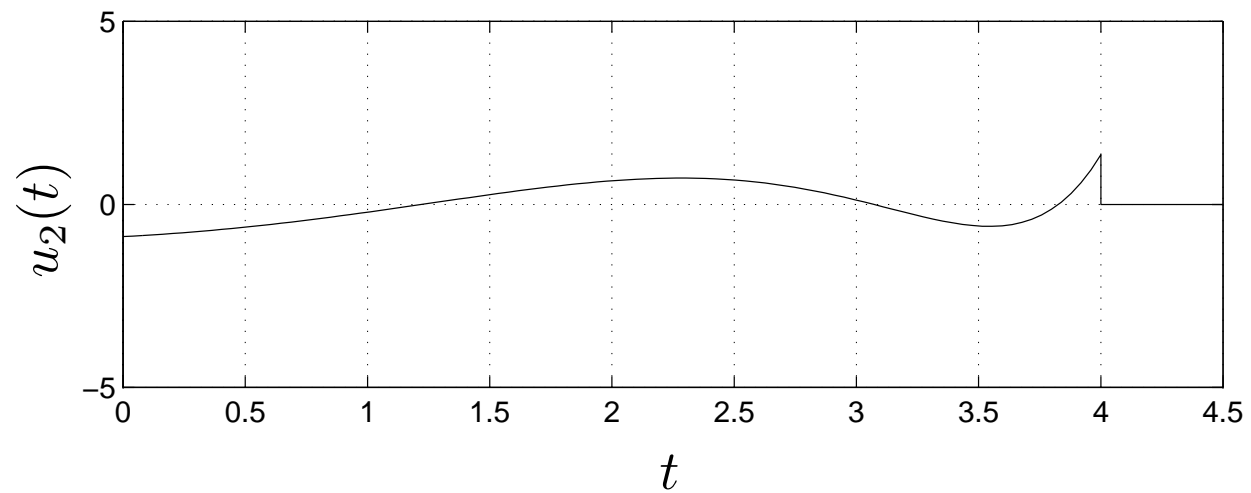
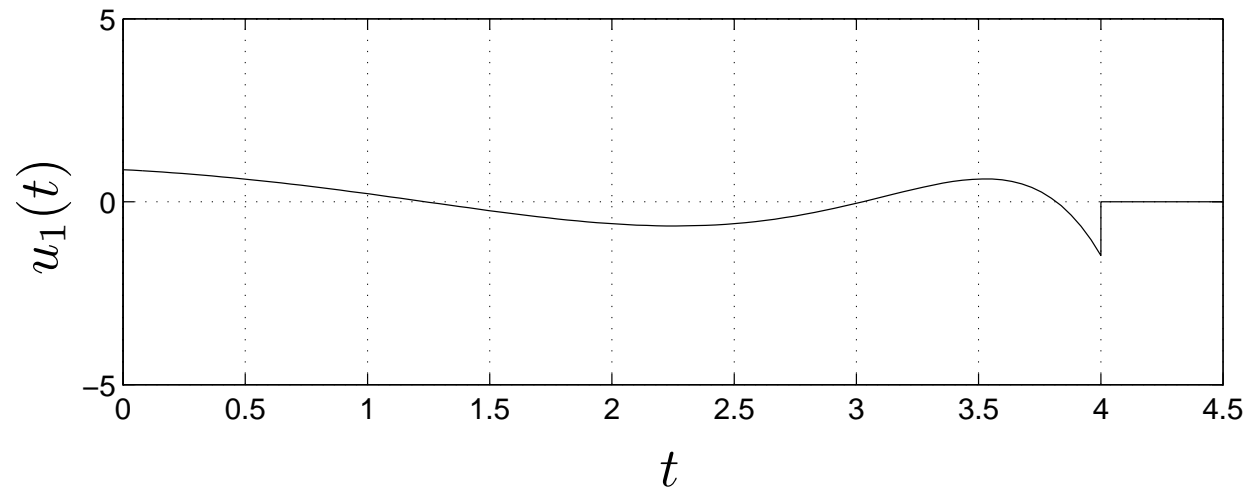
$$\mathcal{E}_{\min} = \int_0^{t_f} \|u_{\min}(\tau)\|^2 d\tau \text{ vs. } t_f:$$



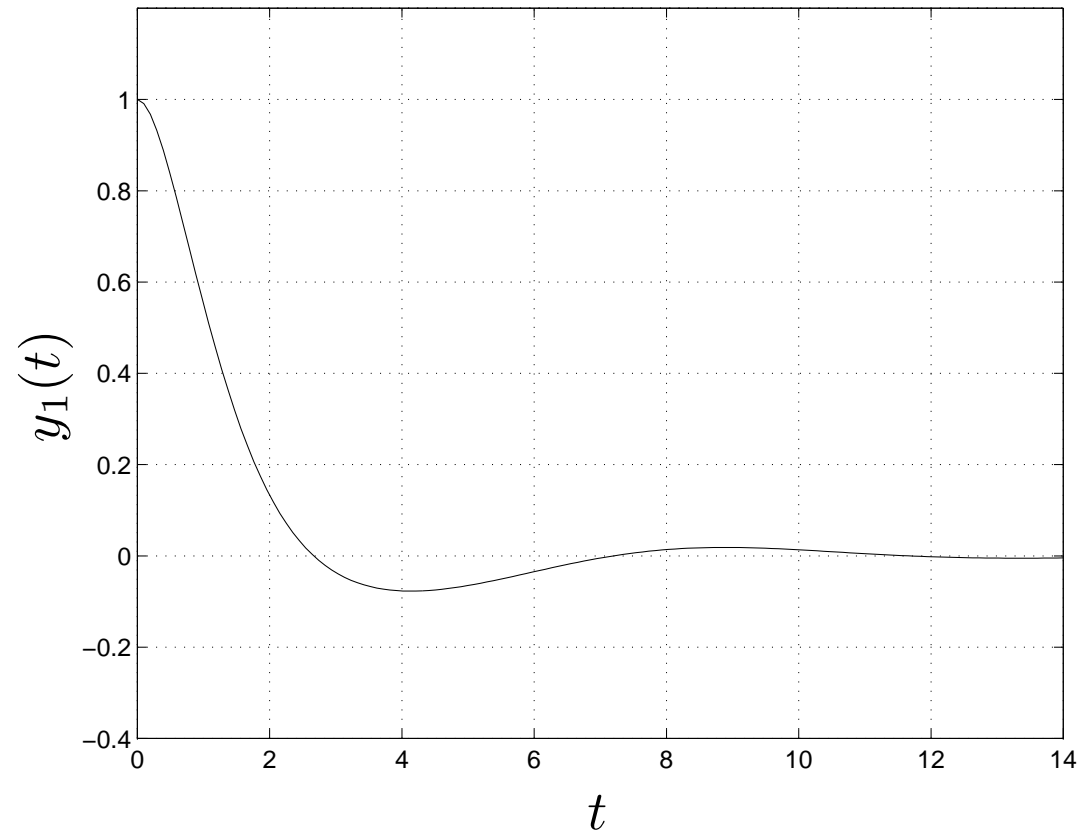
for $t_f = 3$, $u = u_{\text{ln}}$ is:



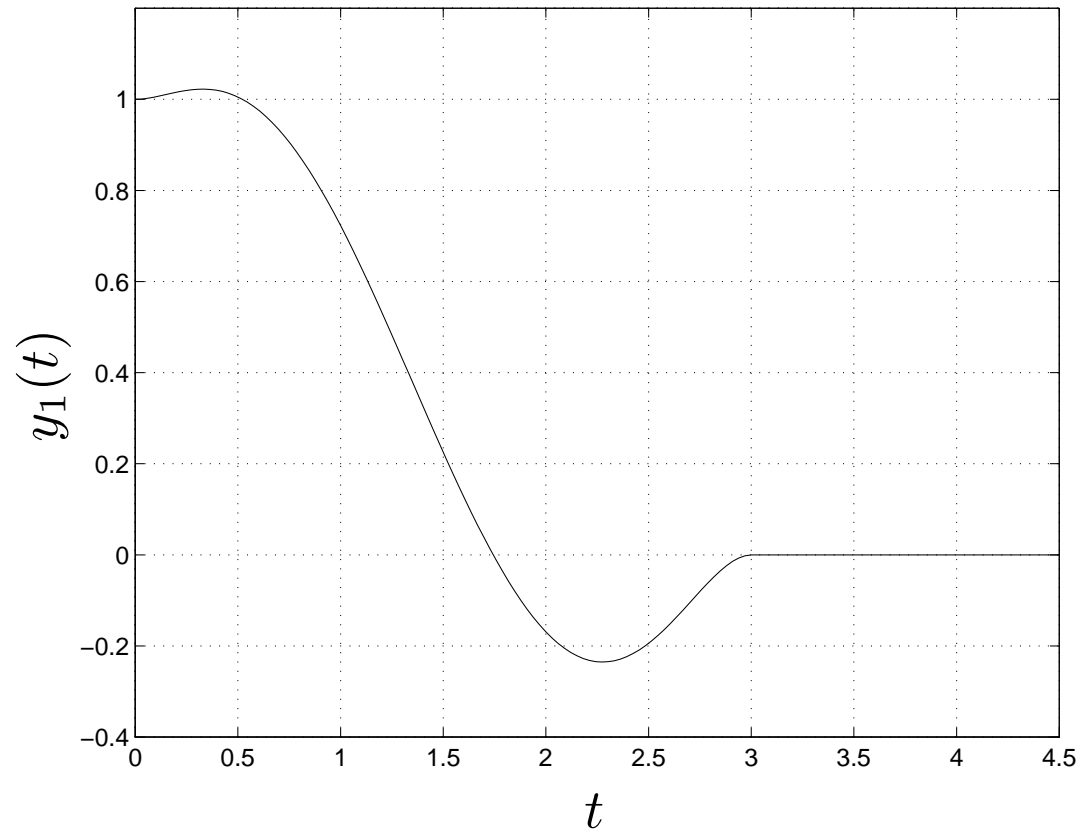
and for $t_f = 4$:



output y_1 for $u = 0$:



output y_1 for $u = u_{\text{In}}$ with $t_f = 3$:



output y_1 for $u = u_{\text{in}}$ with $t_f = 4$:

