不连续控制系统的未来发展与挑战

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报告提纲

1. 不连续控制系统的定义
2. 不连续控制系统的类别
3. 不连续控制系统的性质
4. 不连续控制系统中存在的问题
5. 不连续控制系统的未来发展及挑战

1. 不连续控制系统的定义

Consider the following Ordinary Differential Equation (ODE) that describes a typical control system

$$\dot{x} = f(x) + b(x)u$$

where commonly, $x \in R^n, u \in R^m, m < n$. In here, $f(x)$ and $b(x)$ are smooth, and the control $u(x)$ is smooth as well.

AND

The term $f(x) + b(x)u(x)$ satisfies the Lipschitz condition to ensure the *existence and uniqueness of the solutions*.

For discontinuous control, it is of the form (simplest form)

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

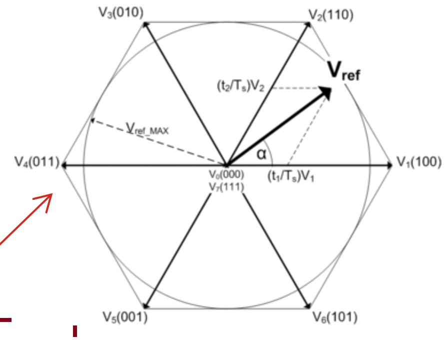
where $u^+ \neq u^-$.

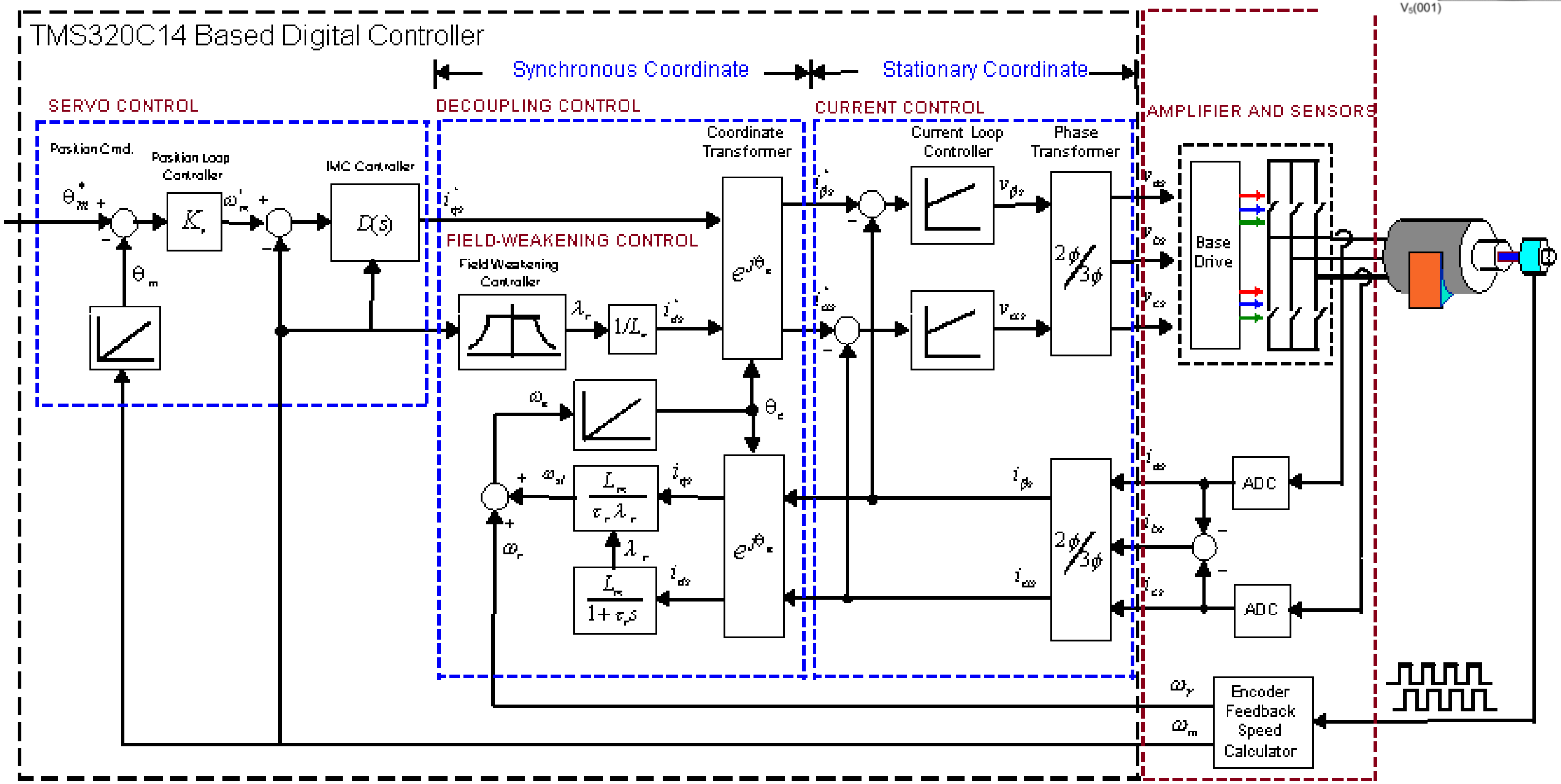
2. 不连续控制系统的类别

- Discontinuous control is everywhere …typical types are
  - *Sliding mode control*
  - *Switching control*
  - *Fuzzy control*
  - *Optimal control*
  - *State vector control*
  - *Impulsive control*
  - *Control in event-triggered systems*

Vector control

- *Vector control of AC Induction Motor*





Fuzzy control

A typical fuzzy control system

For $\dot{x} = f(x) + b(x)u(x)$

Rule 1: $IF\ x_1\ is\ A_{11}\ and\ x_2\ is\ A_{12}\ \ldots\ldots x_n\ is\ A_{1n}\ THEN\ u = u_1$

Rule 2: $IF\ x_1\ is\ A_{21}\ and\ x_2\ is\ A_{22}\ \ldots\ldots x_n\ is\ A_{2n}\ THEN\ u = u_2$

.

.

.

Rule m: $IF\ x_1\ is\ A_{m1}\ and\ x_2\ is\ A_{m2}\ \ldots\ldots x_n\ is\ A_{mn}\ THEN\ u = u_m$

where A_{ij} is fuzzy value

Optimal control

Consider the 2nd order dynamical system

$$\dot{x}_1 = x_2,; \quad \dot{x}_2 = u; \quad |u| \leq 1$$

The time optimal control is

$$u = \mathrm{sgn}[\Xi(x)]$$

$$\Xi(x) = \begin{cases} \xi(x) = x_1 + \frac{1}{2}x_2|x_2|; & \xi(x) \neq 0 \\ x_2; & \xi(x) = 0 \end{cases}$$

Impulsive control

A typical Impulsive control system

$$\dot{x} = f(x) + b(x,t) \qquad t \in (t_{k-1}, t_k]$$

$$\Delta x = cu(t_k),\ t = t_k,\ k = 0,1,2,\ldots$$

The impulsive control occurs at $t = t_k$.

Control in event-triggered systems

A typical event triggered system

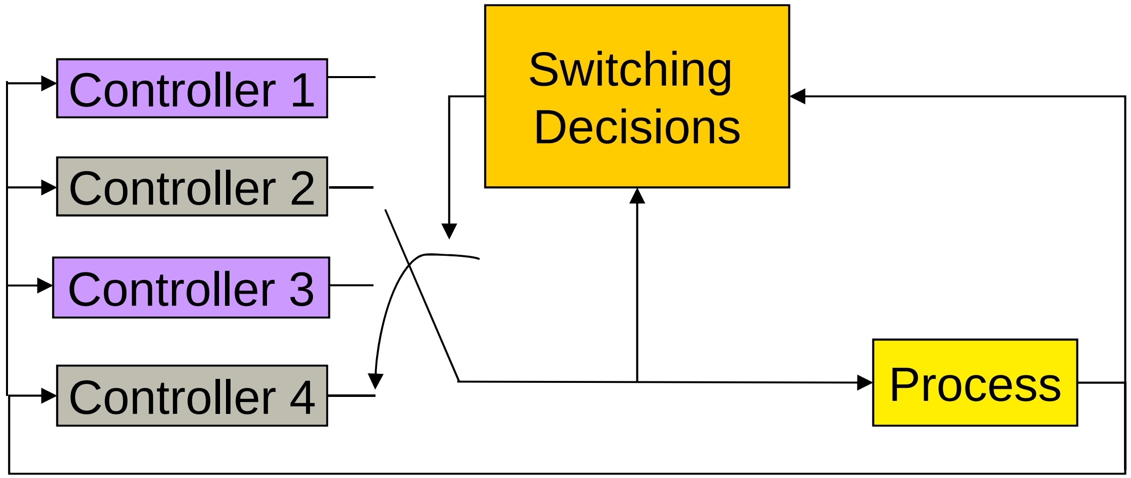
For $\dot{x} = Ax + bu,\ x \in R^n, u \in R^m$

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

The event time $t = t_k$ is determined by an event-trigger $e(t) = x(t_k) - x(t)$.

If $\gamma^2\|e\|^2 = \|x\|^2$, then $x\left({t_k}^{+}\right) = x(t)$ such that $e\left({t_k}^{+}\right) = 0$.

Switching control



For $\dot{x} = f(x) + b(x)u(x)$

$$u = u_i(x) \text{ if condition } i \text{ is satisfied}$$

Sliding mode control

Consider single-input control system

$$\dot{x} = f(x) + b(x)u$$

1. Define a switching manifold which prescribe the desirable properties $s(x)$
2. Design a discontinuous control $u(x)$

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

such that

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

Note: This is not the same as $s\dot{s} < 0$ which is often wrongly used!

Robustness in SMC systems

- Consider a single input single output (SISO) system

$$\dot{x} = f(x) + g(x)u + \xi(x,t)$$

- where x is the state, u is the control and ξ represents uncertainties and disturbance, f and g are smooth functions.
- When an ideal sliding mode is created, we have

$$\dot{s} = 0, s = 0$$

- There exists a virtual control, called equivalent control,

$$u_{eq} = -\left(\frac{\partial s}{\partial x} g(x)\right)^{-1} \left(\frac{\partial s}{\partial x}\big(f(x) + \xi(x,t)\big)\right)$$

- When the matching condition is satisfied

$$\dot{x} = \left(I - g(x)\left(\frac{\partial s}{\partial x} g(x)\right)^{-1} \frac{\partial s}{\partial x}\right) f(x)$$

No uncertainty nor disturbance is involved!

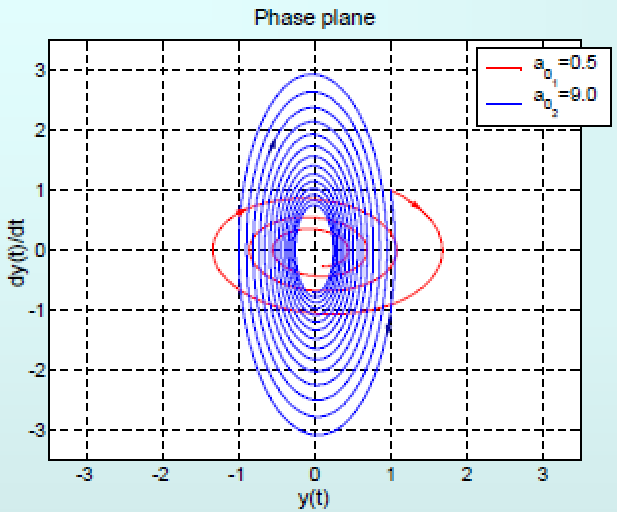
3. 不连续控制系统的性质 – *可利用的优势*

- The benefits of switching are enormous … for example,

$$\ddot{y} + a_1\dot{y} + a_{01}y = 0 \qquad \textit{system 1}$$
$$\ddot{y} + a_1\dot{y} + a_{01}y = 0 \qquad \textit{system 2}$$

  - $a_1 > 0$ the systems are both asymptotically stable.
  - $a_1 = 0$ the systems are both marginally stable.
  - $a_1 < 0$ the systems are both unstable.

稳定系统可切换成不稳定系统

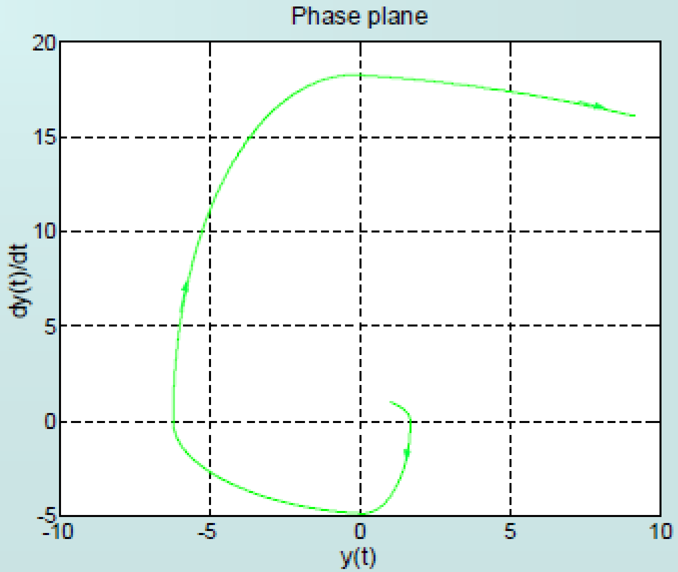


$$\dot{y}(t)y(t) \geq 0 \quad system\,1$$
$$\dot{y}(t)y(t) < 0 \quad system\,2$$
$$0 < a_{01} < a_{02}$$

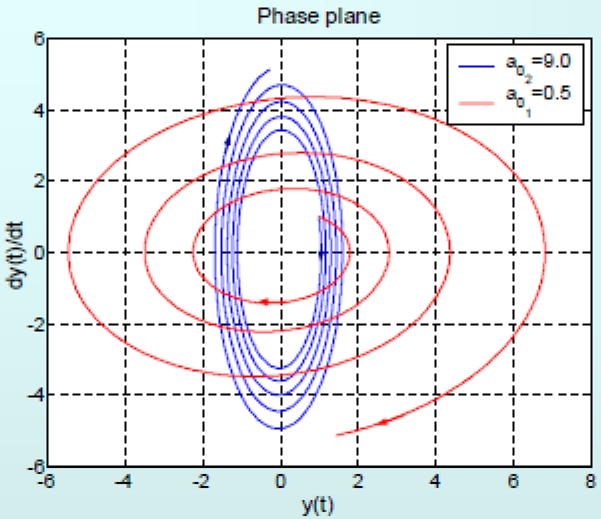
Switched unstable dynamics

$$a_1 = 0.1$$

Both dynamics are asymptotically stable



不稳定系统可切换成稳定系统



$$a_1 = -0.1$$

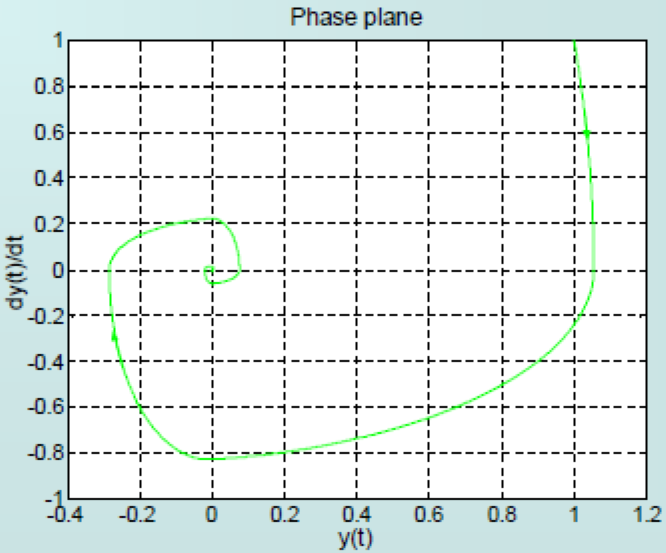
Both dynamics are unstable

$$\dot{y}(t)y(t) < 0 \quad system\,1$$

$$\dot{y}(t)y(t) \geq 0 \quad system\,2$$

$$0 < a_{01} < a_{02}$$

Switched asymptotically stable dynamics



不连续控制类别之间的关系

- The relationship between these various discontinuous controls is ambiguous …

Consider a double integrator given by

$$\ddot{y} = u(t)$$

Consider the feedback control

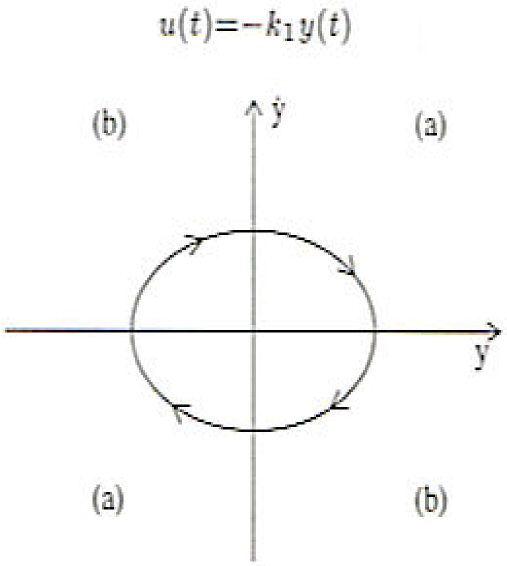
$$u = -ky(t)$$

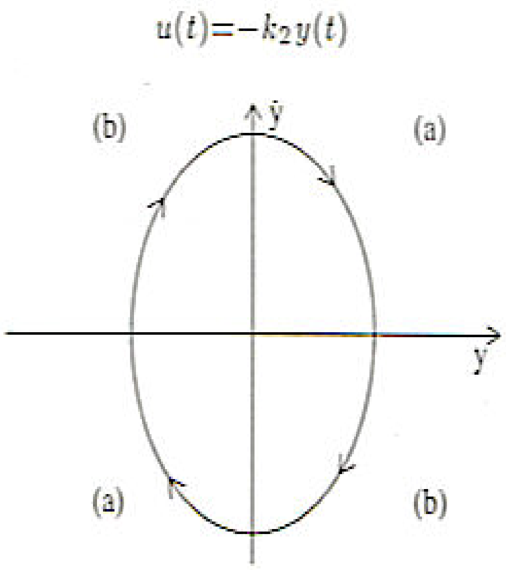
where $k>0$. If we take the Lyapunov function

$$V(y) = \frac{1}{2}(\dot{y}^2 + ky^2)$$

Then

$$\dot{V} = 0 \;\Rightarrow\; V = c,\; c > 0$$



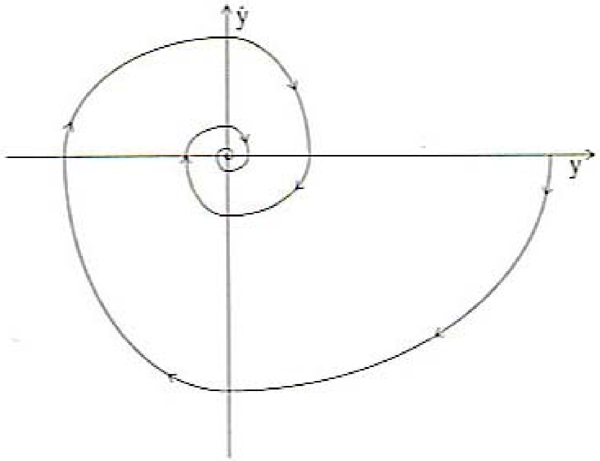


For $0<k_1<1<k_2$

However, if we choose

$$u = \begin{cases} -k_1 y & if \;\; y\dot{y} < 0 \\ -k_2 y & otherwise \end{cases}$$

and a new Lyapunov function



Then $$V(y) = \frac{1}{2}(\dot{y}^2 + y^2)$$

$$\dot{V} = y\dot{y} + \dot{y}\ddot{y} = \dot{y}(y+u) = \begin{cases} y\dot{y}(1-k_1) & if \;\; y\dot{y} < 0 \\ y\dot{y}(1-k_2) & if \;\; y\dot{y} > 0 \end{cases}$$

It is a switching control!

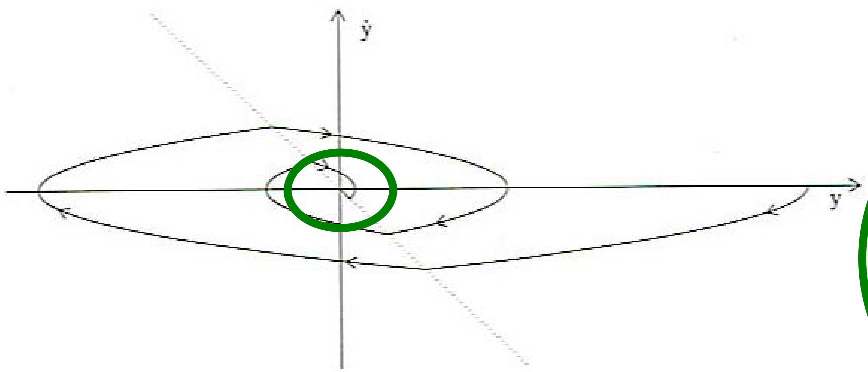
However, if we choose a switching line $s = \dot{y} + cy$

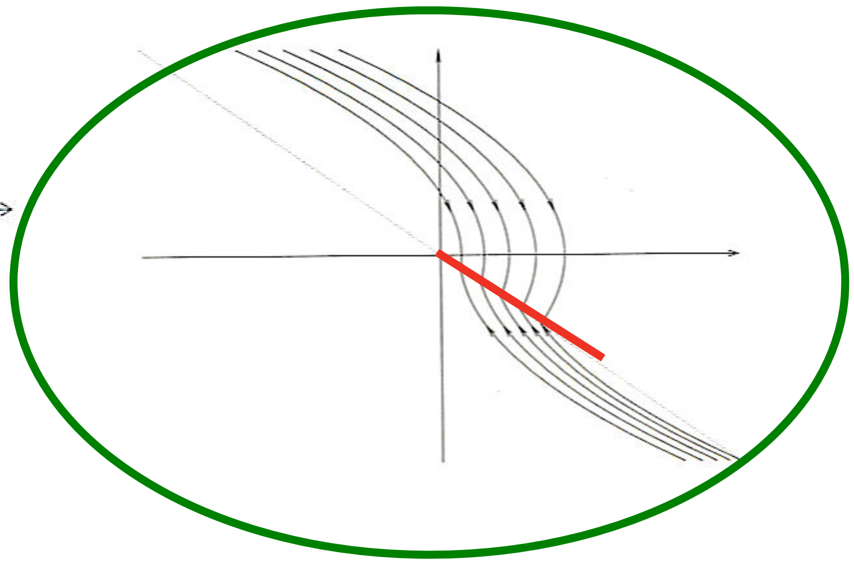
The control is chosen as

$$u = -\operatorname{sgn}(s) = \begin{cases} -1 & if \;\; s > 0 \\ 1 & if \;\; s < 0 \end{cases}$$

Then, when $c|\dot{y}| < 1$

$$s\dot{s} = s(c\dot{y} + \ddot{y}) = s(c\dot{y} - \operatorname{sgn}(s)) = |s|(c|\dot{y}| - 1) < 0$$

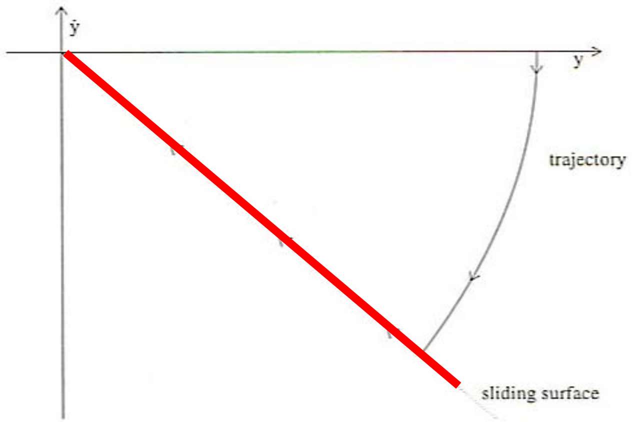


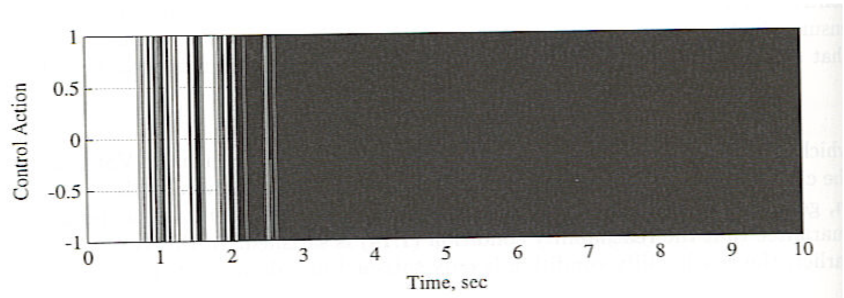


When $s=0$ is reached,

That is,

$$\dot{y} = -cy, \;\; c > 0 \qquad y(t) = \exp(-ct)\,y(0) \to 0, \;\; for \;\; t \to \infty$$





It is a local sliding mode control inside a global switching control!

Relation between discontinuous control and finite time control …

Consider the 2nd dynamical system

$$\dot{x}_1 = x_2,; \quad \dot{x}_2 = u; \quad |u| \le 1$$

Time optimal control

$$u = \operatorname{sgn}[\Xi(x)]$$

$$\Xi(x) = \begin{cases} \xi(x) = x_1 + \frac{1}{2}x_2|x_2|; & \xi(x) \neq 0 \\ x_2; & \xi(x) = 0 \end{cases}$$

Take very large odd integer q and p, we have

$$x_1 + \frac{1}{2}x_2^{p/q} \approx x_1 + \frac{1}{2}x_2|x_2| = \xi(x).$$

Switching control can approximate finite time control!

Finite control versus linear control (asymptotical convergence)

- For the 1st order dynamics

$$\dot{x}_1 = -\alpha x_1 - \beta x_1^{q/p}$$

- The Jacobian is

$$J = \frac{\partial \dot{x}_1}{\partial x_1} = -\alpha - \frac{\beta q}{p x_1^{\frac{p-q}{q}}} \qquad J \to -\infty \quad \text{when} \quad x_1 \to 0^+$$

- Exact reaching time

$$t^s = \frac{p}{\alpha(p-q)}(\ln(\alpha x_1(0)^{(p-q)/p} + \beta) - \ln \beta)$$

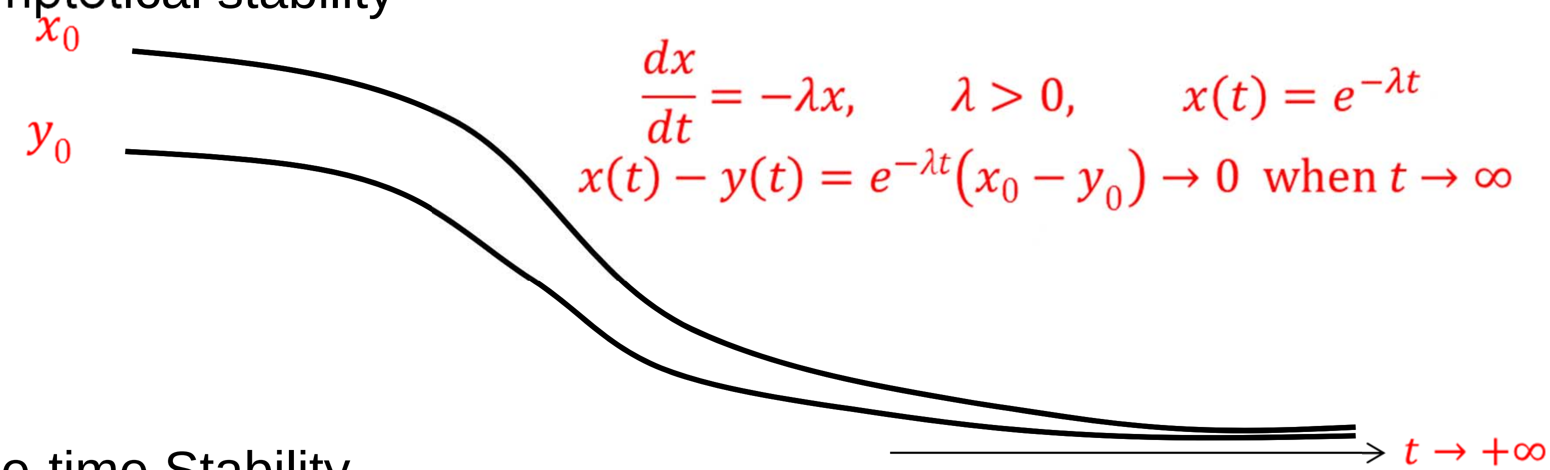
- With *α=1, β=1,* at $t^s = 1.03969999999990$,
- For *p=3, q=1*, $x_1(t^s) = 0.00000009178540$ *finite control!*
- For *p=1, q=1,* $x_1(t^s) = 0.12500519281775$ *linear control!*

Finite time stability versus asymptotical time stability

- Continuous-Time ODE based
- Many new methods: e.g. Hinf,
- Fundamentally the Liptschiz condition must be satisfied
- Asymptotical stability
- The problem with asymptotical stability …
  - It requires ‘enormous’ control efforts to improve precision
  - Lets take a very simple example:

$$\dot{x} = u, \qquad u = \begin{cases} -\lambda x \\ -\lambda x^{1/3} \end{cases}, \qquad \lambda > 0$$

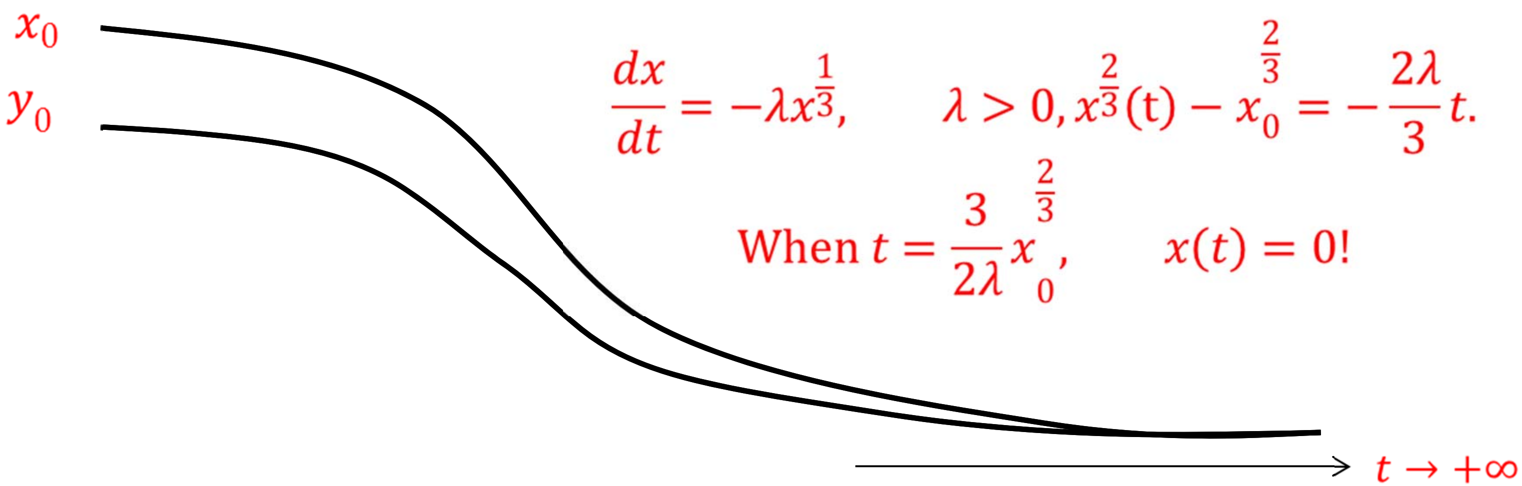
- Asymptotical stability



$$\frac{dx}{dt} = -\lambda x, \qquad \lambda > 0, \qquad x(t) = e^{-\lambda t}$$

$$x(t) - y(t) = e^{-\lambda t}\left(x_0 - y_0\right) \to 0 \ \text{ when } t \to \infty$$

- Finite-time Stability



$$\frac{dx}{dt} = -\lambda x^{\frac{1}{3}}, \qquad \lambda > 0, x^{\frac{2}{3}}(\mathrm{t}) - x_0^{\frac{2}{3}} = -\frac{2\lambda}{3} t.$$

$$\text{When } t = \frac{3}{2\lambda} x_0^{\frac{2}{3}}, \qquad x(t) = 0!$$

Precision and robustness properties - 1

- If there is a disturbance, $|\xi| < \varepsilon > 0$, such that
  - $\dot{x} = u + \xi,\ u = \begin{cases} -\lambda x \\ -\lambda x^{1/3} \end{cases},\ \lambda > 0$
- Then

For $u = -\lambda x$, $|x(\infty)| < \frac{\varepsilon}{\lambda}$.

For $u = -\lambda x^{1/3}$, $|x(\infty)| < \left(\frac{\varepsilon}{\lambda}\right)^3$

So, for $\lambda > \varepsilon$, $\frac{\varepsilon}{\lambda} \ll \left(\frac{\varepsilon}{\lambda}\right)^3$. Less steady state error if using a non-smooth control!

Precision and robustness properties - 2

- If implemented digitally with a sample period *h*, and assuming we use Euler approximation, then

  - $x(k+1) = x(k) + hu(k),\ u(k) = \begin{cases} -\lambda x(k) \\ -\lambda x^{\frac{1}{3}}(k) \end{cases},\ \lambda > 0$

- Then

  For $u = -\lambda x$, $|x(\infty)| < h$.

  For $u = -\lambda x^{1/3}$, $|x(\infty)| < \max\left(\left(\frac{\lambda h}{2}\right)^{3/2}, h\right)$ so to maintain the required fast convergence speed while retaining the required accuracy, $\lambda < 2h^{-1/2}$

Some typical finite-time control systems

- (Bhat & Bernstein, 2001)

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = u, \qquad u = -x_2^{\frac{1}{3}} - \left(x_1 + \frac{3}{5}x_2^{5/3}\right)^{1/3}$$

- (Levant, 2001)

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = u, \qquad u = -\alpha\, sgn(x_2 + |x_1|^{\frac{1}{2}} sgn(x_1))$$

- (Yu & Man, 1996; Feng, Yu & Man, 2002)

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = u, \qquad u = -\alpha\, sgn(s) - c\gamma \dot{x}_2^{2-\frac{1}{\gamma}},$$

$$s = x_1 + \frac{1}{c} x_2^{\frac{1}{\gamma}}, \qquad 0 < \gamma < 1$$

- (Hong, Xu & Huang, 2002)

$$\dot{x}_1 = x_2, \quad \dot{x}_2 = -c_1 sgn\, x_1 |x_1|^{\alpha_1} \text{-} -c_1 sgn\, x_2 |x_2|^{\alpha_2}$$

The terminal sliding mode concept

- The dynamical performance of a SMC system is determined by the prescribed switching manifolds. The most commonly used switching manifolds are linear hyperplanes which guarantee only asymptotic stability.

- Nonlinear switching manifolds can be created purposefully to improve performance. Terminal sliding mode (TSM) is a nonlinear dynamics that provides finite time mechanism (Man & Yu 1994, Yu and Man, 1996, Feng et al, 2001).

Singularity problem ...

Consider $s = \beta x_1^{q/p}(t) + \dot{x}_1(t),\ \beta > 0$ Take *V=0.5s²*. Then

$$\dot{V} = s\dot{s} = s(\ddot{x}_1 + \frac{q}{p}\beta x_1^{q/p-1}\dot{x}_1)$$

Since $q/p < 1$, singularity occurs *before sliding mode realised!*

$$\dot{x}_1(t) = -\beta x_1^{q/p}(t)$$

$$\dot{V} = s\dot{s} = s(\ddot{x}_1 + \frac{q}{p}\beta x_1^{q/p-1}\dot{x}_1) = s(\ddot{x}_1 - \frac{q}{p}\beta^2 x_1^{2q/p-1})$$

During the sliding mode,

No singularity during the sliding mode if $\boxed{\tfrac{1}{2} < q/p < 1}$

Nonsingular TSM

In order to overcome the singularity problem during the reaching phase, a nonsingular TSM is proposed

$$s(t) = x_1(t) + \frac{1}{\beta}\dot{x}_1^{p/q}(t)$$

Take $V=0.5s^2$. Then

$$\dot{V} = s\dot{s} = s(\dot{x}_1 + \frac{p}{q}\dot{x}_1^{p/q-1}\ddot{x}_1)$$

Since $p/q>1$, there is NO singularity.

3. 不连续控制系统的性质 – *从空间(状态）的角度看*

- Typical discontinuities are
  - *Switching between different dynamics*
    - *Sliding mode control*
    - *Fuzzy control*
    - *Time optimal control*
    - *Bang-bang control*
  - *Jumping in systems states*
    - *Impulsive control*
    - *Control in event-triggered systems*

3. 不连续控制系统的性质 – *从时间（切换频率 ）的角度看*

- **Zeno Phenomena**
- The Zeno phenomenon appears when the execution of the discontinuous control system is such that

$$\lim_{i\to\infty} \tau_i = \sum_{i=0}^{\infty} (\tau_{i+1} - \tau_i) = \tau_\infty < \infty$$

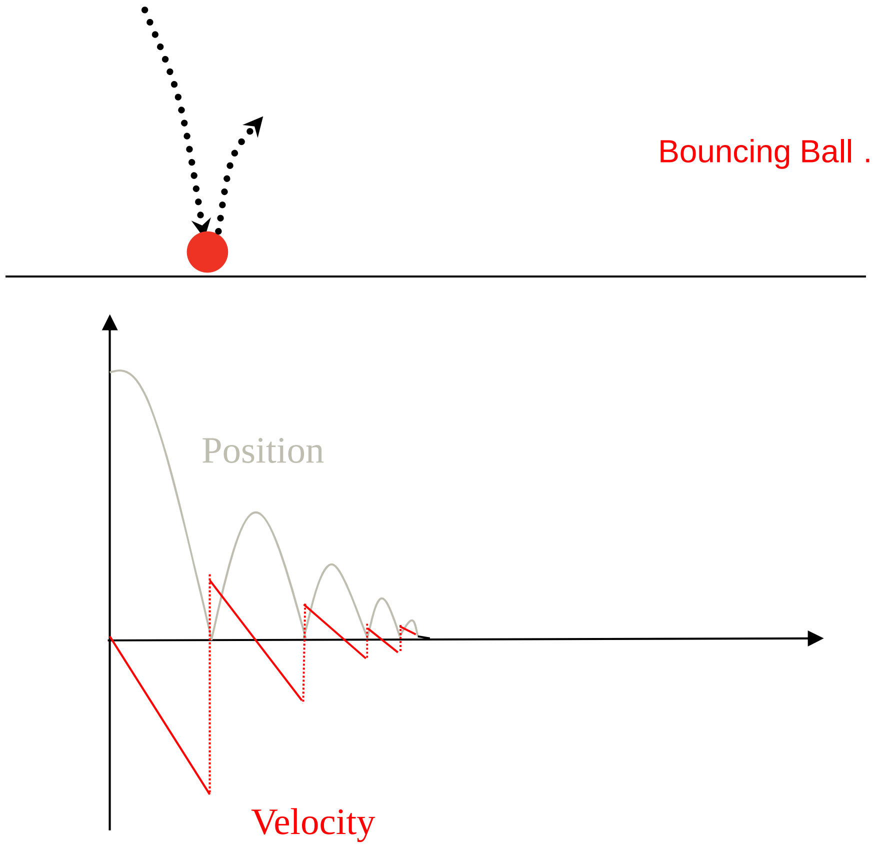
- where τ_∞ (the Zeno time) is a right accumulation point for the time constants sequence

$$(\tau_{i+1} - \tau_i) \xrightarrow[i\to\infty]{} 0$$

- The switching frequency tends to be infinite!
- Definitions
  - Chattering Zeno: $\exists J > 0, \forall j > J, (\tau_{i+1} - \tau_i) = 0$
  - Genuinely Zeno: $\exists J > 0, \forall j > J, (\tau_{i+1} - \tau_i) > 0$

Bouncing ball …

[Zeno behavior] occurs when there are an infinite number of discrete transitions in a finite amount of time.



Bouncing Ball ……

(Liberzon, 2003)

Impact of switching frequency …

The frequency influences significantly the behaviour of dynamics – even methodology may differ significantly due to frequency range

- Low frequency - many existing methodologies can be used by 'piecing-together' various 'smooth' subsystems – in time or in state.

- Medium frequency – same as Low frequency though presents challenges of using Lyapunov theory, e.g. piece-wise Lyapunov function. Various causes: deliberate medium frequency such as switched control systems; time-delay due to digitization, etc.

- High frequency – tends to violate usual 'smooth' dynamics based approaches, may need to use drastically different method such as Fillipov theory!

Low/Medium frequency – impact on discontinuous control systems

Consider a second order system

$$\dot{x}_1 = x_2 \qquad\qquad u = \begin{cases} a^+ x_1 & x_1 s > 0 \\ a^- x_1 & x_1 s < 0 \end{cases}$$

$$\dot{x}_2 = -b x_2 + u$$

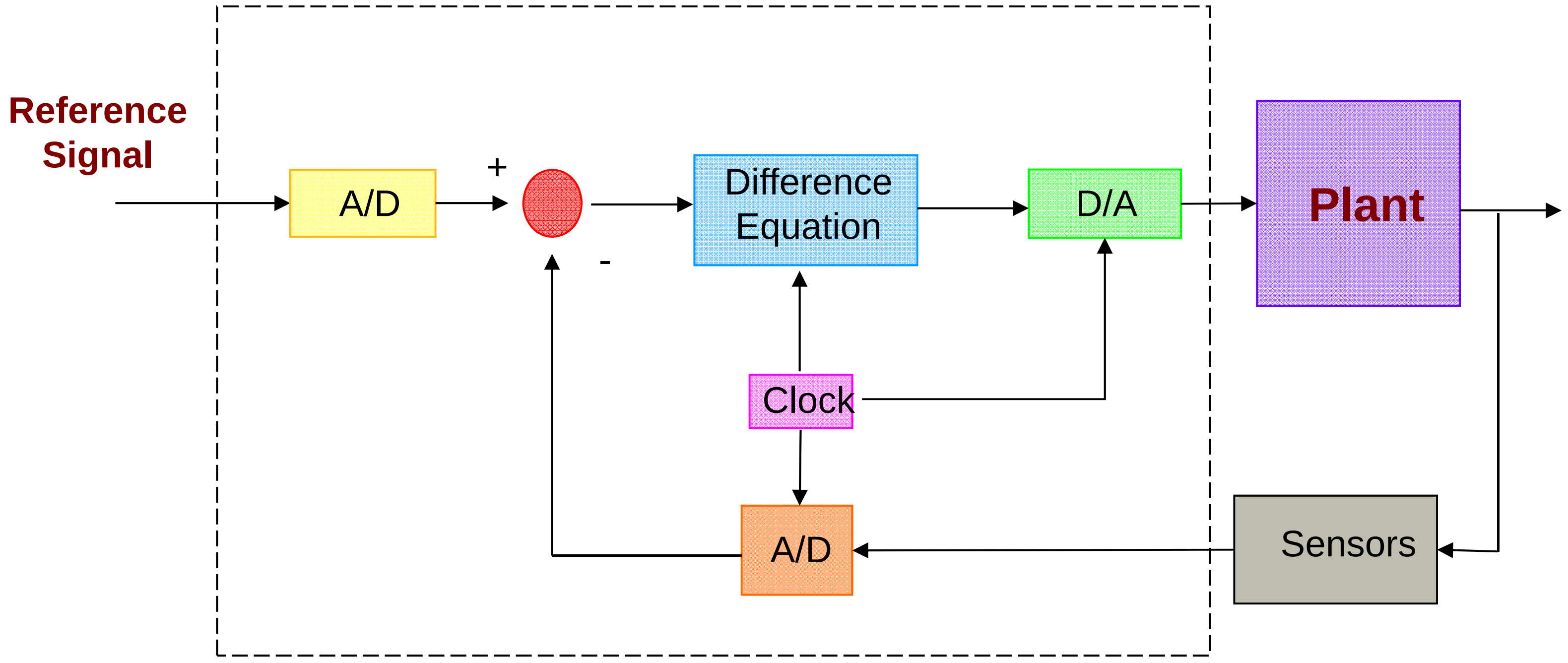
where

$$b > 0,\ c > 0,\ s = c x_1 + x_2$$

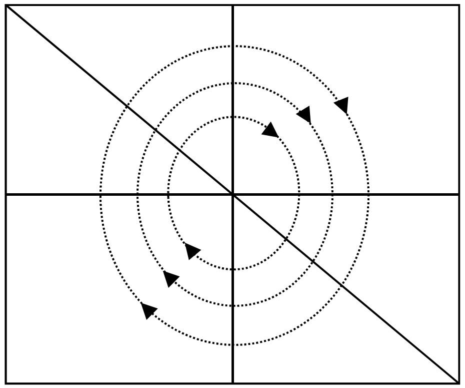
Equivalently,

$$\ddot{x} + b\dot{x} + a^{\mp} x = 0$$

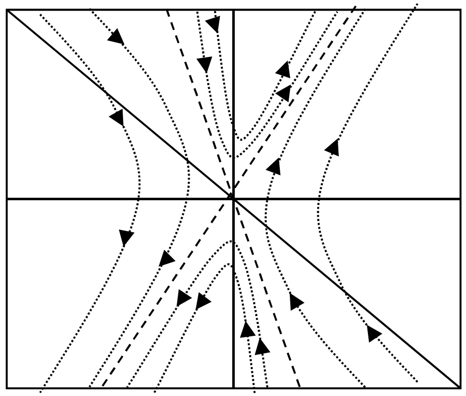
Discretization for control



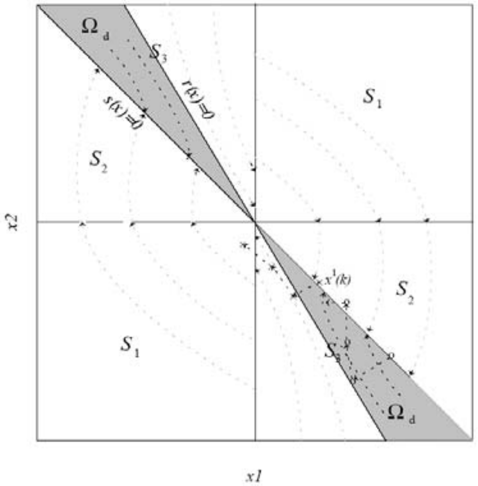
- Discretization (emulation) design
  - Controller designed based in continuous-time systems then digitized for implementation
- Discrete-time design
  - Controller design in discrete-time based on discrete-time system models



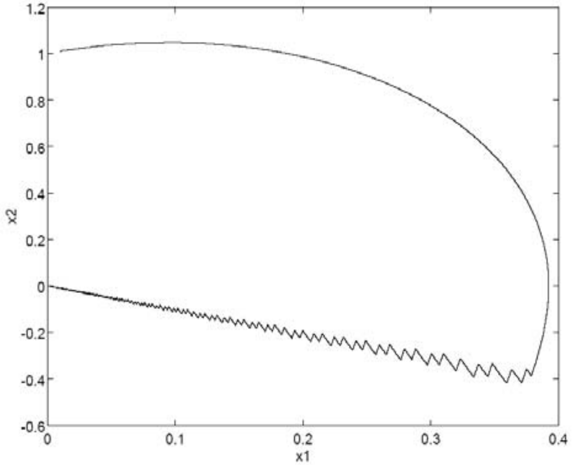
Phase plane portrait for ‘+’ ($s>0$, $a^{+}>0$)



Phase plane portrait for ‘-’ ($s<0$, $a^{-}<0$)

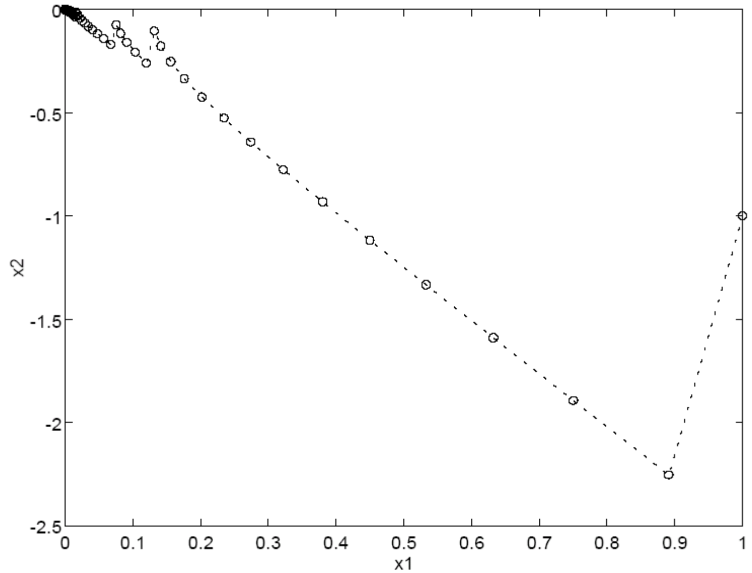


Phase plane portrait

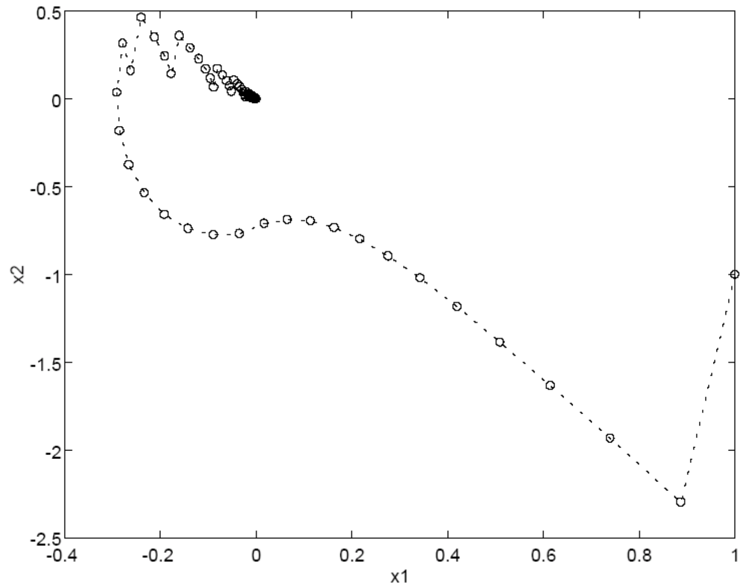


Near continuous-time behavior …

Some interesting discretization behaviors ……

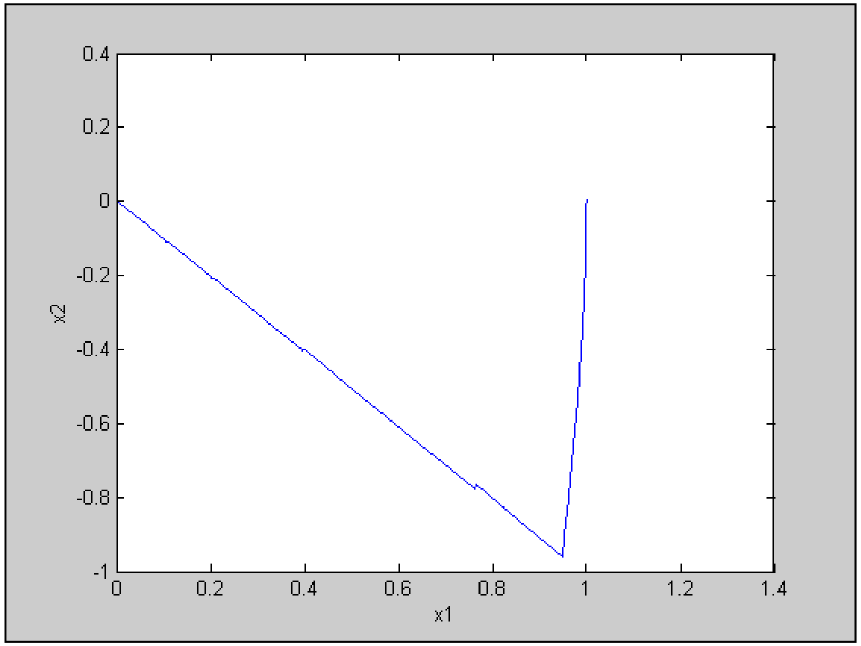


Discrete-time behavior…

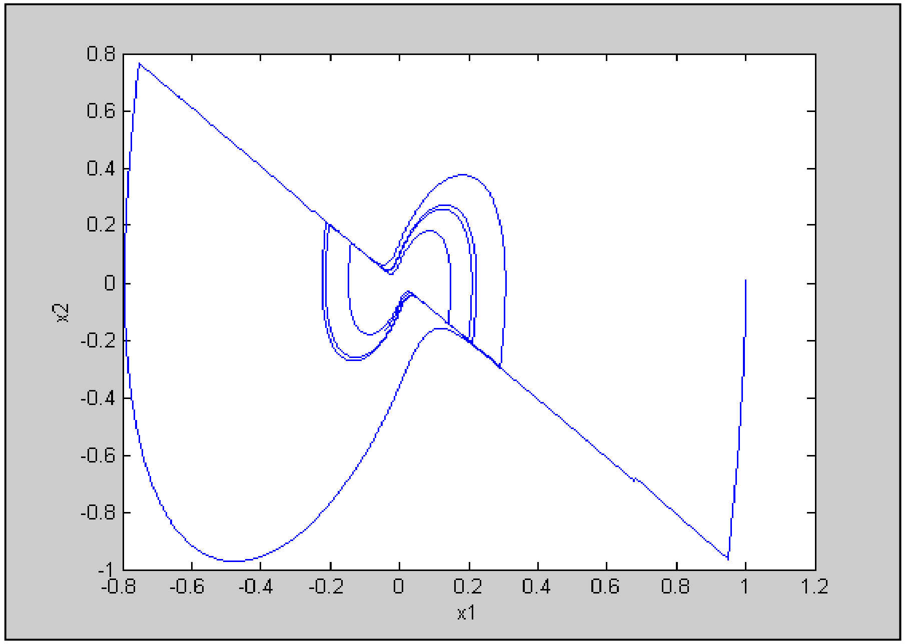


Discrete-time bifurcating behavior…

Is it true that a 'small enough' sampling period will not cause chaotic motions in control systems?



h=0.00158



h=0.00165

With b=-4.1, α=4.1, c=1, according to the upper bound formulae (Potts & Yu, 1991), the maximum H is 0.0016!

Another example

$$\dot{x}_1 = x_2 \qquad u = -\mathrm{sgn}(s)$$
$$\dot{x}_2 = u$$

where $c > 0,\ s = cx_1 + x_2$ Equivalently, $\ddot{x} \pm 1 = 0$

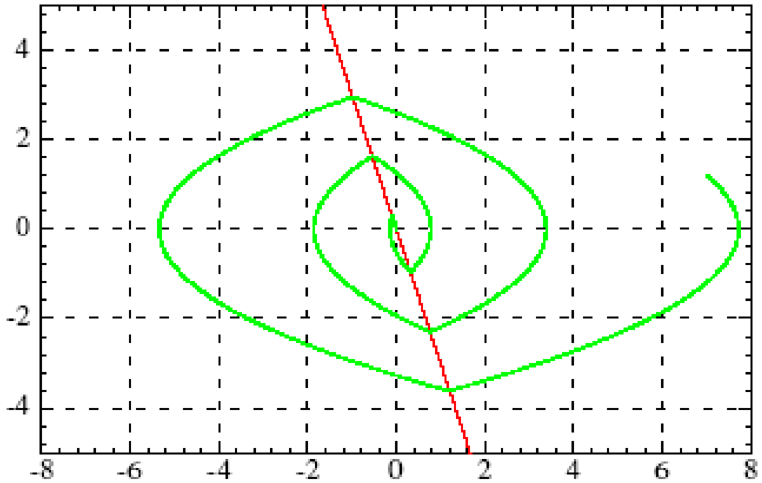


Fig. 1. Continuous time system, $c_1 = 3$, initial point $(x_1, x_2) = (7, 1.2)$,

Some interesting behaviors

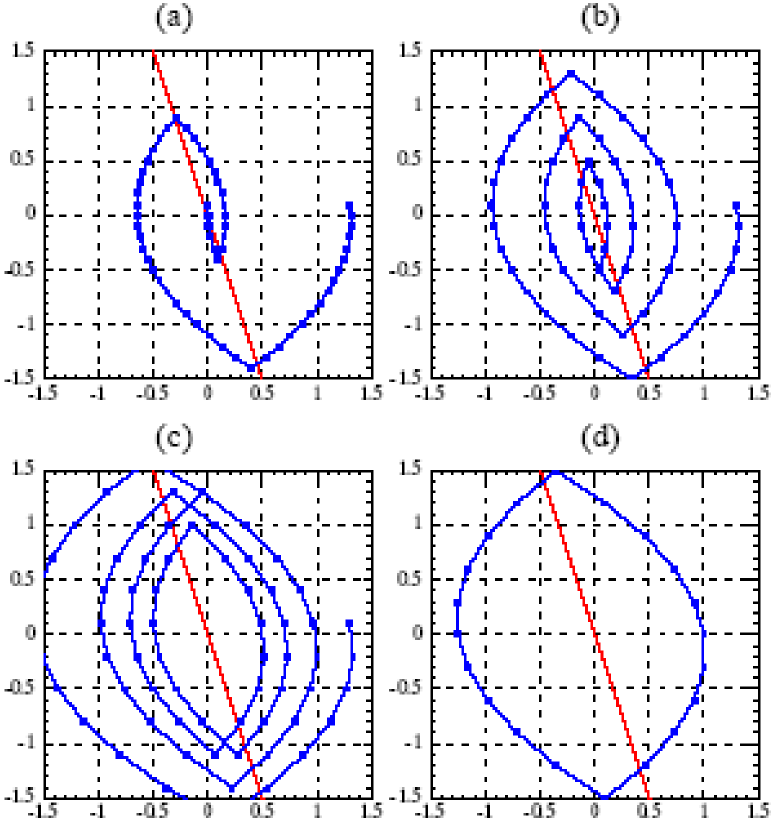


Fig. 4. Effects of discretization with different time steps, $c_1 = 3$, (a) $h = 0.1$, trajectory converges to a period–4 orbit, (b) $h = 0.2$, trajectory converges to a period–10 orbit, (c) $h = 0.3$, trajectory converges to a complex period–48 orbit, (c) $h = 0.3$, period–24 orbit of type (19), $(x_1, x_2) = (0.1, -1.5)$

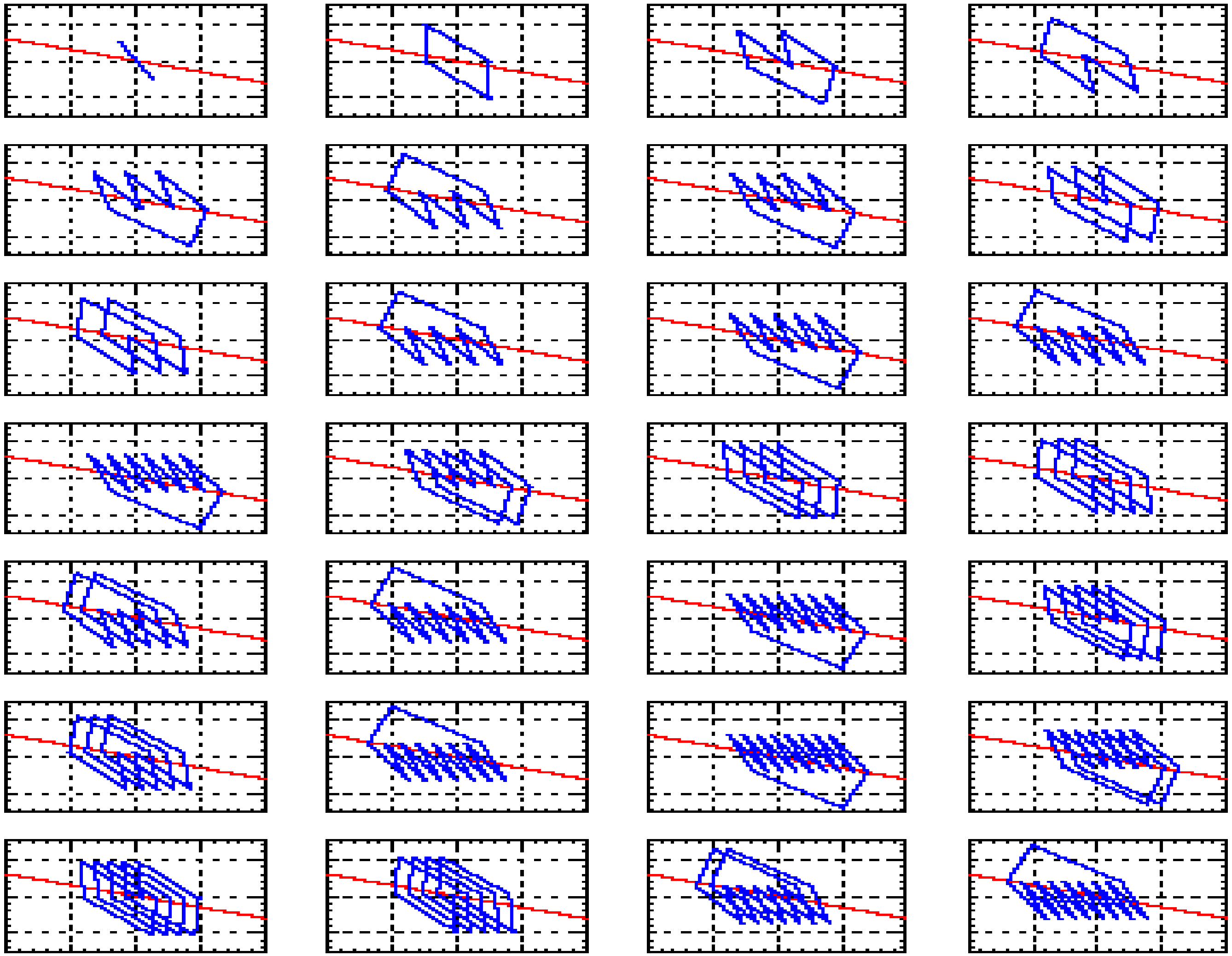


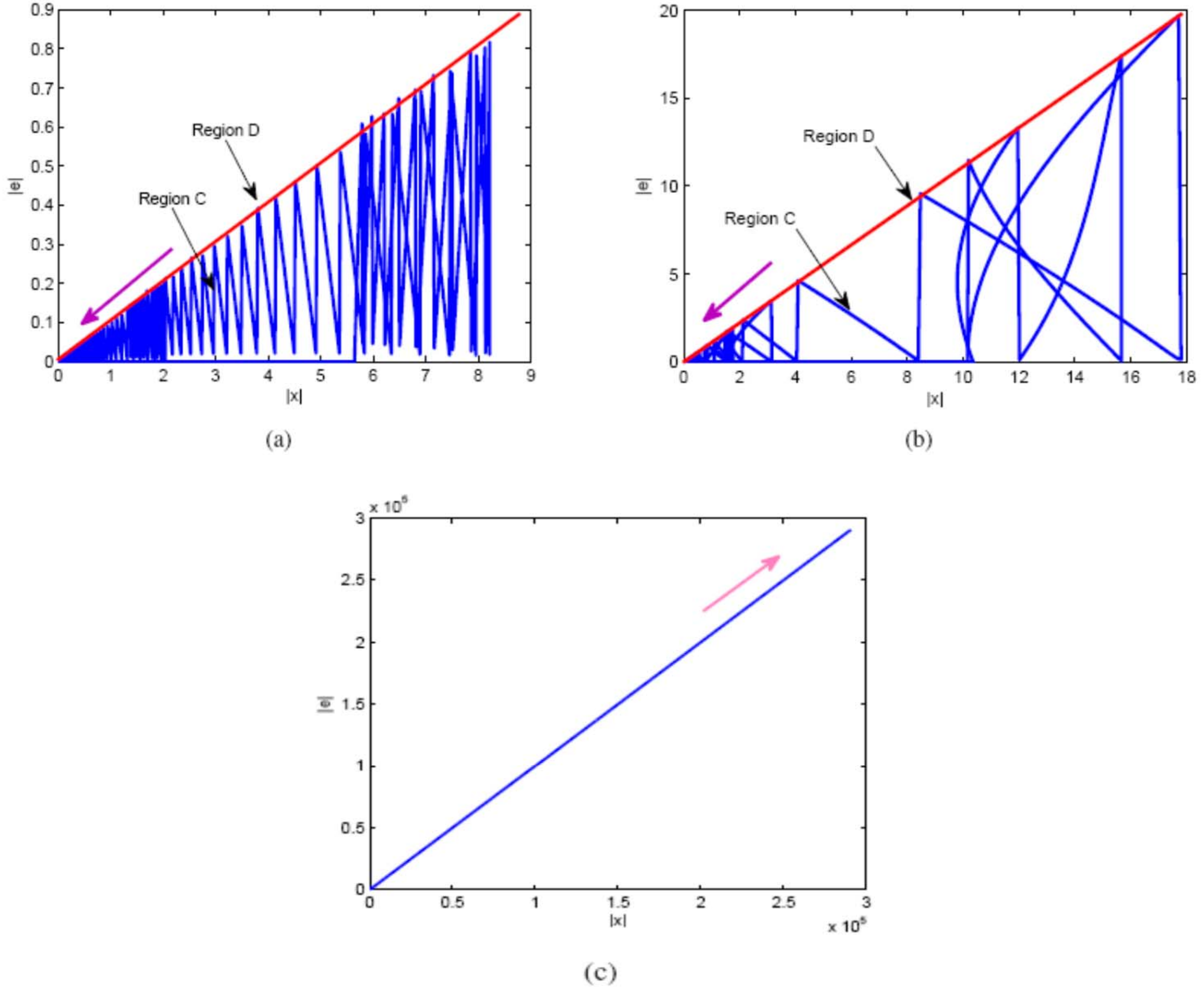
Fig. 2. Short cycles for $h = 0.1$, $c_1 = 3$

n	s	x_2	x_1
2	$-+$	$-1/20$	$[-7/600, 1/60)$
4	$--++$	$-1/10$	$[0, 1/100)$
6	$--+-++$	$-7/60$	$[7/1800, 19/1800)$
6	$--++-+$	$-1/12$	$[-7/1800, 1/360)$
8	$--+-+-++$	$-1/8$	$[7/1200, 13/1200)$
8	$--++-+-+$	$-3/40$	$[-7/1200, -1/1200)$
10	$--+-+-+-++$	$-13/100$	$[7/1000, 11/1000)$
10	$--+-++--++$	$-11/100$	$[7/3000, 19/3000)$
10	$--++--++-+$	$-9/100$	$[-7/3000, 1/600)$
10	$--++-+-+-+$	$-7/100$	$[-7/1000, -3/1000)$
12	$--+-+-+-+-++$	$-2/15$	$[7/900, 1/90)$
12	$--++-+-+-+-+$	$-1/15$	$[-7/900, -1/225)$
14	$--+-+-+-+-+-++$	$-19/140$	$[1/120, 47/4200)$
14	$--+-+-++--+-++$	$-17/140$	$[1/200, 11/1400)$
14	$--+-++--++--++$	$-3/28$	$[1/600, 19/4200)$
14	$--++--++--++-+$	$-13/140$	$[-1/600, 1/840)$
14	$--++-+--++-+-+$	$-11/140$	$[-1/200, -3/1400)$
14	$--++-+-+-+-+-+$	$-9/140$	$[-1/120, -23/4200)$
16	$--+-+-+-+-+-+-++$	$-11/80$	$[7/800, 9/800)$
16	$--+-++--+-++--++$	$-9/80$	$[7/2400, 13/2400)$
16	$--++--++-+--++-+$	$-7/80$	$[-7/2400, -1/2400)$
16	$--++-+-+-+-+-+-+$	$-1/16$	$[-7/800, -1/160)$
18	$--+-+-+-+-+-+-+-++$	$-5/36$	$[49/5400, 61/5400)$
18	$--+-+-+-++--+-+-++$	$-23/180$	$[7/1080, 47/5400)$
18	$--+-++--++--++--++$	$-19/180$	$[7/5400, 19/5400)$
18	$--++--++--++--++-+$	$-17/180$	$[-7/5400, 1/1080)$
18	$--++-+-+--++-+-+-+$	$-13/180$	$[-7/1080, -23/5400)$
18	$--++-+-+-+-+-+-+-+$	$-11/180$	$[-49/5400, -37/5400)$

TABLE I

SHORT CYCLES FOR $h = 0.1$, $c_1 = 3$

Event triggered systems also have complex behaviors …



Phase-plane portraits of an event triggered system (a) $\gamma = 10.2$; **(b)** $\gamma = 0.9$; **(c)** $\gamma = 0.82$.

Low frequency - Stability of switching control systems

For $\dot{x} = f(x) + b(x)u(x)$, If there exist Lyapunov function $V_p, p \in P$, two class K_∞ functions α_1 and α_2, and a positive number ρ_0, such that

$$\alpha_1(|x|) \leq V_p \leq \alpha_2(|x|)$$
$$\frac{\partial V_p}{\partial x}(f(x) + b(x)u(x)) \leq -2\rho_0 \, V_p(x)$$
$$V_p(x) \leq \mu V_q(x), \; \forall p, q \in P$$

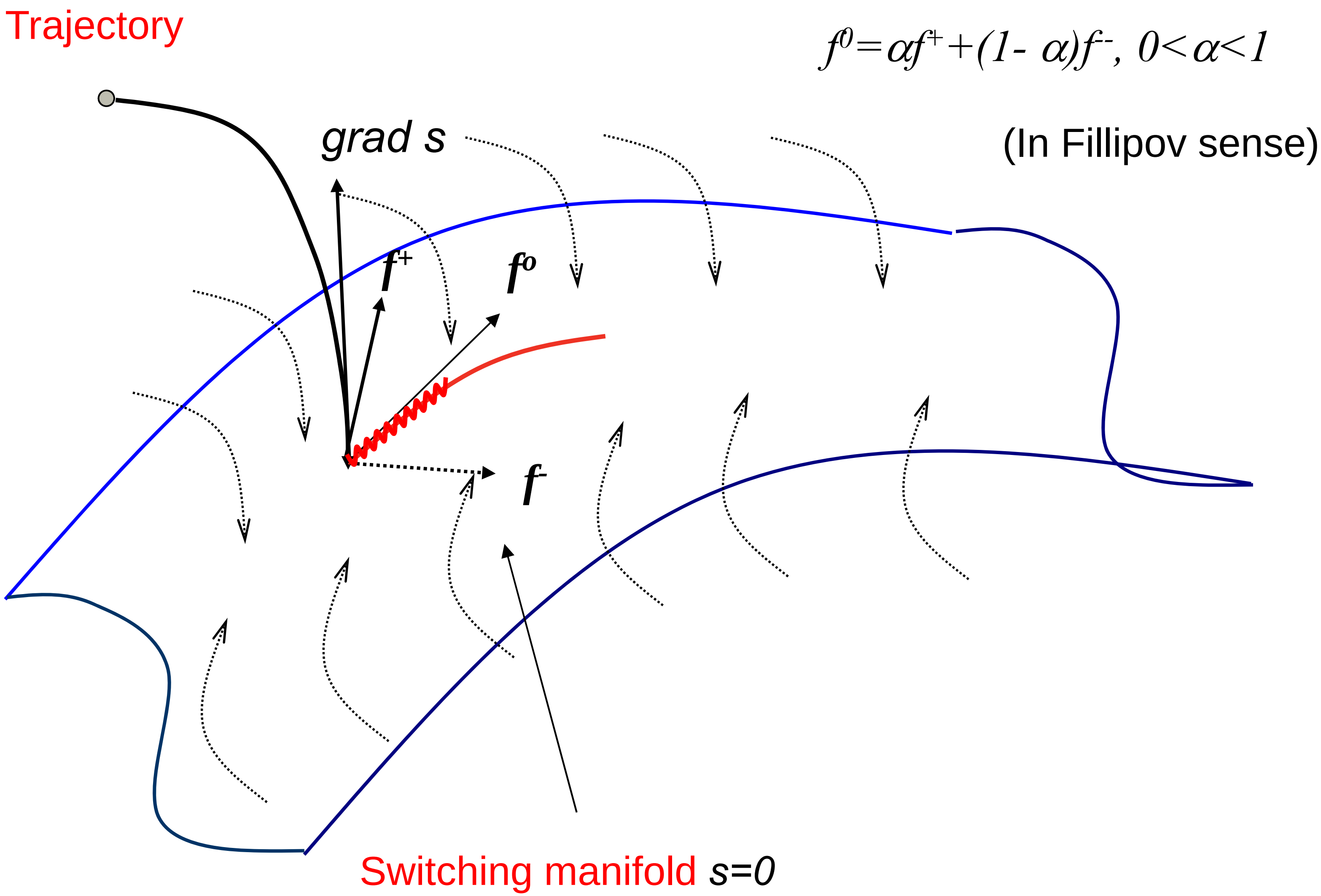
Then switched control system is globally asymptotically stable for every switching signal with average dwell time

$$\tau > \frac{\log \mu}{2\rho_0}$$

[Daniel Liberzon, Switching in Systems and Control, 2003]

High frequency – impact on discontinuous control systems

$\dot{x} = f(x,t)$ is equivalent to $\dot{x} = f_0(x,t)$



4. 不连续控制系统中存在的问题

- Gaps between methodologies dealing with discontinuous control systems
  - *How to analyze and design discontinuous control systems using a unified theoretical framework which can deal with switching frequencies ranging from low to very high?*
- Impact of time delay type element on dynamics
  - *Lack of effective tools to study rich dynamics of 'periodical' nature of steady states (e.g. limit cycle and finite state cycle)*
  - *The gap between continuous-time and digitized time-delayed discontinuous control systems …*
- Multiple time scales: *Inherent response speeds at different levels*
- Chattering is still a problem especially for sliding mode control types

5. 不连续控制系统的未来发展及挑战

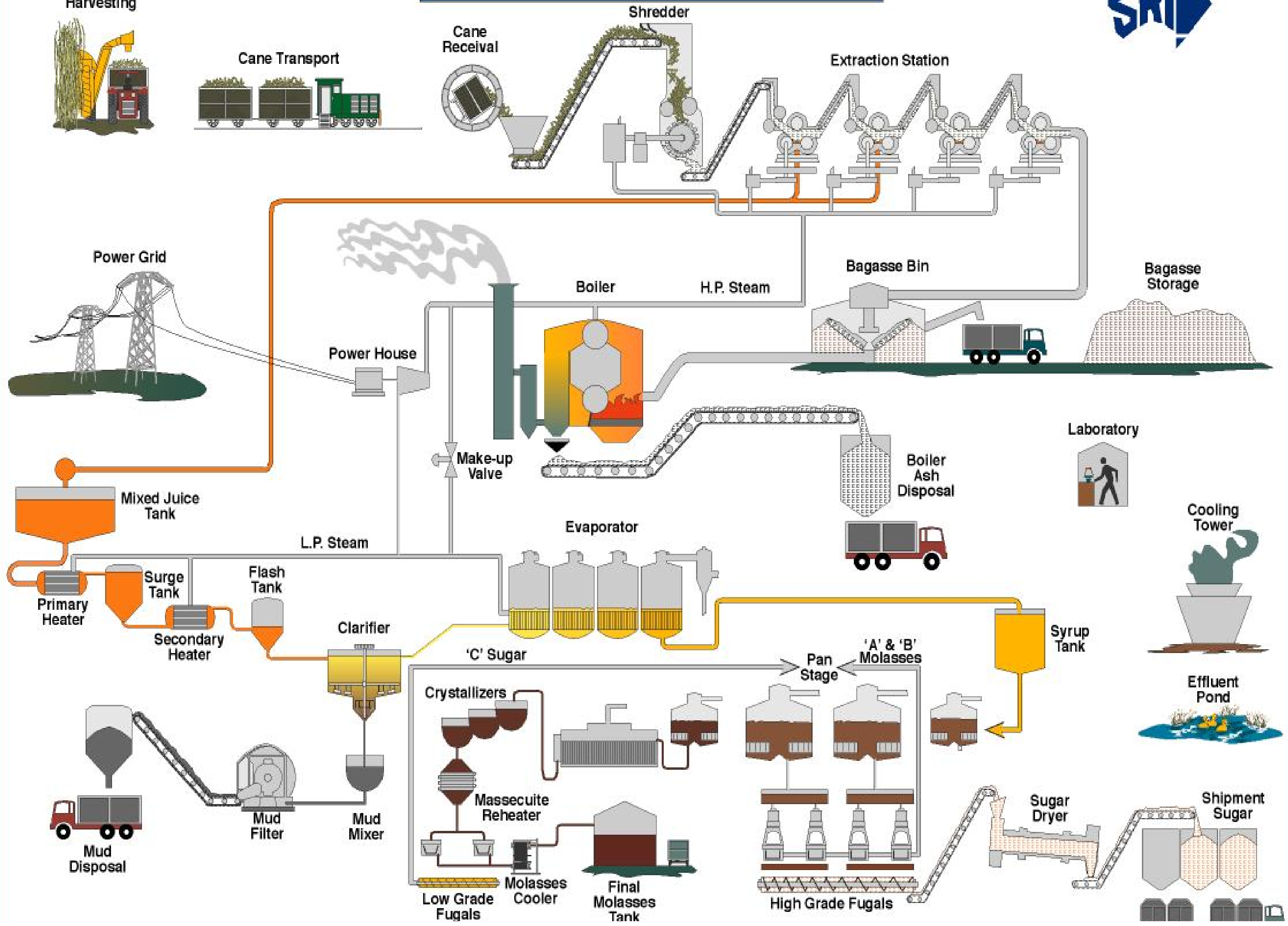
The scale and complexity of the industrial systems are growing exponentially

- *Big data environments*
- *Network environments*
- *Ever increasing complexity*
- *Time-scale issues: Inherent response speeds at different levels*
- *The impact of scale and complexity on control theories*
- *Human and machine interactions*
- *Switching in complex systems may result in much richer behaviors*

即便是传统的工业系统也面临严重的挑战。。。

- ❑Dynamic (temporal/real-time) nature
- ❑Different data/model platforms
- ❑Influenced by resources and demands
- ❑Interactions between machines and people
- ❑Continuous-time and discrete-time
- ❑Embedded, semi-automation
- ❑Different kinds of decisions (non-structured, semi-structured, structured)

PRODUCTION OF RAW SUGAR



未来智能电网是一个典型的例子。。。

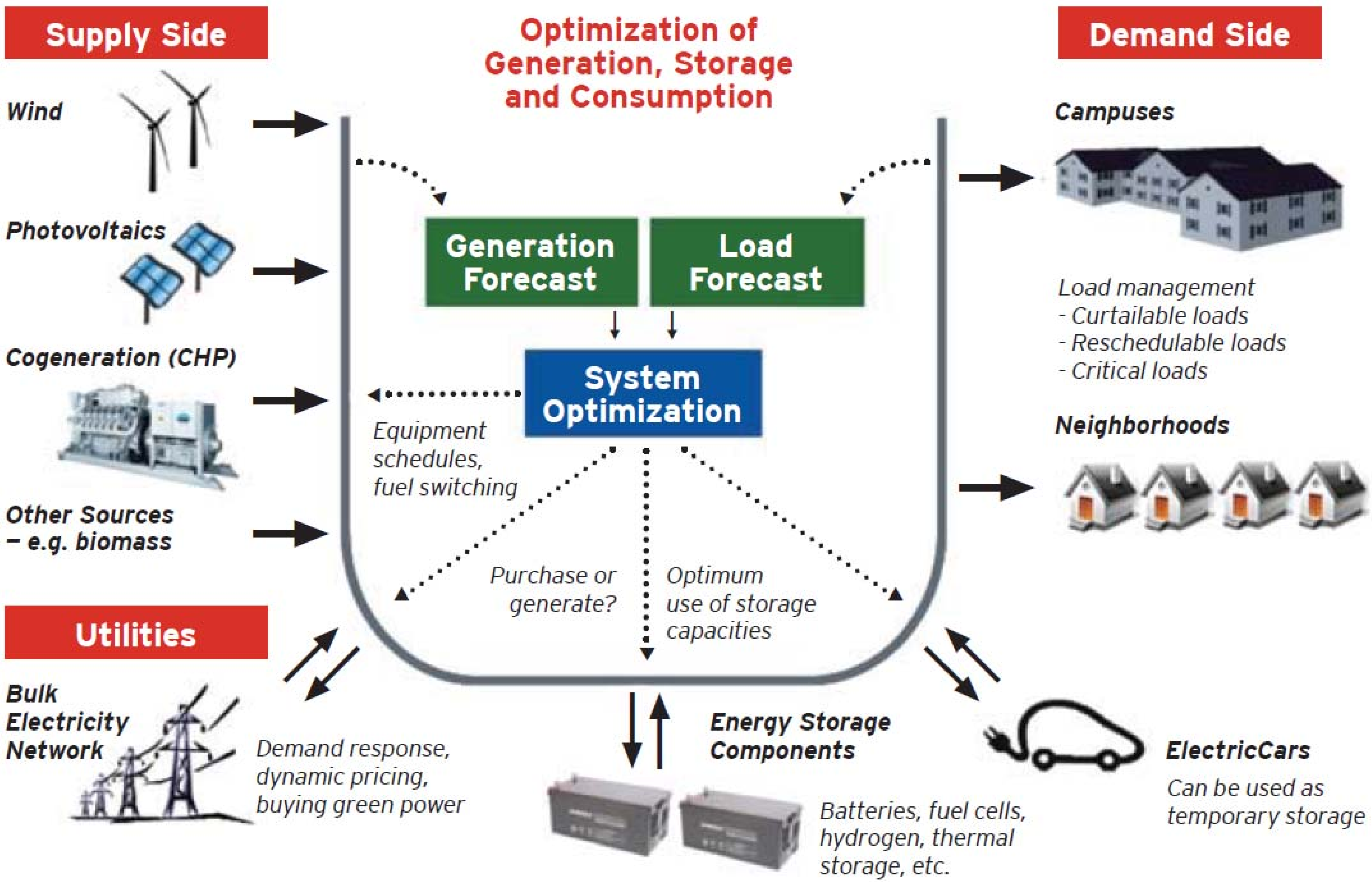
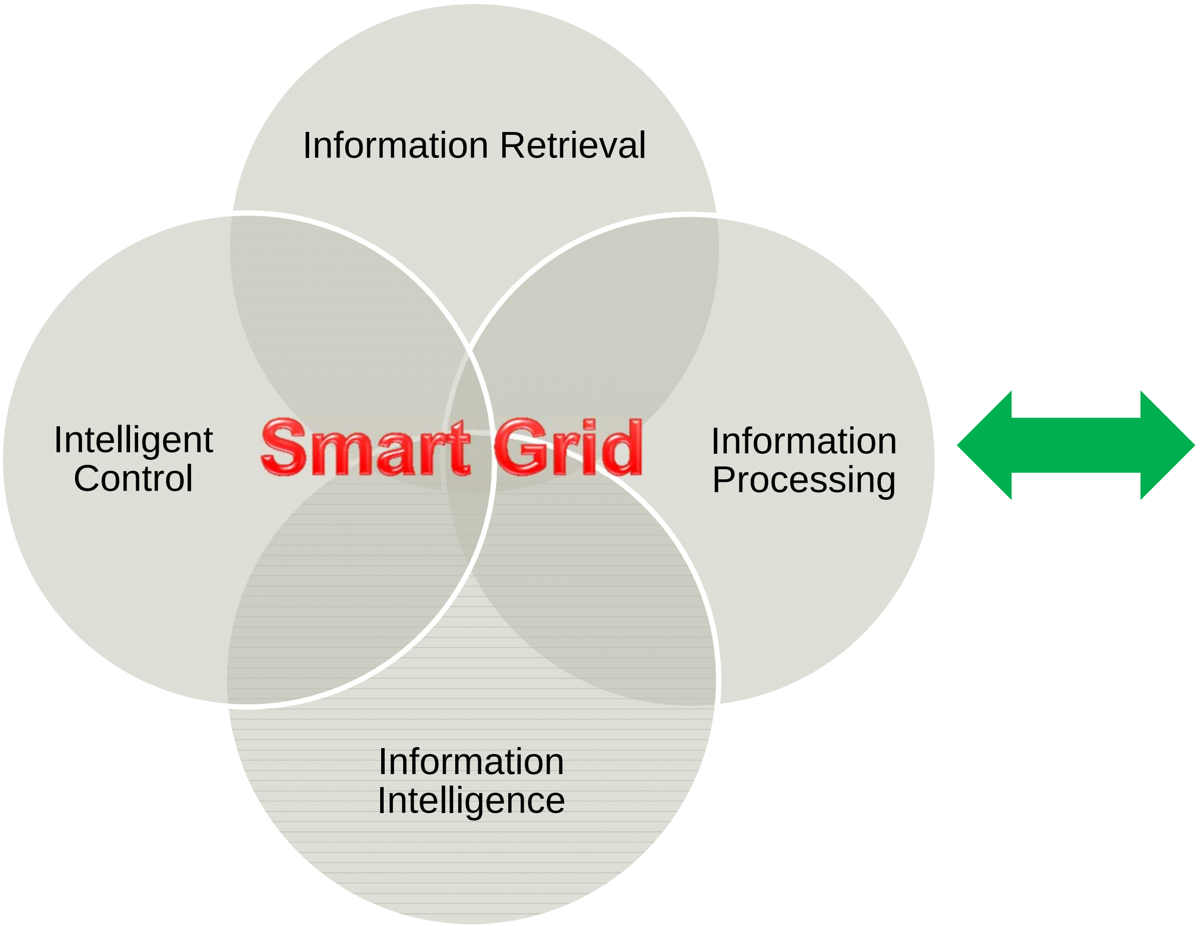


Figure courtesy of Petr Stluka, Honeywell

智能电网的高度复杂性。。。

- High complexity: large-scale, nonlinear, switched, uncertain, networked, multi-agent, multi-objective, inertial versus non-inertial mechanisms
- Bidirectional electricity flows
- Intermittent availability
- Randomness (e.g. Electric Vehicle charging behaviours)
- Massive nodes (e.g. renewable energy sources, smart meters)
- Smart metering data stream mining applications
- Different time scales in operations
- Power quality monitoring and control
- Security and safety issues
- Integration within the Cyber-Physical mega-system framework
- Social behaviours (flocking, swarming, human psychological behaviors)

智能电网的信息与控制问题。。。



Control issues

- Milti-level monitoring and diagnosis – *self awareness*
- Distributed adaptive control – self-organising
- Reconfigurability – self-healing
- Big Data Intelligence

The key question is how to handle the sheer size and complexity of smart grids effectively in real time?

Thank you!