Sliding Mode Control with Industrial Applications

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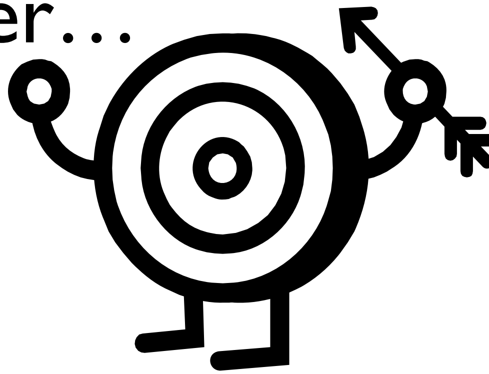
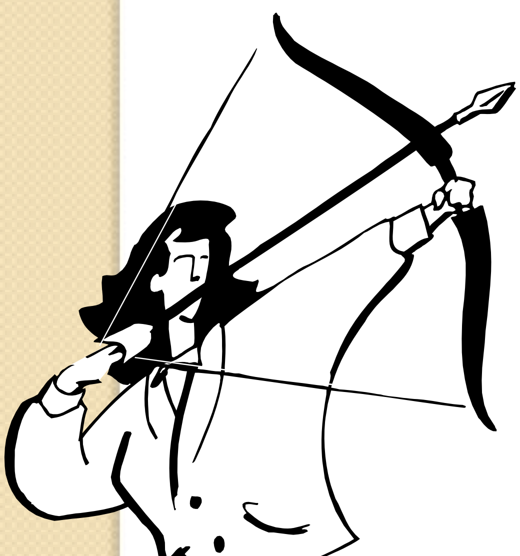
Prelude

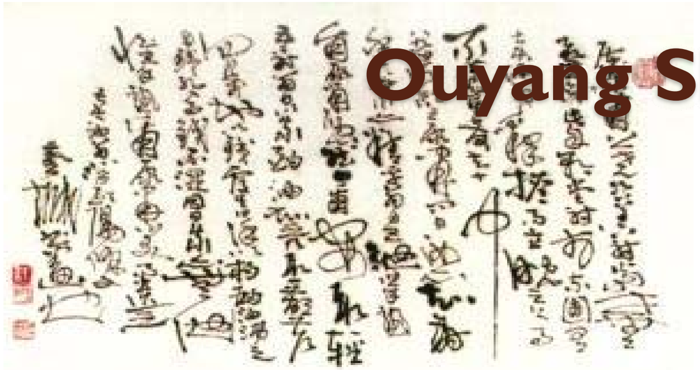
A Control Engineer as an Archer…





to drive the state to the target.

The Old Oil-Peddler



Ouyang Show(1007~1072A.D.)

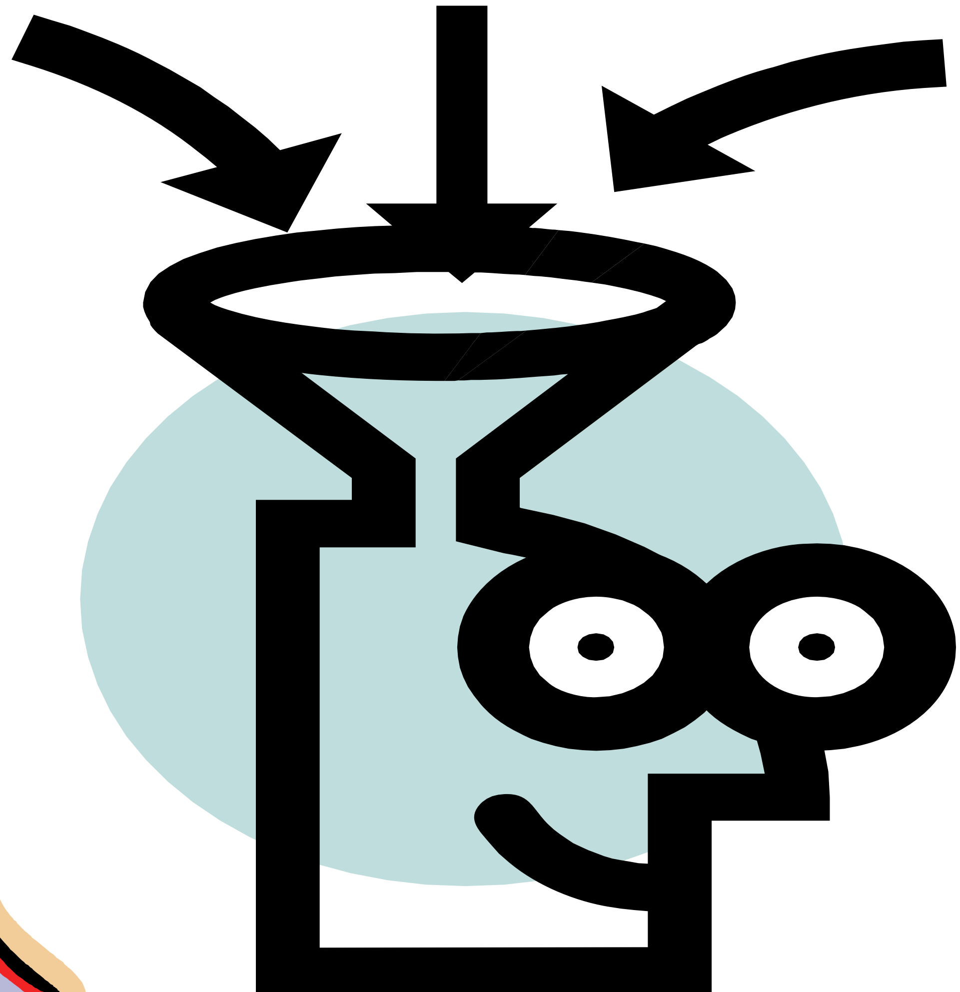
賣油翁　　　　　**宋　歐陽修**

陳康肅公堯咨善射，當世無雙，公亦以此自矜。嘗射於家圃，有賣油翁釋擔而立，睨之，久而不去。見其發矢十中八九，但微頷之。

康肅問曰：「汝亦知射乎?吾射不亦精乎？」翁曰：「無他，但手熟爾。」康肅忿然曰：「爾安敢輕吾射！」翁曰：「以我酌油知之。」乃取一葫蘆置於地，以錢覆其口，徐以杓酌油瀝之，自錢孔入，而錢不濕。因曰：「我亦無他，惟手熟爾。」康肅笑而遺之。

http://baike.baidu.com/

Sliding Mode: an illustration



to fill oil into a bottle through a funnel

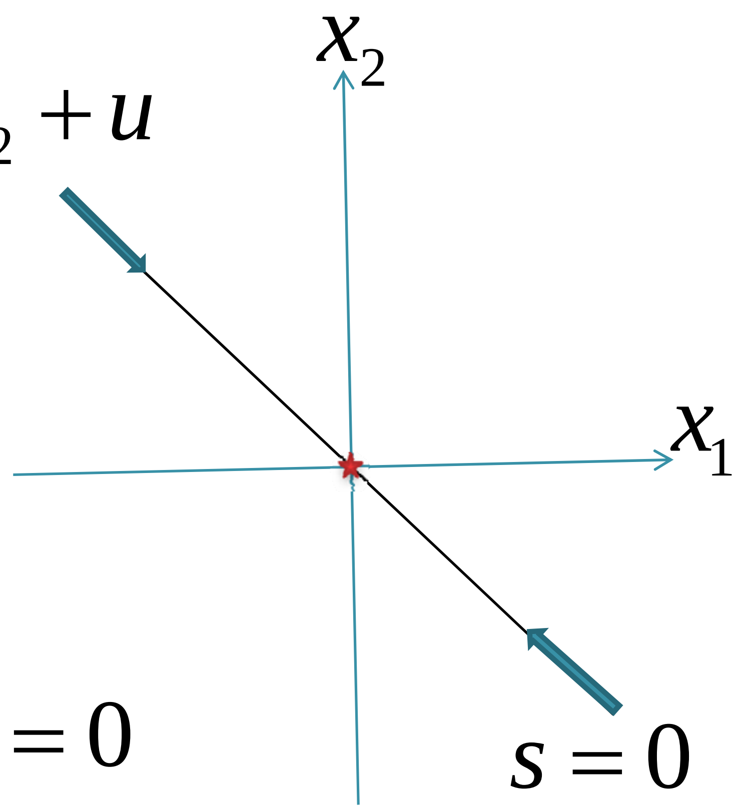
A "funnel-like" domain

System: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 2x_1 - 3x_2 + u \end{cases}$

Target: $(x_1, x_2) = (0, 0)$

Funnel: $x_2 = -x_1$

New target: $s = x_1 + x_2 = 0$



A Physical Example

Coulomb Friction

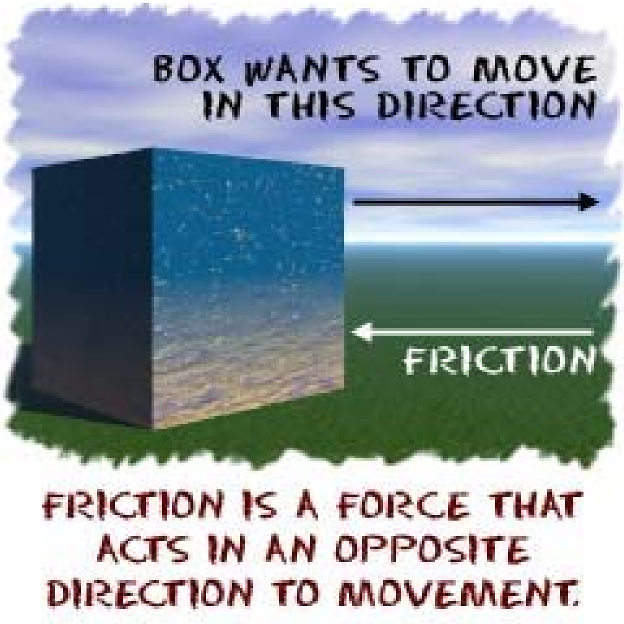
$$m\frac{dv}{dt} = -K\,\mathrm{sgn}(v) + f_a$$

$$f_a : \text{applied force}$$

$$\textit{For example, } K = 3,\ f_a = -2$$

$$v > 0 \Rightarrow m\frac{dv}{dt} = -3 - 2 < 0 \Rightarrow v \downarrow$$

$$v < 0 \Rightarrow m\frac{dv}{dt} = \ 3 - 2 \ > 0 \Rightarrow v \uparrow$$



http://www.physics4kids.com

$$\text{sliding mode: } \boxed{v \equiv 0} \ \ (\text{if } |f_a| < K).$$

Contents (1/2)

- Introduction to Sliding Mode
  - Variable Structure Systems
  - Invariance Condition (Matching Condition)
- Variable Structure Systems (VSS) Design
  - Sliding Surface Design
  - Discontinuous Control
- Discrete-Time Sliding Mode
  - $O(T)$ *v.s.* $O(T^2)$ Boundary Layer
  - Switching *v.s.* Continuous Control

Contents (2/2)

- Minimum-Time Torque Control (SRM)
- Temperature Control (Plastic Extrusion P.)
- Rod-less Pneumatic Cylinder Servo
- Wireless Network Power Control

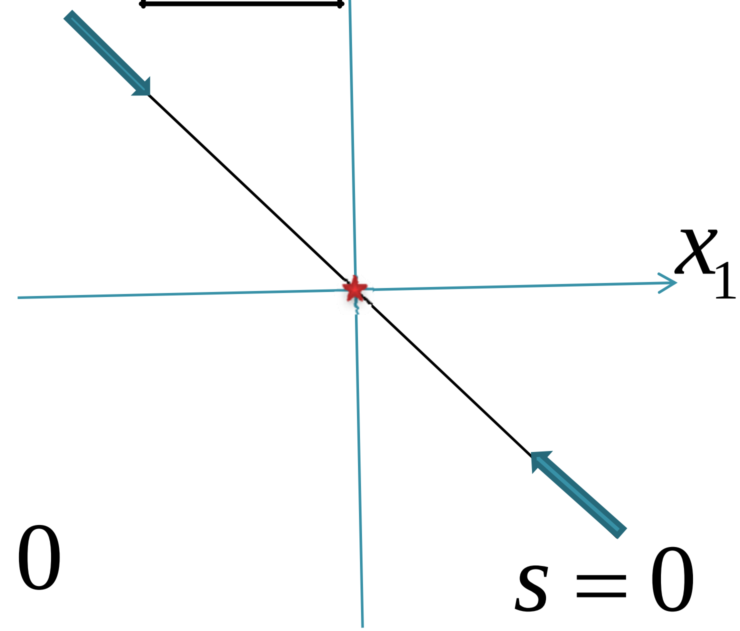
- Singular Perturbations
- Distributed Parameter Systems

A "funnel-like" domain (cont.)

disturbance

System: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 2x_1 - 3x_2 + u + \boxed{f(t)} \end{cases}$

Target: $(x_1, x_2) = (0, 0)$



<u>**Funnel:**</u> $x_2 = -x_1$

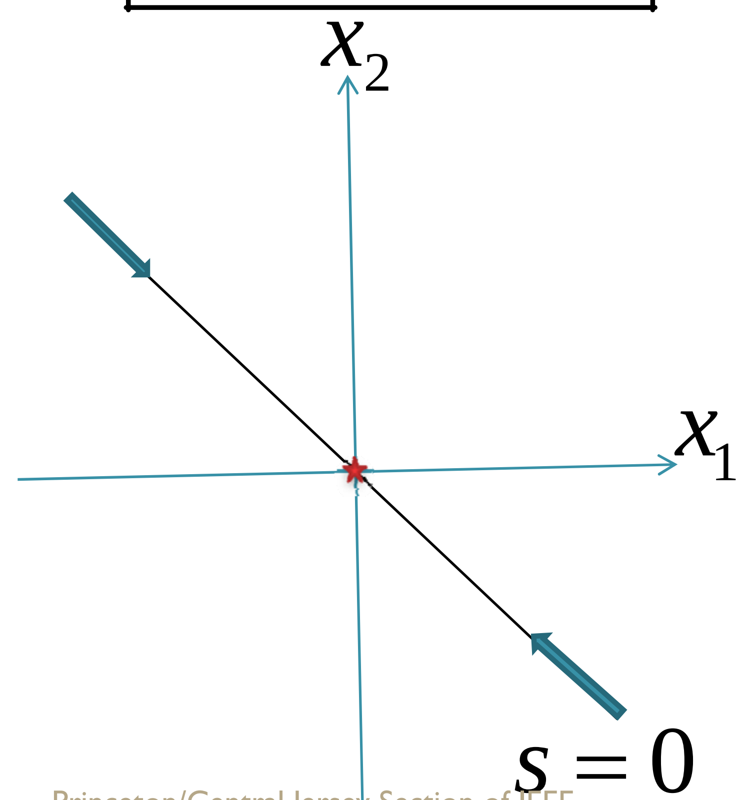
New target: $s = x_1 + x_2 = 0$

A "funnel-like" domain (cont.)

Parameter variations

System: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 2x_1 - 3x_2 + u + \boxed{(\Delta_1 x_1 + \Delta_2 x_2)} \end{cases}$

Target: $(x_1, x_2) = (0, 0)$



<u>Funnel</u>: $x_2 = -x_1$

New target: $s = x_1 + x_2 = 0$

Introduction to Sliding mode - Variable Structure Systems

$$\text{System}: \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = ax_2 - bu \end{cases}$$

(K. D. Young, 1978)

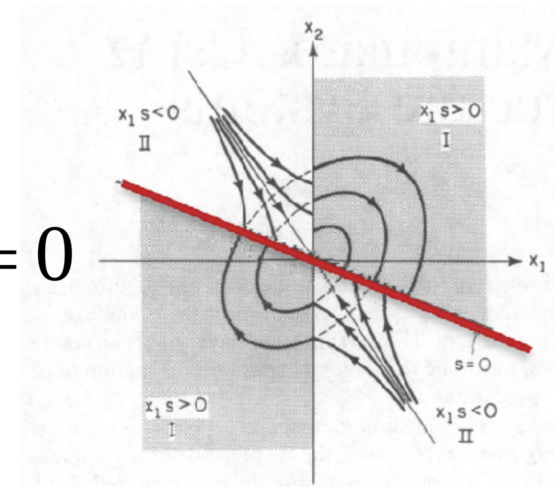


Fig. 1. Sliding mode in a second order VSS.

$$\text{Switching line}: s = cx_1 + x_2 = 0$$

(Sliding Surface)

$$\text{Control}: u = \begin{cases} \alpha x_1, & \text{if } x_1 s > 0 \text{ (region I)} \\ -\alpha x_1, & \text{if } x_1 s < 0 \text{ (rigion II)} \end{cases}$$

Introduction to Sliding mode - Variable Structure Systems

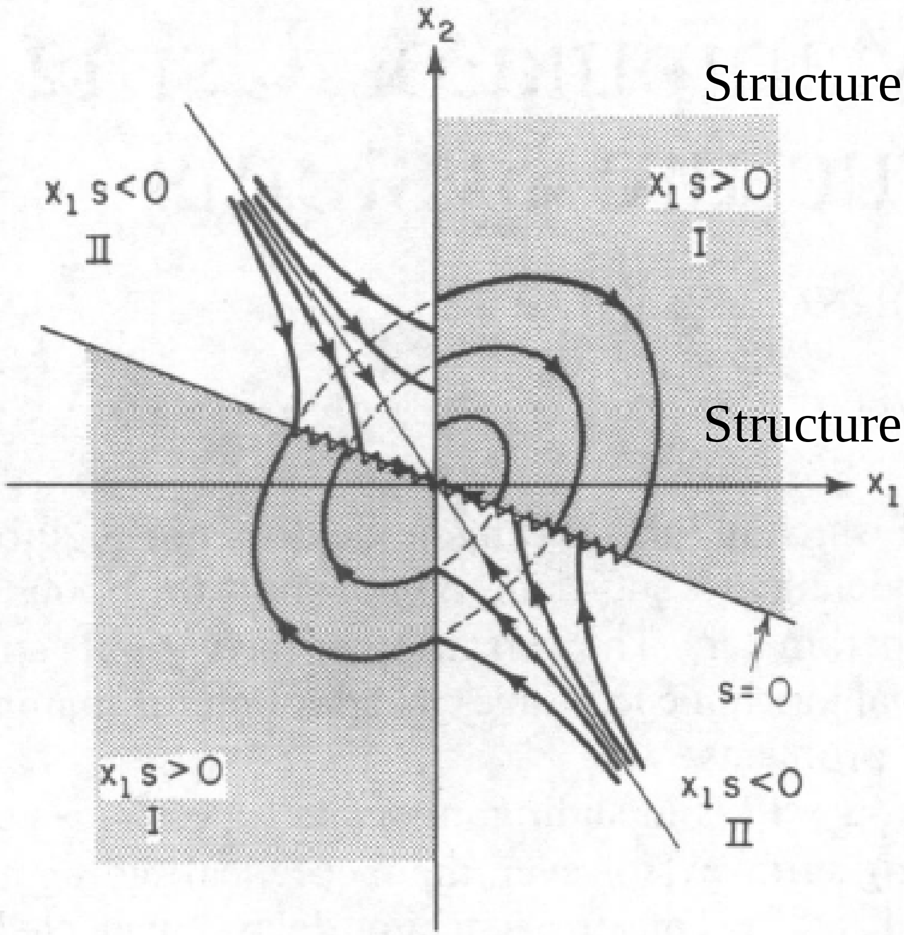


Fig. 1. Sliding mode in a second order VSS.

Structure I : $\dot{\underline{x}} = \begin{bmatrix} 0 & 1 \\ -b\alpha & a \end{bmatrix} \underline{x}$

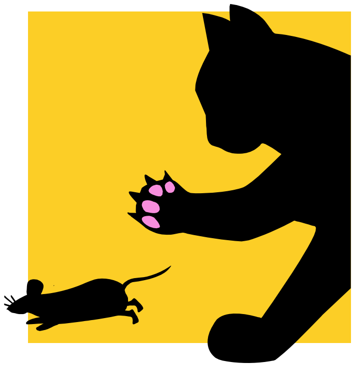
$s^2 - as + b\alpha = 0$: spiral out

Structure II : $\dot{\underline{x}} = \begin{bmatrix} 0 & 1 \\ b\alpha & a \end{bmatrix} \underline{x}$

$s^2 - as - b\alpha = 0$: saddle point

Introduction to Sliding mode - Invariance Condition

Q: Can the control law possibly reject the disturbance out of the system?



$$\dot{\underline{x}} = A\underline{x} + \begin{bmatrix} 0 & 2 \\ -1 & 1 \\ 2 & -1 \end{bmatrix} \underline{u} + \begin{bmatrix} 2 \\ -1 \\ 3 \end{bmatrix} f(t)$$

$$= A\underline{x} + \begin{bmatrix} 0 \\ -1 \\ 2 \end{bmatrix} u_1 + \begin{bmatrix} 2 \\ 1 \\ -1 \end{bmatrix} u_2 + \begin{bmatrix} 2 \\ -1 \\ 3 \end{bmatrix} f(t)$$

Introduction to Sliding mode - Invariance Condition

Control subspace: $span\left\{\begin{bmatrix}0\\-1\\2\end{bmatrix},\begin{bmatrix}2\\1\\-1\end{bmatrix}\right\}$

Disturbance subspace: $span\left\{\begin{bmatrix}2\\-1\\3\end{bmatrix}\right\}$

* The disturbance can be rejected by the control law if (and only if) **the control subspace covers the disturbance subspace.**

Introduction to Sliding mode - Invariance Condition

In this example, $\begin{bmatrix} 2 \\ -1 \\ 3 \end{bmatrix} = 2\begin{bmatrix} 0 \\ -1 \\ 2 \end{bmatrix} + \begin{bmatrix} 2 \\ 1 \\ -1 \end{bmatrix}$

If $d(t)$ is known, then the control law

$$u_1 = v_1 - 2f(t)$$
$$u_2 = v_2 - f(t)$$

Will lead to

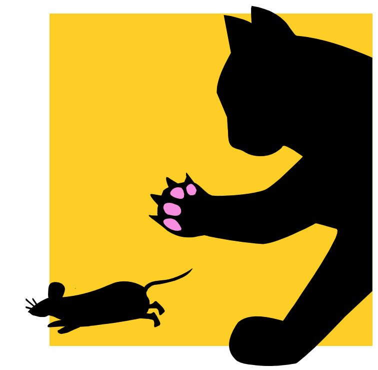
$$\dot{x} = Ax + \begin{bmatrix} 0 \\ -1 \\ 2 \end{bmatrix} v_1 + \begin{bmatrix} 2 \\ 1 \\ -1 \end{bmatrix} v_2 + (-2\begin{bmatrix} 0 \\ -1 \\ 2 \end{bmatrix} - \begin{bmatrix} 2 \\ 1 \\ -1 \end{bmatrix}) f(t) + \begin{bmatrix} 2 \\ -1 \\ 3 \end{bmatrix} f(t) = Ax + \begin{bmatrix} 0 & 2 \\ -1 & 1 \\ 2 & -1 \end{bmatrix} \underline{v}$$

Introduction to Sliding mode - Invariance Condition

(Drazenovic, 1969):

The system with disturbance

$$\dot{x} = Ax + Bu + Ef(t)$$



is invariant of $f(t)$ in sliding mode $s \equiv 0$ iff

$$rank\left[B \mid E\right] = rank\left[B\right].$$

In the previous example,

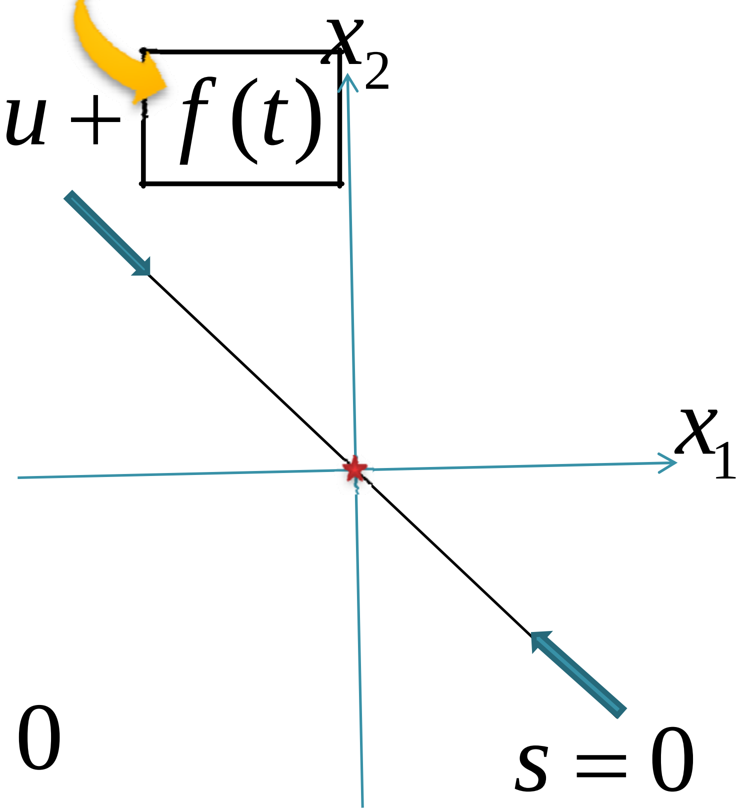
$$rank\left[\begin{array}{cc|c} 0 & 2 & 2 \\ -1 & 1 & -1 \\ 2 & -1 & 3 \end{array}\right] = rank\begin{bmatrix} 0 & 2 \\ -1 & 1 \\ 2 & -1 \end{bmatrix} = 2.$$

A “funnel-like” domain (revisit)

disturbance

System: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 2x_1 - 3x_2 + u + \boxed{f(t)} \end{cases}$

Target: $(x_1, x_2) = (0, 0)$



<u>Funnel:</u> $x_2 = -x_1$

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A “funnel-like” domain (revisit)

Parameter variations

System: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 2x_1 - 3x_2 + u + \boxed{(\Delta_1 x_1 + \Delta_2 x_2)} \end{cases}$

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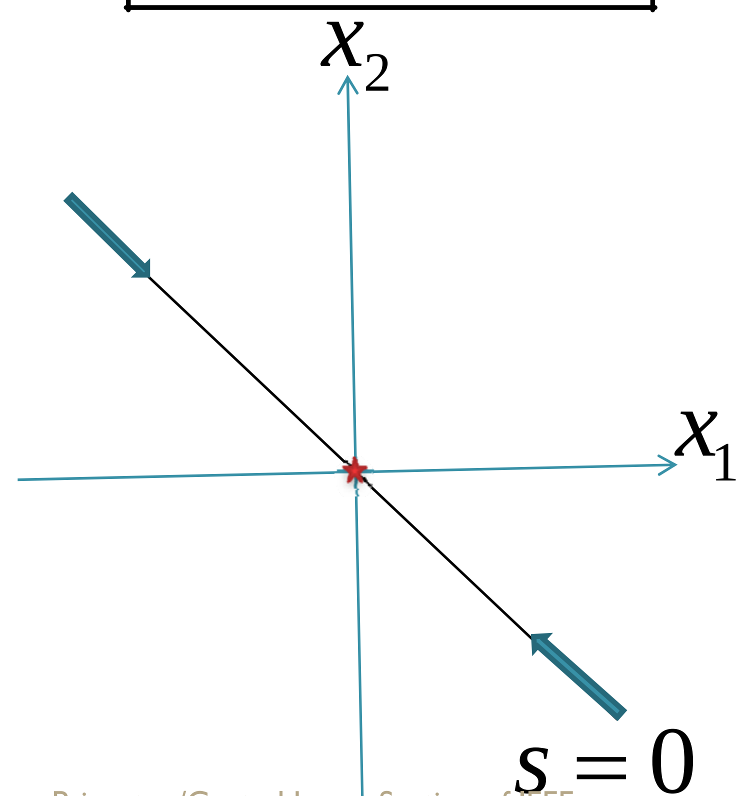


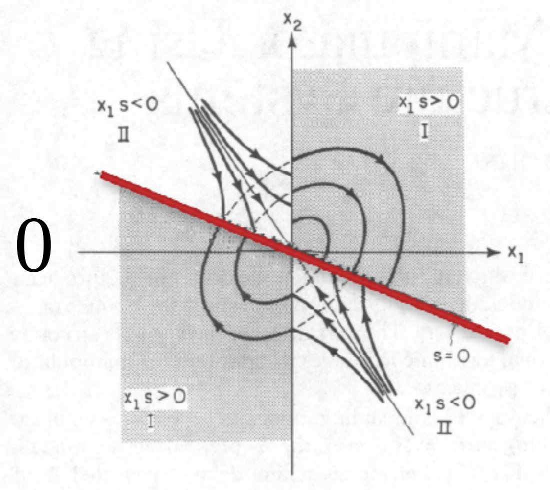
<u>Funnel</u>: $x_2 = -x_1$

New target: $s = x_1 + x_2 = 0$

VSS Design

$$\text{System}: \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = ax_2 - bu \end{cases}$$

(K. D. Young, 1978)



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(Sliding Surface)

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VSS Design

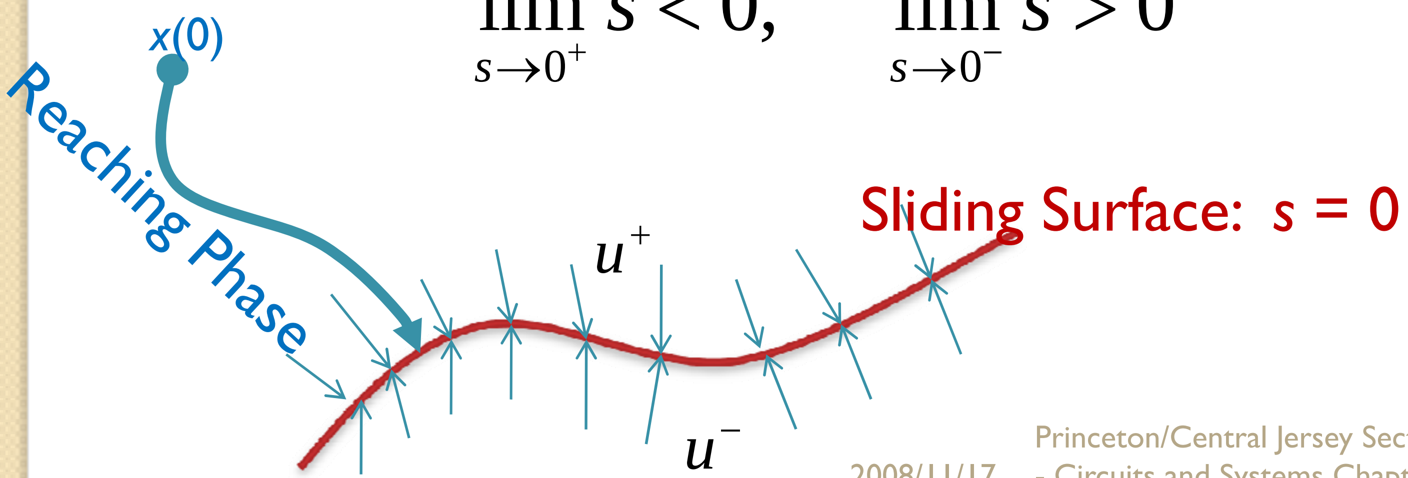
Existence of sliding mode

i. Reaching condition (sufficient, global)

$$\dot{s} < -\sigma \operatorname{sgn}(s), \quad \sigma > 0$$

ii. Sliding condition (sufficient, local)

$$\lim_{s \to 0^+} \dot{s} < 0, \qquad \lim_{s \to 0^-} \dot{s} > 0$$



VSS Design

Finite time reaching: $\dot{s} < -\sigma \operatorname{sgn}(s), \quad \sigma > 0$

Lyapunov function

$$V = s^2$$

$$\frac{dV}{dt} = 2s\dot{s} = -2\sigma |s| < 0$$

$$\therefore \quad s(x) \to 0$$

Reaching time $T < \dfrac{\sqrt{V(0)}}{\sigma} = \dfrac{|s(0)|}{\sigma}$

VSS Design

A heuristic example

$$(D^3 + a_3 D^2 + a_2 D + a_1) y(t) = (b_3 D^2 + b_2 D + b_1)(u + f(t)), \quad D = \frac{d}{dt}$$

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -a_1 & -a_2 & -a_3 \end{bmatrix} \underline{x} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} f(t)$$

$$y = \begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix} \underline{x}$$

(i) Sliding surface $s(\underline{x}) = x_3 + c_2 x_2 + c_1 x_1 = 0$

Sliding mode dynamics:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \end{cases}, \text{ with } x_3 = -c_1 x_1 - c_2 x_2 .$$

VSS Design

(ii) $$\frac{ds(x)}{dt}=\frac{\partial s}{\partial x}\frac{dx}{dt}$$

$$\dot{s}=\dot{x}_3+c_2\dot{x}_2+c_1\dot{x}_1$$

$$=-a_1x_1-a_2x_2-a_3x_3+u+f(t)+c_2x_3+c_1x_2$$

(iii) Discontinuous control

$$u=a_1x_1+(a_2-c_1)x_2+(a_3-c_2)x_3-(f_{\max}+\sigma)\operatorname{sgn}(s)$$

- Reaching condition $\dot{s}<-\sigma\operatorname{sgn}(s), \quad \sigma>0$ satisfied if $|f(t)|<f_{\max}$.

VSS Design

Two steps in VSS design

$$\underline{\dot{x}} = \underline{f}(\underline{x}, u, t)$$

1. Choose **sliding surface**

$$s(\underline{x}) = 0$$

2. Design **discontinuous control** to render sliding mode

$$\underline{\dot{x}} = \begin{cases} \underline{f}(\underline{x}, u^{+}, t) = \underline{f}^{+}, & s > 0 \\ \underline{f}(\underline{x}, u^{-}, t) = \underline{f}^{-}, & s < 0 \end{cases}$$

VSS Design

- Sliding Surface

$$\underline{\dot{x}} = A\underline{x} + B\underline{u} + Df(t)$$

Eigenspace Approach *v.s.* Lyapunov Approach

Nonsingular transformation

$$TB = \begin{bmatrix} 0_{(n-m)\times m} \\ B_2 \end{bmatrix}, \quad T\underline{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Canonical form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} u + \begin{bmatrix} 0 \\ D_2 \end{bmatrix} f(t)$$

Sliding surface

$$x_2 = -Kx_1, \text{ or } \; s(\underline{x}) = [K \quad \mathrm{I}_{m\times m}]T\underline{x}$$

Stabilizing feedback

$$\underline{\dot{x}} = A\underline{x} - BK\underline{x} + Df(t)$$

Lyapunov function

$$PA_s + A_s^T P = -Q$$

$$V(\underline{x}) = \frac{1}{2}\underline{x}^T P\underline{x}$$

Sliding surface

$$s(\underline{x}) = B^T P\underline{x}$$

VSS Design
- Discontinuous Control

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} + Df(t)$$

$$\text{sliding surface: } s(\underline{x}) = C\underline{x} = 0$$

$$\dot{s} = CA\underline{x} + CB\underline{u} + CDf(t)$$

Signum function

(Single-input case)

$$u = -(CB)^{-1}CAx - (CB)^{-1}(\sigma + d_{\max})\operatorname{sgn}(s)$$

v.s.

Unit Control

(Multi-input case)

$$u = -(CB)^{-1}CAx - (CB)^{-1}(d_{\max} + \sigma)\cdot\frac{s}{\|s\|}$$

Discrete-Time Sliding Mode

Continuous-time

$$\dot{x} = Ax + Bu + Df(t)$$

Sliding surface: $s(t) = Cx(t) = 0$

Sampled-data

$$x_{k+1} = \Phi x_k + \Gamma u_k + d_k$$

Sliding surface: $s_k = Cx_k = 0$

$$\Phi = e^{AT},\ \Gamma = \int_0^T e^{A\tau} d\tau B,$$

$$d_k = \int_{kT}^{(k+1)T} e^{A(t-\tau)} Df(\tau) d\tau = \int_0^T e^{A\lambda} Df((k+1)T - \lambda) d\lambda$$

Discrete-Time Sliding Mode

$$x_{k+1} = \Phi x_k + \Gamma u_k + d_k$$

$$\Gamma = \int_0^T e^{A\lambda} d\lambda B, \;\; d_k = \int_0^T e^{A\lambda} Df((k+1)T - \lambda) d\lambda$$

Issues on disturbance rejection:

1. Matching condition fails $d_k \notin \text{range}(\Gamma)$

   However, $d_k = \Gamma f(kT) + O(T^2)$

2. Non-causal disturbances

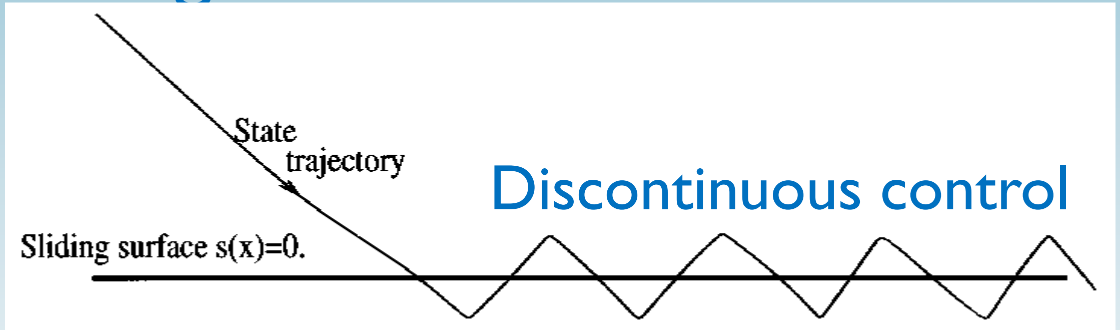
   However, $d_k = d_{k-1} + O(T^2)$

$$d_{k-1} = x_k - \Phi x_{k-1} - \Gamma u_{k-1}$$

Ultimate achievable accuracy: $O(T^2)$

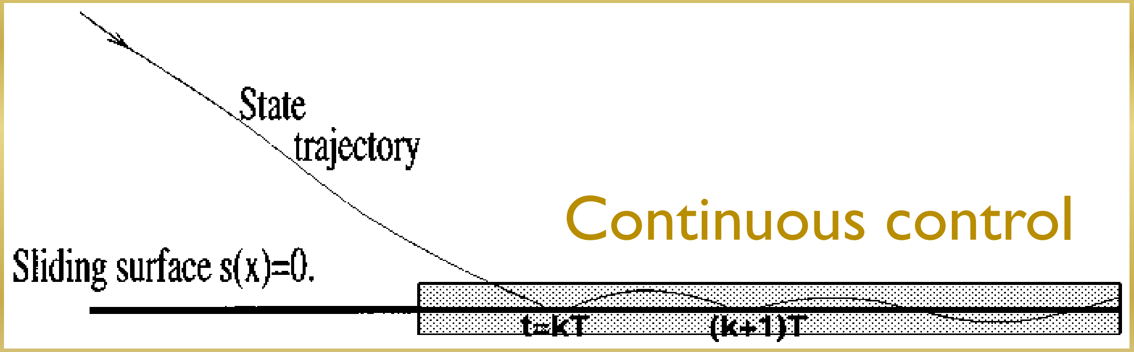
Discrete-Time Sliding Mode

Quasi-sliding mode $s_k = O(T), \quad s(t) = O(T)$



Discontinuous control

Discrete-time sliding mode $s_k = 0, \;\; s(t) = O(T^2)$



Continuous control

Discrete-Time Sliding Mode

Ukin's discrete-time equivalent control

(Continuous control law)

$$s_{k+1} = C\Phi x_k + C\Gamma u_k + Cd_k = 0$$

$$u_k^{eq} = -(C\Gamma)^{-1} C(\Phi x_k + d_k)$$

Discrete-time $O(T^2)$ sliding mode control

(Modification of u_k^{eq})

$$u_k = -(C\Gamma)^{-1} C(\Phi x_k + d_{k-1})$$

$$\Rightarrow s_{k+1} = C(d_k - d_{k-1}) = O(T^2)$$

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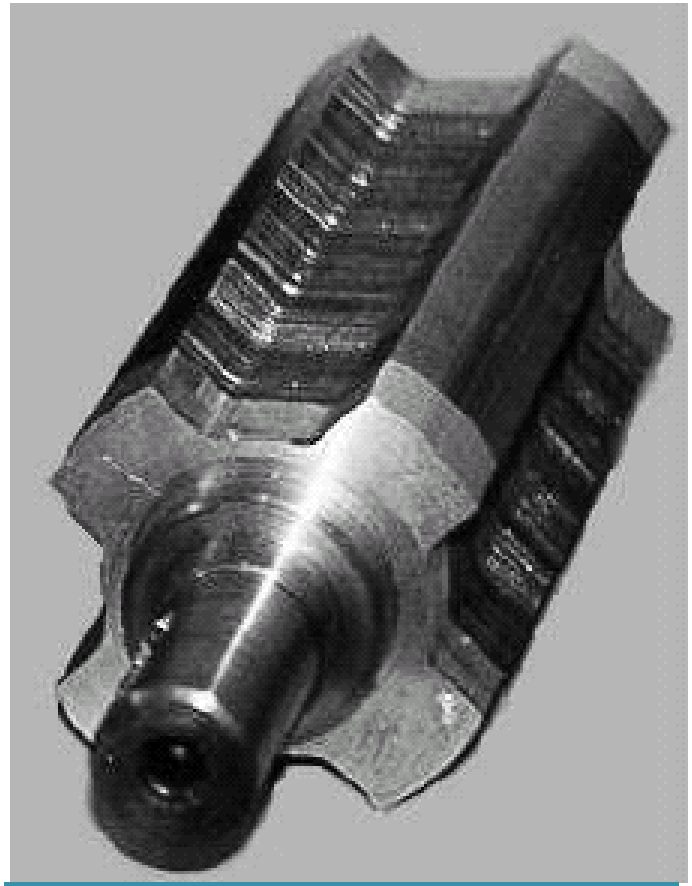
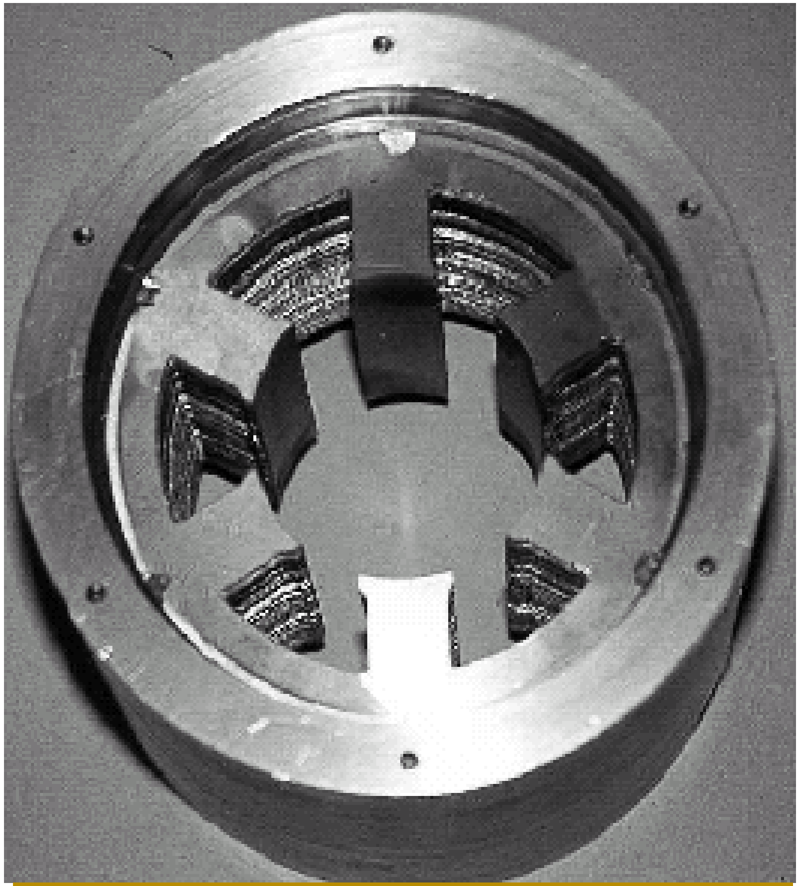
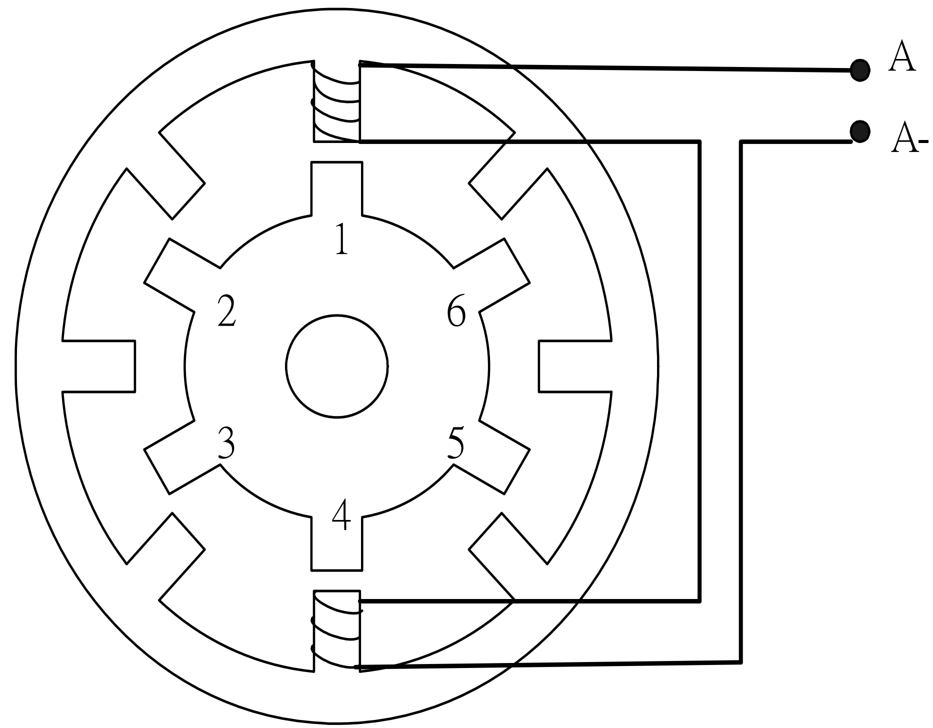
Switched Reluctance Motors


Rotor

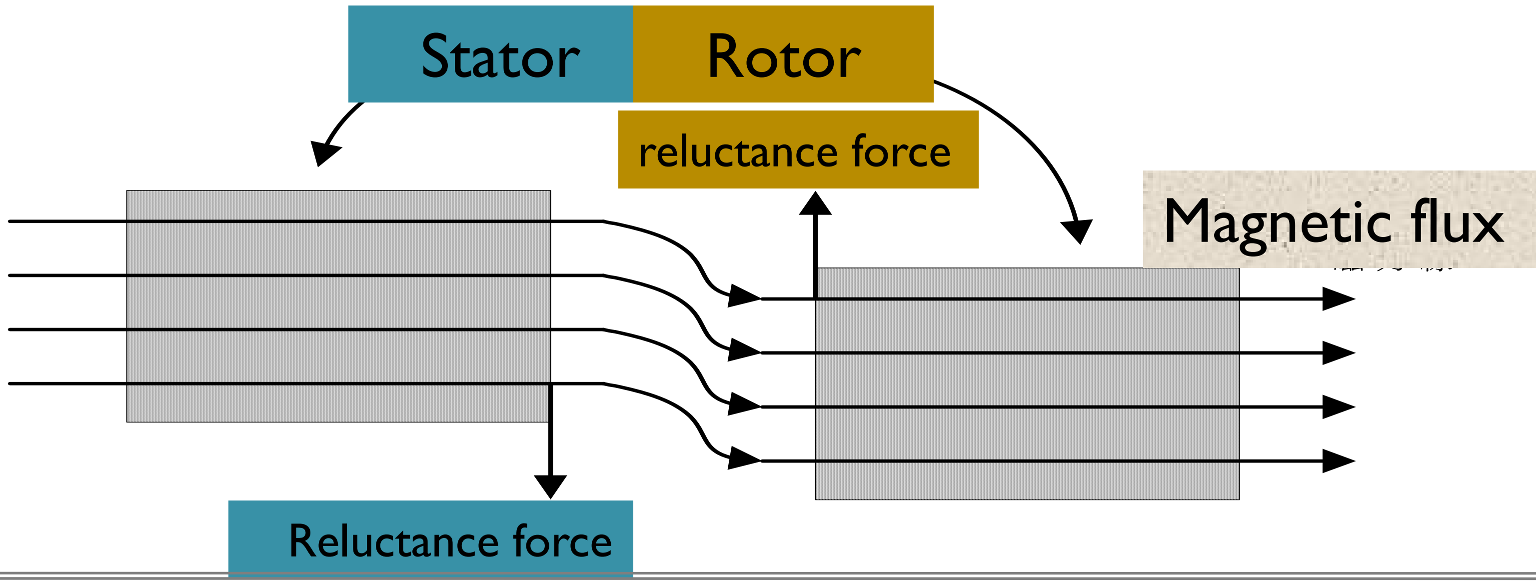

Stator

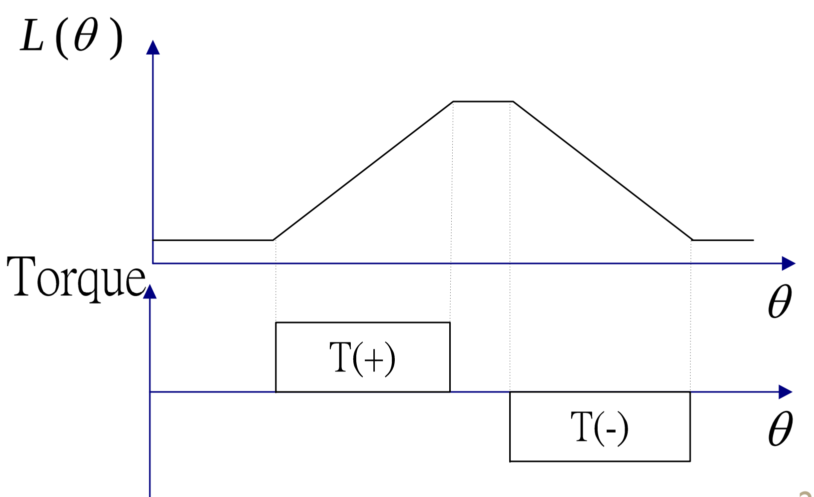
Switched Reluctance Motors

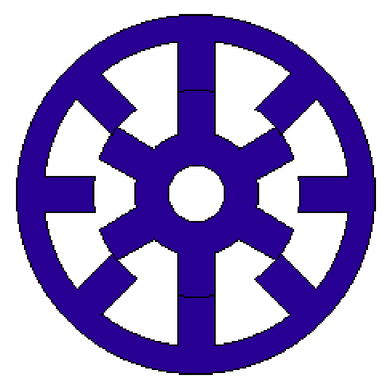


4-phase, 8/6-pole SRM

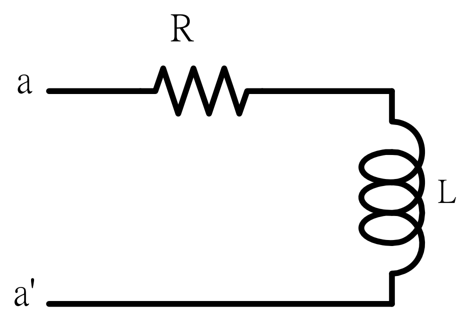
Switched Reluctance Motors

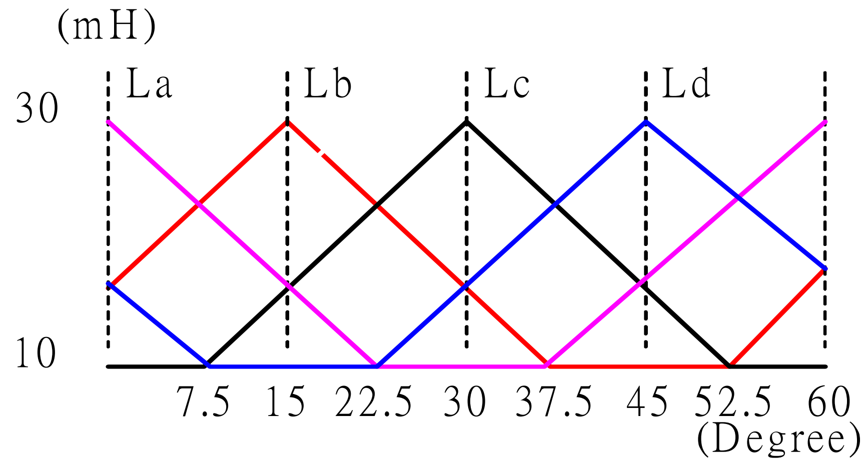






Switched Reluctance Motors

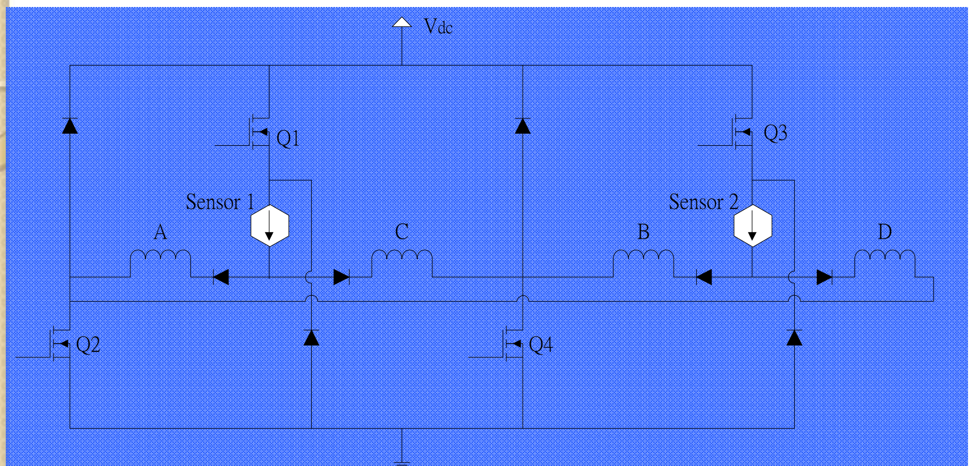




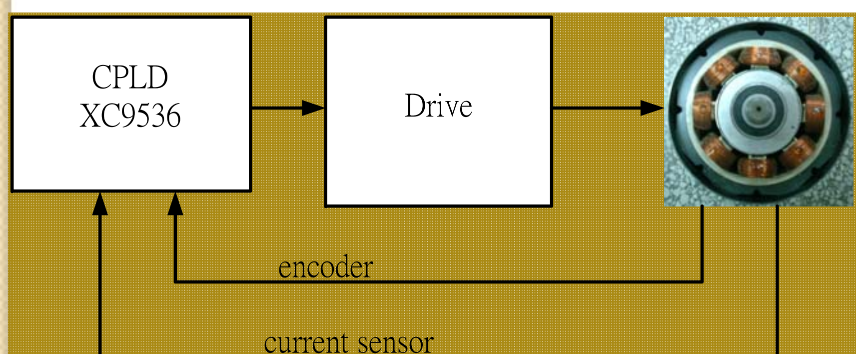
$$V_j = L_j(\theta)\frac{di_j}{dt} + \frac{dL_j(\theta)}{dt} i_j + R_j i_j, \quad j = A, B, C, D$$

$$\text{Torque} \propto i^2 : \; T_j = \frac{1}{2}\frac{dL_j(\theta)}{d\theta} i_j^2$$

Minimum-Time Torque Control



Drive Circuit



Control System Setup

System dynamics:

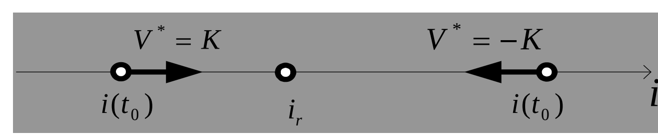
$$\frac{di}{dt} = -A(\theta,\omega)i + B(\theta)V(t)$$

Sliding surface:

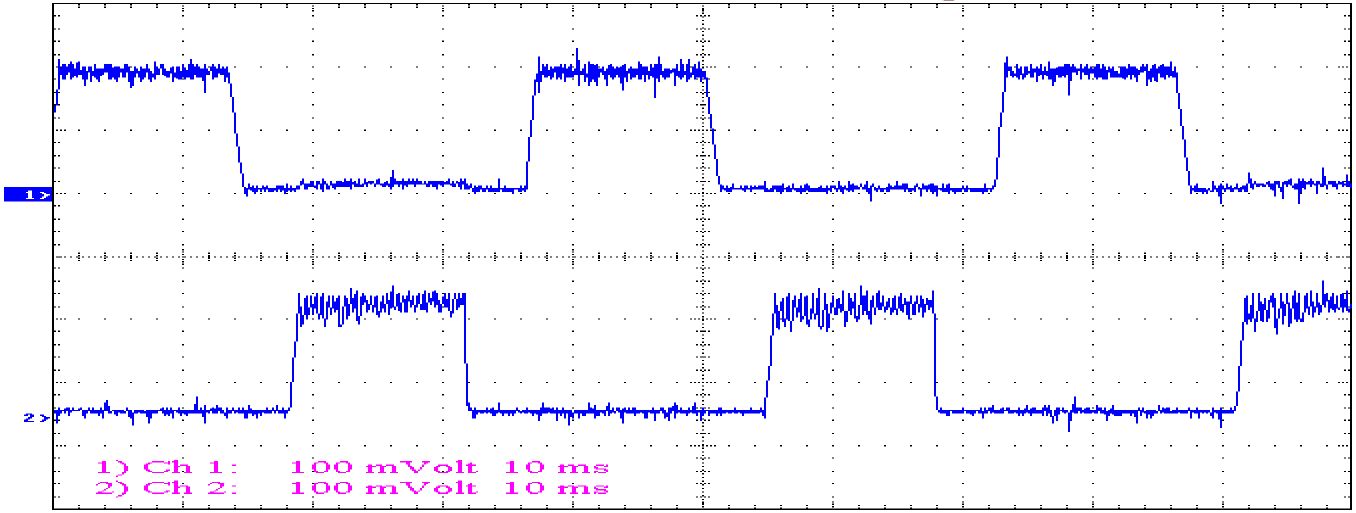
$$s = i - i_r = 0$$

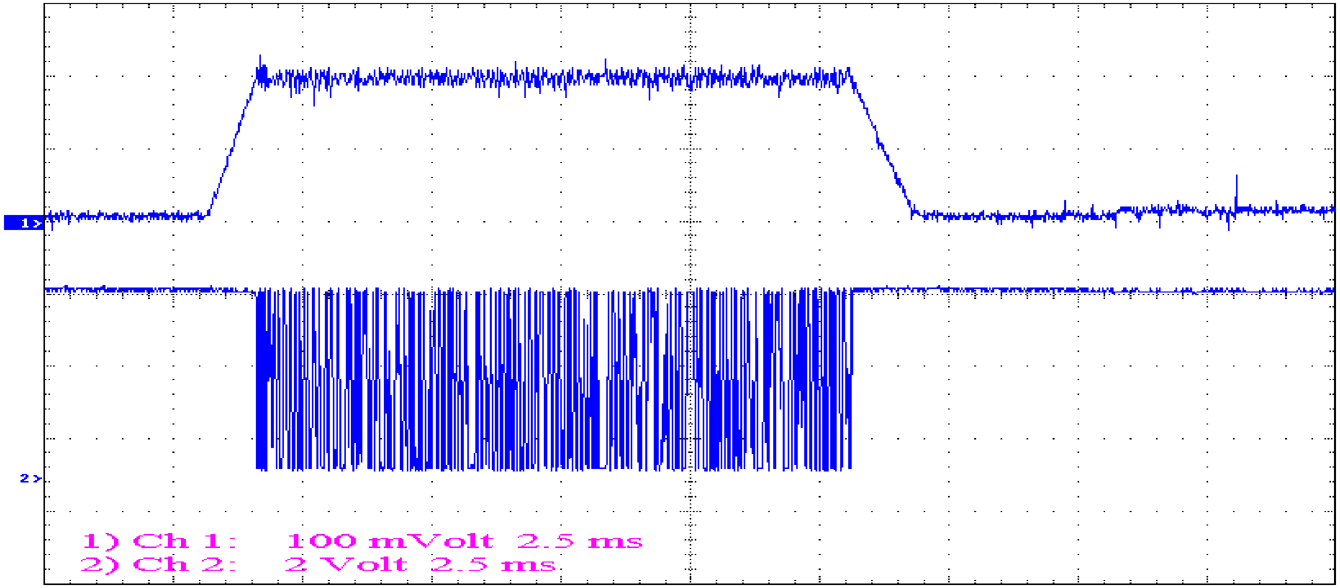
Minimum-Time VSC:

$$V(t) = \begin{cases} -V_{dc},\ if\ \ i(t) > i_r \\ V_{dc},\ if\ \ i(t) < i_r \end{cases}$$

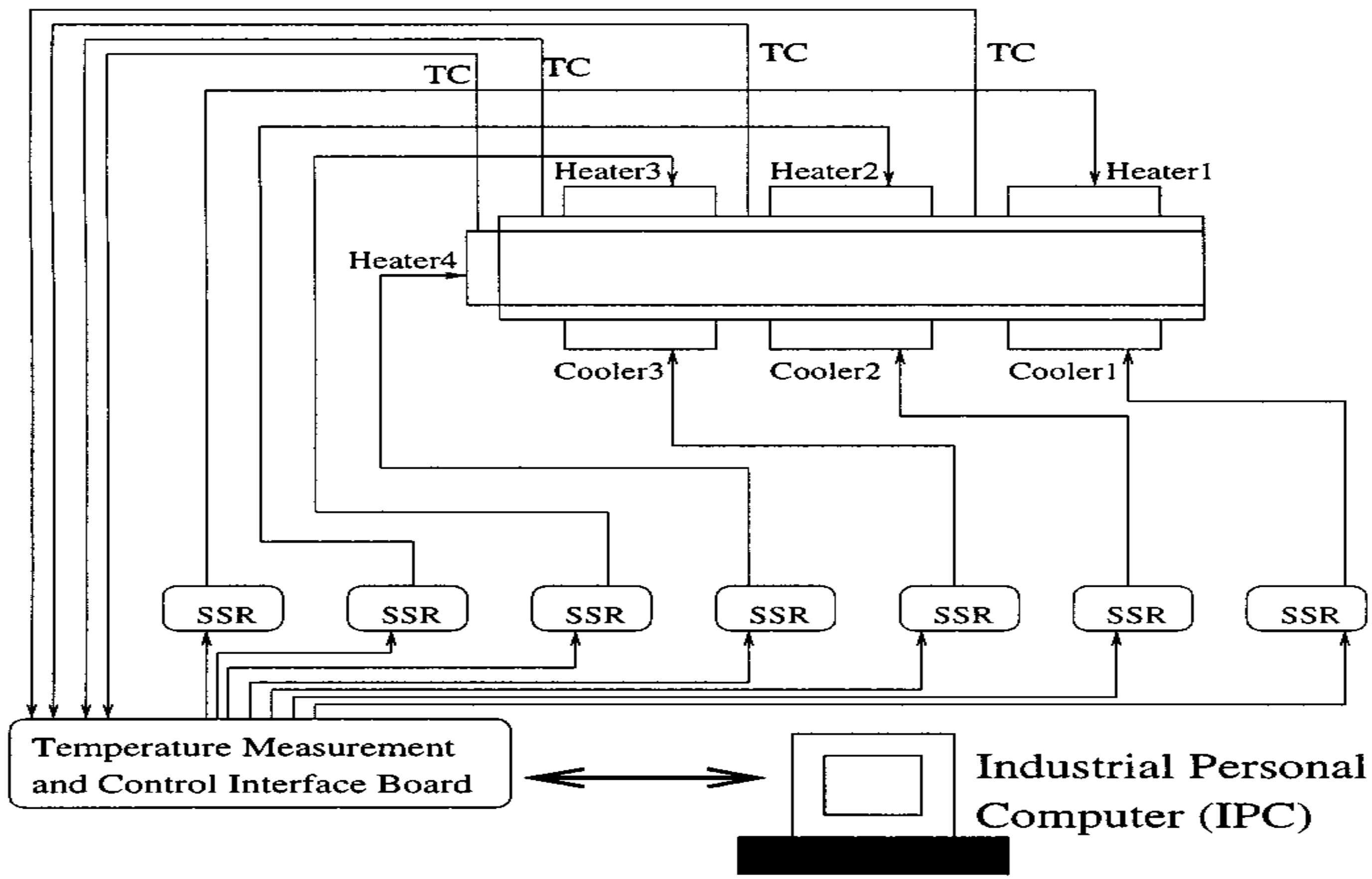


Minimum-Time Torque Control





Temperature Control
- A Plastic Extrusion Process



System setup: ITRI (Industrial Technology Research Institute), Taiwan, R.O.C.

Temperature Control
- A Plastic Extrusion Process

Dynamics of Channel temperature:

$$\frac{dy}{dt} = -\frac{hA}{\rho c V} y + \frac{hA}{\rho c V} y_\infty + \frac{1}{\rho c V} w$$

Rate of change of energy input:

$$\frac{dw}{dt} = a(w,u,t) = \begin{cases} a^+(w,u,t), u \geq 0 \\ a^-(w,u,t), u < 0 \end{cases}$$

Single-channel dynamics:

$$\dot{y} = -my + v$$

$$\dot{v} = \frac{a(w,u,t)}{\rho c V} + \xi$$

Temperature Control
- A Plastic Extrusion Process

Single-channel dynamics:

$$\dot{y} = -my + v$$

$$\dot{v} = \frac{a(w,u,t)}{\rho c V} + \xi$$

Sliding surface (PI control):

$$\dot{v} = -K_P \dot{e} - K_I e \quad or \quad V(s) = (K_P + \frac{K_I}{s})(y_{desired}(s) - Y(s))$$

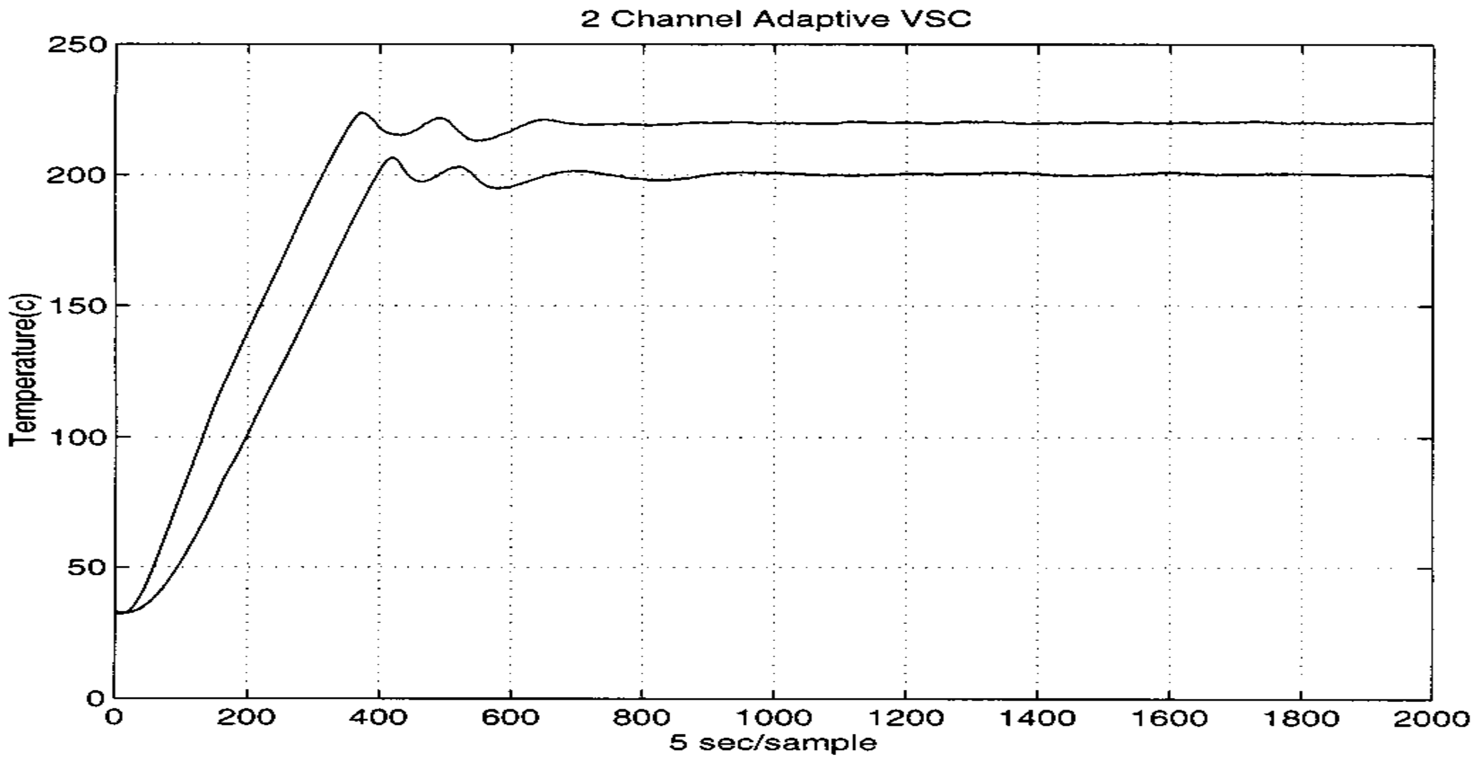
Output feedback sliding mode control

$$s = \ddot{e} + (K_P + m)\dot{e} + K_I e$$

$$s_k \approx a_1 s_{k-1} + b_0 e_k + b_1 e_{k-1}$$

Temperature Control
- A Plastic Extrusion Process

Switching control law: $u_k = \begin{cases} \text{heat}, & s_k < 0 \\ \text{water}, & s_k > 0 \end{cases}$



Rod-less Pneumatic Cylinder Servo

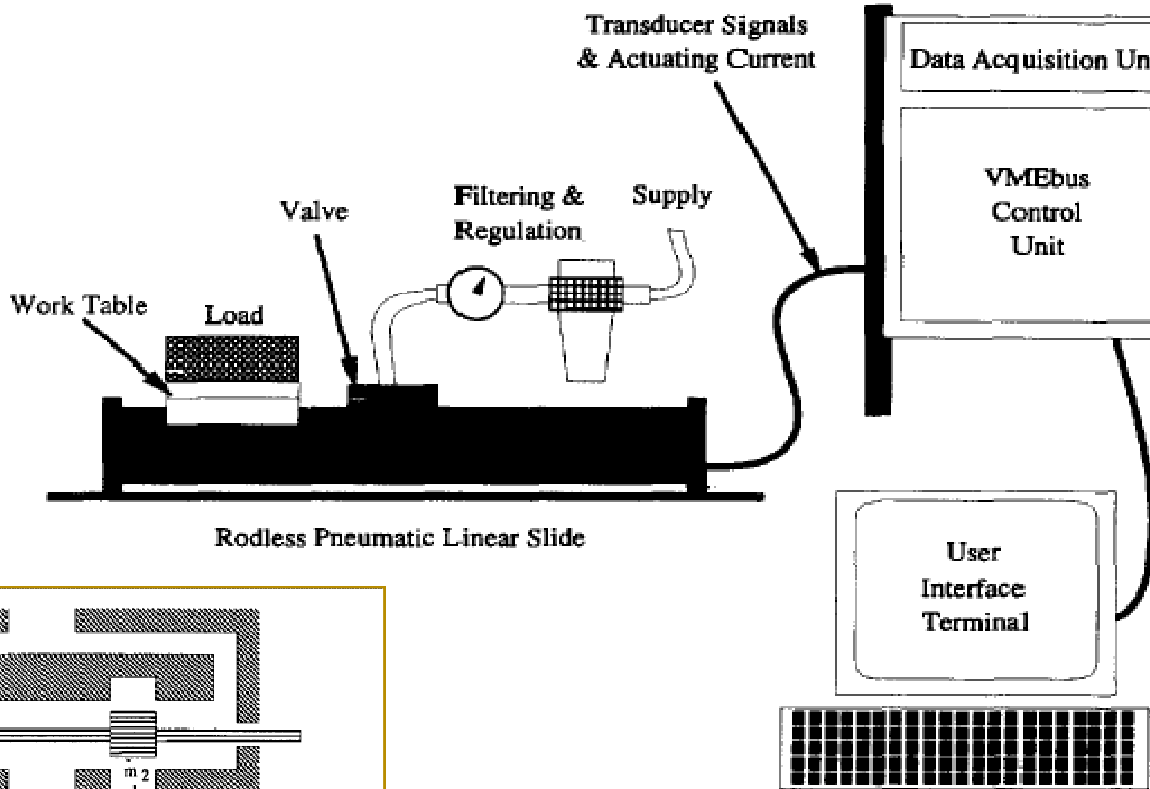


Fig. 1. General hardware layout.

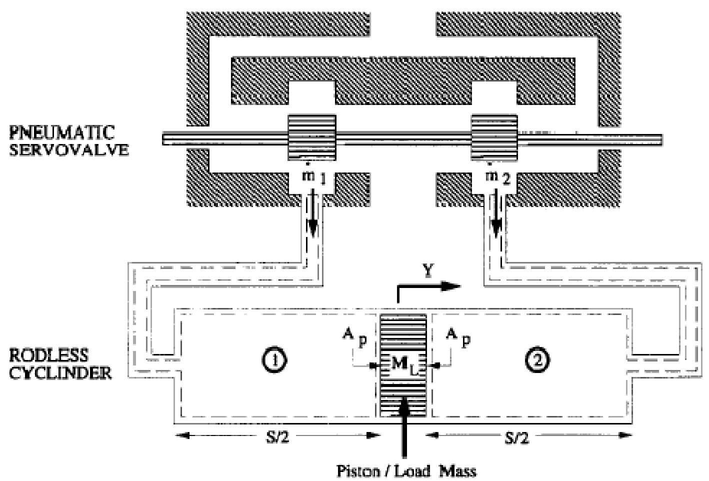


Fig. 2. Schematic of a rodless cylinder.

Rod-less Pneumatic Cylinder Servo

Equation of motion:

$$M_L \ddot{Y} = -\mu_u \dot{Y} - \mu_c \operatorname{sgn} \dot{Y} + A_T \Delta P$$

Pressure dynamics:

$$\Delta \dot{P} = \psi_1(P_1, P_2, Y, X)X + \psi_2(P_1, P_2, Y, \dot{Y}, X)$$

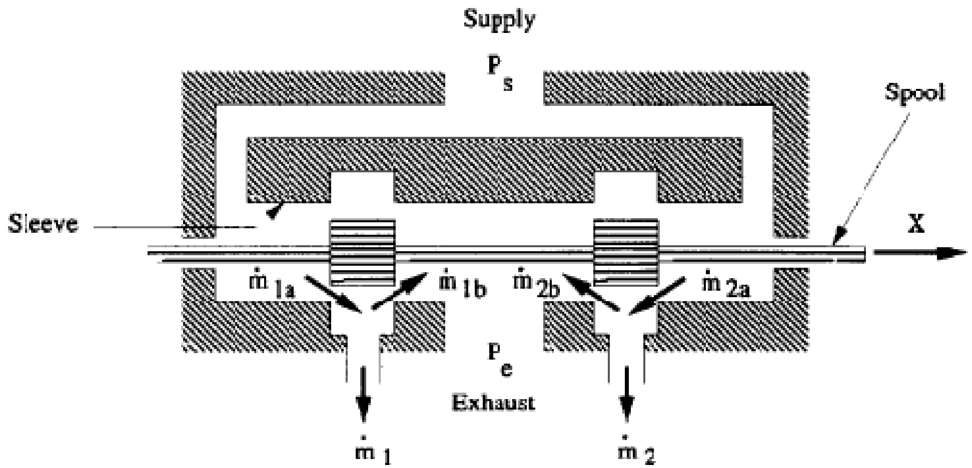


Fig. 3. Schematic of a four-way servovalve.

Rod-less Pneumatic Cylinder Servo

Sliding surface:

$$\sigma = \Delta P - \frac{M_L}{A_T}\left[\ddot{Y}_d + k_1(\dot{Y}_d - \dot{Y}) + k_2(Y_d - Y)\right] + \frac{1}{A_T}\left[\mu_u \dot{Y} + \mu_c \operatorname{sgn} \dot{Y}\right]$$

Variable Structure Control: $X = -X_v \operatorname{sgn}(\sigma)$

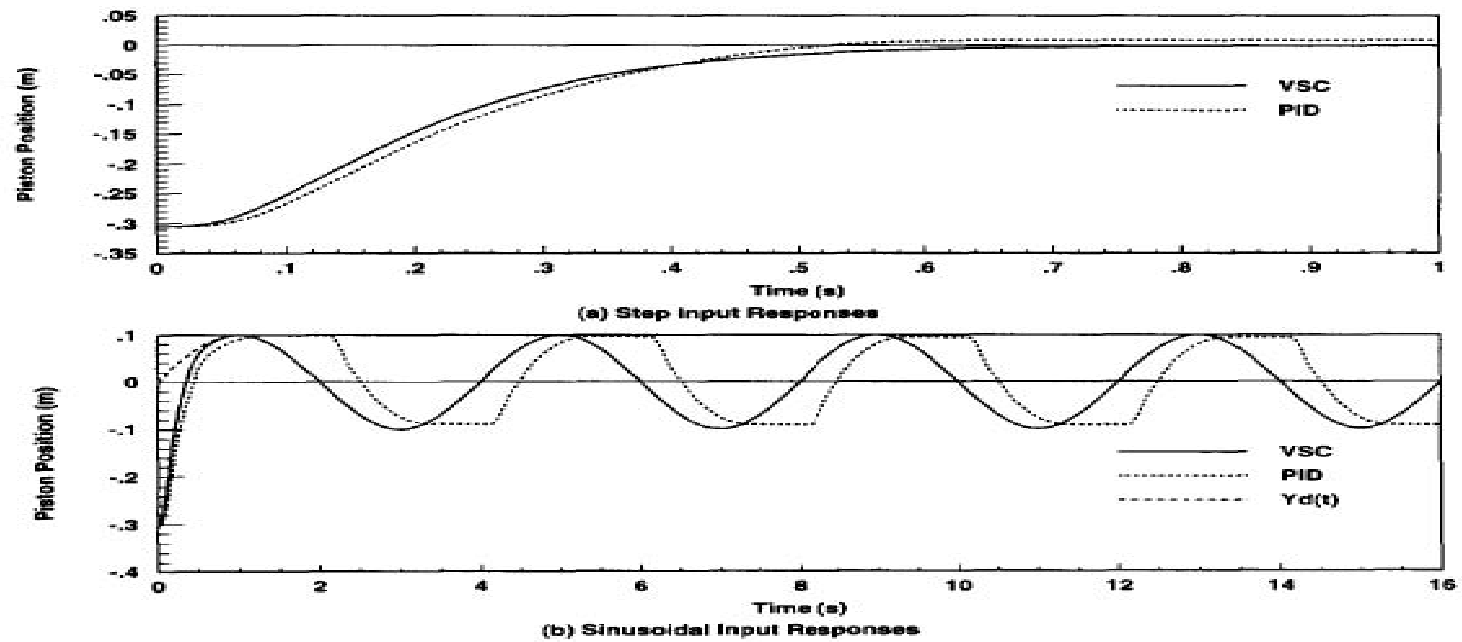
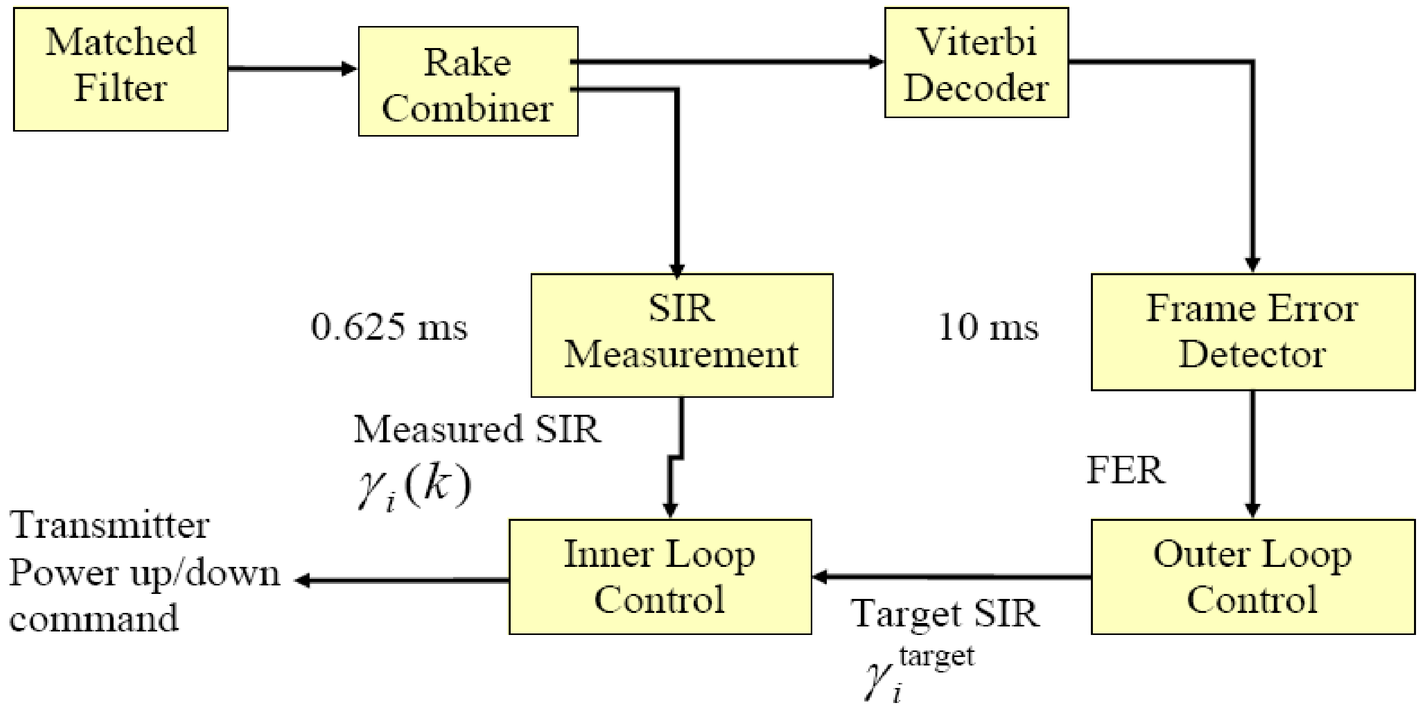


Fig. 8. Comparison of variable-structure control and classic PID control.

Wireless Network Power Control



Base Station Behavior

Zoran Gajic, Plenary Lecture 2007 CACS International Automatic Control Conference National Chung Hsing University, Taichung, Taiwan, November 9-11, 2007

Wireless Network Power Control

Signal-to-interference ratio (SIR) for the *i*th user

$$\bar{\gamma}_i(t) = \frac{\bar{g}_{ii}(t)\bar{p}_i(t)}{\bar{I}_i(t)} = \frac{\bar{g}_{ii}(t)\bar{p}_i(t)}{\sum_{j\neq i}\bar{g}_{ij}(t)\bar{p}_j(t)+\bar{\upsilon}_i(t)}, \; i=1,2,\cdots,N.$$

Control objective: $\bar{\gamma}_i(t) \to \bar{\gamma}_i^{tar}$

Logarithmic scale representation

$$\gamma_i = g_{ii} + p_i - I_i(p_{-i})$$

System dynamics:

$$\dot{p}_i(t) = u_i(t), \quad i=1,2,\cdots N$$

$$\gamma_i(t) = p_i(t) + f_i(t)$$

Wireless Network Power Control

Sliding surface $s_i(t) = \gamma_i(t) - \gamma_i^{tar} = 0$

Discrete-time representation

$$s_i(k+1) = s_i(k) + Tu_i(k) + d(k) + v(k)$$

Discrete-time SMC (continuous)

$$u_i(k) = -\frac{1}{T}s_i(k) - \frac{1}{T}(d(k-1) + v(k-1))$$

Stability analysis

$$\begin{bmatrix} s_i(k+1) \\ u_i(k+1) \end{bmatrix} = \begin{bmatrix} 1 & T \\ -\frac{1}{T} & -1 \end{bmatrix} \begin{bmatrix} s_i(k) \\ u_i(k) \end{bmatrix} - \begin{bmatrix} 1 \\ 2 \end{bmatrix} \frac{1}{T}(d(k) + v(k))$$

$$\boxed{\det \begin{bmatrix} z-1 & -T \\ \frac{1}{T} & z+1 \end{bmatrix} = z^2 = 0}$$

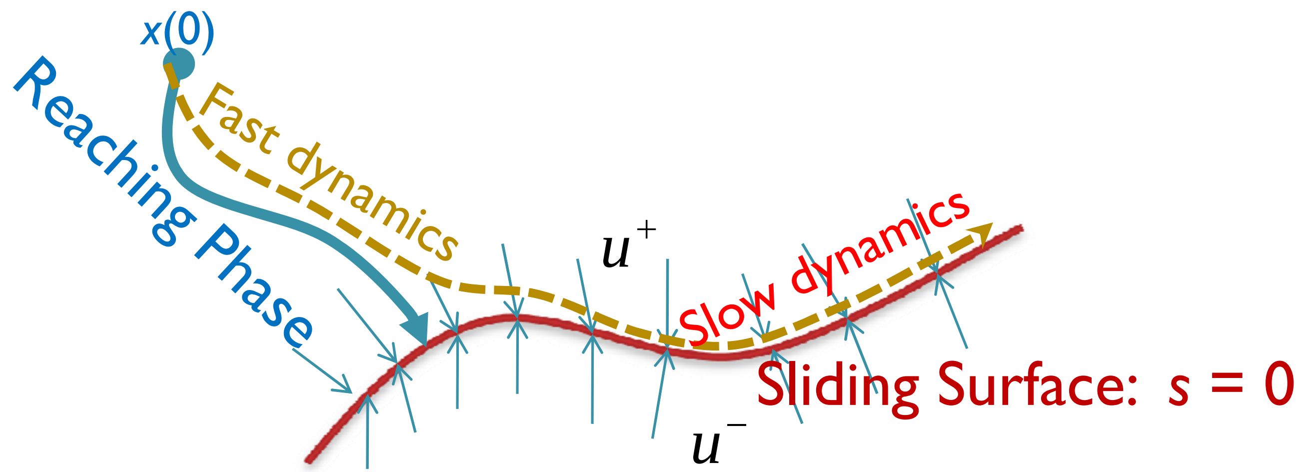
Contents (2/2)

- Minimum-Time Torque Control (SRM)
- Temperature Control (Plastic Extrusion P.)
- Rod-less Pneumatic Cylinder Servo
- Wireless Network Power Control

- Singular Perturbations
- Distributed Parameter Systems

Extended Research Problems

- Singular Perturbations



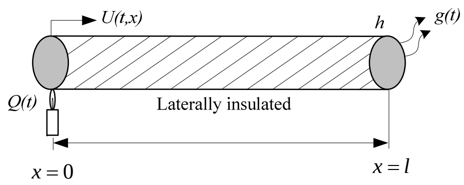
Singularly Perturbed Systems	VSS
Quasi-steady state (slow mode)	Sliding mode
Fast mode	Reaching phase
Continuous control	Discontinuous control
Infinite-time reaching (boundary layer)	Finite-time reaching

Extended Research Problems

- Distributed Parameter Systems

Heat Conduction System:

$$U_t(x,t) = \alpha U_{xx}(x,t) + \beta U(x,t)$$



Boundary conditions $U(0,t) = 0$

$$U(l,t) = Q(t) + f(t)$$

Kernel function

$k(x,y)$

$U(x,t)$

$w(x,t)$

$$w_t = \alpha w_{xx} - cw$$

$$w(0,t) = 0$$

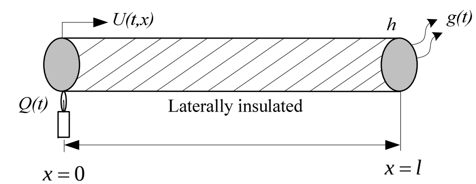
$$w(l,t) = Q(t) + f_w(t)$$

Extended Research Problems

- Distributed Parameter Systems

Sliding surface:

$$S(t) = \omega_x(l,t) = 0$$



$$\text{Kernel function}: k(x,y) = -\lambda y \frac{I_1\left(\sqrt{\lambda(x^2-y^2)}\right)}{\sqrt{\lambda(x^2-y^2)}}$$

$$U(x,t) \longrightarrow w(x,t)$$

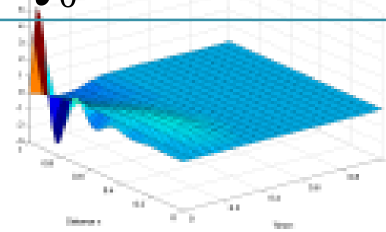
$$w_t = \alpha w_{xx} - cw$$
$$w(0,t) = 0$$
$$w(l,t) = Q(t) + f_w(t)$$

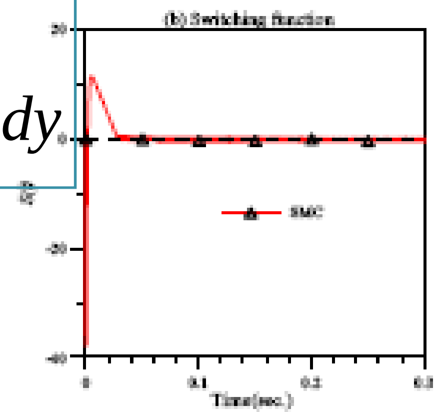
Extended Research Problems

- Distributed Parameter Systems

Sliding surface: $S(t) = w_x(l,t) = 0$

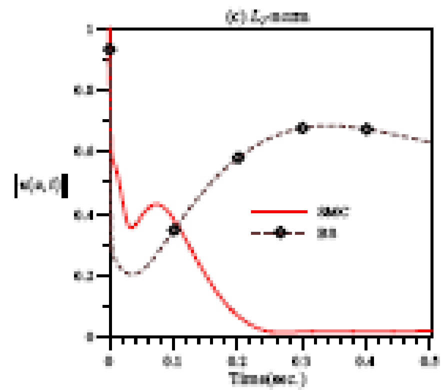
$$S(t) = U_x(l,t) - k(l,l)U(l,t) - \int_0^l k_x(l,y)U(y,t)dy$$

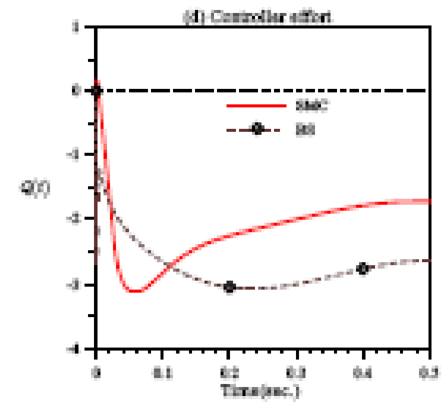




Sliding Mode Control:

$$Q(t) = -K_m \int_0^t \mathrm{sgn}(S(\tau))d\tau$$





Conclusions

- Merits of VSS
  - Robustness (against disturbances and system parameter variations)
  - Reduced-order system design
  - Simple control structure
  - Fits switching power electronics control

Conclusions

- Chattering Reduction (Elimination)
  - Discrete-Time Sliding Mode
  - Filtering methods
- Interesting Problems
  - Output feedback
  - Singular Perturbations
  - Infinite-dimensional systems
  - Systems with delays (e.g. wireless network)

Thank You!


陈康肃公尧咨善射，当世无双，公亦以此自矜。尝射于家圃，有卖油翁释担而立，
睨之，久而不去。见其发矢十中八九，但微颔之。康肃问曰："汝亦知射乎？康肃问
曰："汝亦知射乎？吾射不亦精乎？"翁曰："无他，但手熟尔。"康肃忿然曰："
尔安敢轻吾射！"翁曰："以我酌油知之。"乃取一葫芦置于地，以钱覆其口，徐以
杓酌油沥之，只钱孔入，而钱不湿。因曰："我亦无他，为手熟尔。"
【卖油翁】
http://www.chneic.sh.cn/