Nonlinear Control

Stuttgart university, May 2018

Intro

Goals of Course

- overview over moder nonlinear analyses and control concepts
- modern methodologies to analyze nonlinear systems
- apply a wide range of nonlinear control method learn the mathmatic basis

Differential equations $\dot{x} = f(x)$

Nonlinear differential eqution $\dot{x} = f(t, x)$

System with input $\dot{x} = f(x, u)$

System with input and output $\dot{x} = f(x, u), \quad y = g(x, u)$

Input-output methods

Scope

[1] Khalil Nonlinear System, Prentice Hall, 2002

[2] Sepulchre Constructive Nonlinear Control, Springer-Verlag 1997

1 Differential equations

Consider differential equality

$$\frac{d}{dt}x(t) = \dot{x}(t) = f(x(t)), \; x(0) = x_0 \tag{1}$$

Where $f : D \to R^n, \; D \subset R^n$ is open, [here we should explain, what means open set].

Solution to 1 $x : I_{x_0} \to D, \; t \to x(t)$ is differentiable

Interval existence solution

Questions:

existence of solution

"how large" is I_{x_0}

uniquence of solution

Usaly we will add some restrictions on f functions, like continuous.

1.1 Existence of solutions

Definition. Function $f : D \to R^n$ is contiuous at $x' \in D$ if for $\forall \epsilon > 0\ \exists \delta > 0$ such that for $\forall x \in D$, $\|x - x'\| < \delta => \|f(x) - f(x')\| < \epsilon$

Function $f : D \to R^n$ is continuous on D if it's continuous at $\forall x' \in D$

Theorem 1.1 (Piano)**.** If $f : D \to R^n$ continuous, then for each $x_0 \in D\ \exists x : (-\epsilon, \epsilon) \to D,\ \epsilon > 0$ satisfying (1).

Further, given a compact sed $U \subset D$, then $\exists \alpha > 0$ s.t. $\forall x_0 \in U\ \exists x : (-\epsilon, \epsilon) \to D$ satisfying (1).

Example. Consider equation $\dot{x}(t) = x(t)^2,\ \ x(0) = x_0 = 0$. Solution $x(t) = -\frac{1}{t-c},\ \ c = \frac{1}{x_0}$. In this example solution exist in interval $(-c, c)$.

But, what about the number of solutions? Which conditions we should add to garanty uniquence of solution?

1.2 Uniquence of solutions

Definition. Function $f : D \to R^n$ is locally Lipshitz (continuous???) on D if $\forall x \in D$ there is a neighborhood $N(x) \subset D$ and $\exists L > 0$ s.t.

$$||f(x_1) - f(x_2)|| \leq L||x_1 - x_2|| \tag{2}$$

For all $x_1, x_2 \in N$.

- Lipschiz on $W \in D$ if (2) holds $\forall x_1, x_2 \in W$ (with same L)
- globally Lipschitz if (2) holds $\forall x_1, x_2 \in R^n$ (with same L)

We have

localy Lipschitz functions are continuous

differenciable functions are locally Lipschitz

locally Lipschitz functions are Lipschitz on each compact subset of D (Khalil Ex 3.19)

Lemma 1 (Cromwall)**.** Suppose that $0 \le \phi(t) \le c + L\int_0^t \phi(\tau)d\tau$, $c, L > 0$, ϕ – continuous. Then $\phi(t) \le ce^{Lt}$.

Proof. $c + L\int_0^t \phi(\tau)d\tau := \psi(t)$, $\dot{\psi}(t) = L\phi(t) \le L\psi(t)$.

Consider $\frac{d}{dt}\left(\psi(t)e^{-LT}\right) = e^{-Lt}\dot{\psi}(t) - L\psi(t)\,() \le 0$, thus $\psi(t)e^{-LT}$ is decreased, and as a result we have $\phi(t)e^{-Lt} \le \psi(t)e^{-Lt} \le \psi(0) = c$

□

Theorem 1.2 (Picard Lindelof)**.** If function $f : D \to R^n$ is localy Lipschitz then for $\forall x_0 \in D$ $\exists! x : (-\epsilon, \epsilon) \to D$, $\epsilon > 0$ satisfying (1).

Proof. * existence from Piano theorem

Proof of uniqueness

Consider two solutions $x_1(.)$ and $x_2(.)$ to (1). $\dot{x}_1 - \dot{x}_2 = f(x_1) - f(x_2)$, $x_1(0) = x_2(0)$. Then we can integrate equality: $x_1(t) - x_2(t) = \int_0^t f(x_1(\tau)) - f(x_2(\tau))d\tau$. $|x_1(t) - x_2(t)| \le \int_0^t |f(x_1(\tau)) - f(x_2(\tau))|d\tau \le L\int_0^t |f(x_1(\tau)) - f(x_2(\tau))|d\tau$. Now we can apply Cromwall's lemma with $c = 0$ and $\phi(t) = |x_1(t) - x_2(t)|$, then $\phi(t) \le 0$, then $x_1(t) = x_2(t)$, $\forall t \in (-\epsilon, \epsilon)$ □

Example.

$$\dot{x} = \begin{cases} \sqrt{x}, & \text{if } x \ge 0 \\ 0, & \text{else } x < 0 \end{cases}$$

$$Solutions\ x(t) = \begin{cases} \frac{1}{4}(t-c)^2, & \text{if } t \ge c \ge 0 \\ 0, & \text{else} \end{cases}$$

Global existance & uniqueness

- sufficient condition: f globally Lipschitz
- another sufficient condition: solution entirely lies in a coplex set
- forward completeness has equivalent Lyapunov-like characterization: system is forward-complete iff $\exists$ solution $V : R^n \to R \ge 0$ s.t. $\frac{\partial V}{\partial x} f(x) \le V(x)$, $\forall x \in R^n$

1.3 Lyapunov stability

If functions $\dot{V}(x) < 0$, $\forall x \in D$
$\{0\}$, then x^* is asymptotically stable.

Definition. Equilibrium point $x = 0$ is stable if $\forall \epsilon > 0\ \exists \delta > 0$ s.t. from $\|x_0\| < \delta$ follows $\|x(t)\| \leq \epsilon,\ \forall t \geq 0$.

Definition. Equilibrium point $x = 0$ is asymptotikaly stable if it stable and exist $\delta > 0$ s.t. from $\|x_0\| < \delta$ follows $\lim_{t\to\infty} x(t) \to 0$.

Theorem 1.3 (Lyapunov's direct method)**.** Let $x^* = 0 \in D$ be an equilibrium point of (1), i.e., $f(0) = 0$. Let $f : D \to R^n$ is continious. If there exist a differetiable $V : D \to R$ s.t.

1. $V(x^*) = 0$, $V(x) > 0$, $\forall x \in D$
   $\{0\}$
2. $\dot{V}(x) = \frac{\partial V}{\partial x} f(x) \leq 0$, $\forall x \in D$

then $x^* = 0$ is stable.

Proof. Fix compact $U = \{x : V(x) \leq c\}$ s.t. $U \in D$. By Piano: exist $\alpha > 0$ s.t. any solution x with $x_0 \in U$ exists at least on the interval $[0, \alpha)$.

TODO proof is not full □

Lyapunovs direct method gives us:

- stability
- convergence (if $V < 0$)
- subset of the region of attraction (all compact $U = \{x : V(x) \leq c\} \in D$)
- existance of solution for all times

2 Nonlinear systems

In this section we consider function $f : R \times D \to R^n$, where $D \subseteq R^n$, and D is open.

$$\dot{x}(t) = f(t, x(t)), \quad t \geq t_0 \geq 0, \quad x(t_0) = x_0 \tag{3}$$

The origin $x^* \in D$ is an equilinrium point for (3), if $f(t, 0) = 0, \quad \forall t \geq 0$.

Remark: EP (equilibrium point) $x^* = 0$ can be translation of a nonzero solution.

Suppose $\overline{y}$ is a solution of $\dot{y} = g(t, y)$.

Change of coordinates: $x(t) = y(t) - \overline{y}(t)$, then $\dot{x}(t) = \dot{y}(t) - \dot{\overline{y}}(t) = g(t, x(t) + \overline{y}(t)) - \dot{\overline{y}}(t) := f(t, x(t))$. Since $\dot{\overline{y}}(t) = g * t, \overline{y}(t))$, then $f(t, 0) = 0,\ \forall t \geq 0$.

Existance and uniquence of solution to (3):

- if f continuous, then exist local colution
- if f continuous and locally Lipschitz in x^*, then exist local uniq solution

Now we need new stability definitions.

Definition. Point $x^* = 0$ is stable if $\forall \epsilon > 0$ and $\forall t_0 \geq 0$, $\exists \delta > 0$ s.t. from $||x_0|| < \delta$ follows $||x(t)|| < \epsilon$, $\forall t \geq t_0$.

Definition. Point $x^* = 0$ is uniformly stable if $\forall \epsilon > 0 \;\; \exists \delta > 0$, s.t $\forall t_0 \geq 0$, from $||x_0|| < \delta$ follows $||x(t)|| < \epsilon$, $\forall t \geq t_0$.

Definition. Point $x^* = 0$ asymptoticaly stable if it is stable and $\forall t_0 \geq 0 \;\; \exists c > 0$, s.t from $||x_0|| < c$ follows $\lim_{t \to \infty} ||x(t)|| \to 0$.

Definition. Point $x^* = 0$ uniformly asymptoticaly stable if it is uniformly stable and $\exists c > 0$, s.t $\forall t_0 \geq 0$ from $||x_0|| < c$ follows $\lim_{t \to \infty} ||x(t)|| \to 0$.

Definition. Convergence: $\forall \eta > 0 \;\; \forall t_0 \geq 0$, $\exists T > 0$ such that $\forall t \geq t_0 + T$ follows $||x(t)|| < \eta$.

Definition. Uniform convergence: $\forall \eta > 0 \;\; \exists T > 0$ such that $\forall t_0 \geq 0$ and $\forall t \geq t_0 + T$ follows $||x(t)|| < \eta$.

Example. Consider next equation:

$$\dot{x}(t) = -\frac{x(t)}{1+t}, \quad t_0 \geq 0$$

Solution $x(t) = x(t_0)\frac{1+t_0}{1+t}$. It is uniformly stable, because we can choose $\delta = \epsilon$. But does $x(t)$ convergence uniformly? Answer is no.

Definition. Point $x^* = 0$ is globaly uniformly asymptotically stable if it is uniformly stable with $\delta \to \infty$ for $\epsilon \to \infty$ and $\forall c, \eta \quad \exists T > 0$ such that $\forall t_0 \geq 0$ from $||x_0|| < c$ follows $\|x(t)\| < \eta$, $\forall t \geq t_0 + T$.

2.1 Lyapunov's direct method

Consider some function $V : [0, \infty) \times D \to R$, $(t, x) \to V(t, x)$ such that $\dot{V}(t, x) = \frac{\partial}{\partial t}V(t, x) + \frac{\partial}{\partial x}V(t, x)f(t, x)$.

Theorem 2.1 (Lyapunov's direct method)**.** Let $f : [0, \infty) \times D \to R^n$ is continuous and let $x^* = 0$ be equilibrium point. If there is a differentiable function $V : [0, \infty) \times D \to R$ with:

- $W_1(x) \leq V(t, x) \leq W_2(x)$, $\forall t \geq 0, \;\; x \in D$
- $\dot{V}(t, x) \leq 0$, $\forall t \geq 0, \;\; x \in D$

where $W_1, W_2 : D \to R$ continuous and positive definite, then $x^* = 0$ is uniformly stable.

If further $\dot{V}(t,x) \leq -W_3(x)$, $\forall t \geq 0,\ x \in D$ with $W_3 : D \to R$ continuous and positive definite, the $x^* = 0$ is uniformly asymptotically stable.

If $D = R^n$ and W_1 is radialy unbounded then $X^* = 0$ is globally uniformly asymptotically stable.

Example. Consider the equation $\dot{x}(t) = -(1+t)x(t)$.

Check function $V(t,x) = \frac{1}{2}x^2$ as candidat for Lyapunov's function. Then $W_1(x) = W_2(x) = \frac{1}{2}x^2$ and $\dot{V}(t,x) = -(1+t)x^2 \leq -x^2(t) =: W_3(x)$. Then from theorem we have, that $X^* = 0$ is globally uniformly asymptotically stable.

2.2 Exponential stability

Definition. Point $X^* = 0$ is an exponentially stable EP of (3) if $\exists \lambda, c, k > 0$ s.t. $t \geq t_0 \geq 0$ and all $\|x_0\| < c$ follows $\|x(t)\| \leq K\|x(t_0)\|e^{\lambda(t-t_0)}$.

Remark: from exponential stability follows uniformly asymptoticaly stability.

Lemma 2 (Auxilarity result)**.** Let $\dot{x}(t) = f(t, x(t))$, f scalar and $\dot{\xi}(t) \leq f(t, \xi(t)$ with $\xi(t_0) \leq x(t_0)$. Then $\xi(t) \leq x(t) \quad \forall t \geq t_0$.

Theorem 2.2. Let $f : [0, \infty) \times D \to R^n$ be continuous and $x^* = 0 \in D$ be an EP.

If there is a differentiable function $V : [0, \infty) \times D \to R$ and constants $k_1, k_2, k_3, a > 0$ s.t.

1. $k_1||x||^a \leq V(t,x) \leq k_2\|x\|^a$, $\forall t \geq 0,\ x \in D$
2. $\dot{V}(t,x) \leq -k_3\|x\|^a$

then $x^* = 0$ is exponentially stable.

If $D = R^n$, then X^* is globally exponential stable.

Proof. For $c > 0$ small enough, trajectories initialized in $\{x : k_2||x||^a < c\}$ remain bounded and in D. From 1) and 2) we can conclude $\dot{V} \leq -\frac{k_3}{k_2}V$. Then from previous Lemma $V(t, x(t)) \leq V(t_0, x(t_0))e^{-\frac{k_3}{k_2}(t-t_0)}$. Then $||x(t)|| \leq [from 1)] \leq \left(\frac{V(t,x(t))}{k_1}\right)^{\frac{1}{a}} \leq \left(\frac{V(t_0,x(t_0))e^{-\frac{k_3}{k_2}(t-t_0)}}{k_1}\right)^{\frac{1}{a}} \leq \left(\frac{k_2||x(t_0)||^a e^{-\frac{k_3}{k_2}(t-t_0)}}{k_1}\right)^{\frac{1}{a}}$ $\left(\frac{k_2}{k_1}\right)^{\frac{1}{a}} ||x(t_0)||e^{-\frac{k_3}{k_2 a}(t-t_0)}$ ∎

Example. Consider the equation $\dot{x}(t) = -(1+t)x(t)$.

Here $V(t,x) = \frac{1}{2}x^2$ then X^* is exponentially stable.

2.3 Comparsion function

Definition. A function $\alpha : [0, \delta) \to [0, \infty)$ is (of) "klass K" if it is continous, strictly increasing, and $\alpha(0) = 0$.

Definition. A function $\alpha : [0, \delta) \to [0, \infty)$ is "class K_∞ if $\alpha in K$ and $\lim_{r \to \infty} \to \infty$.

Example. Function $\alpha(r) = \tan^{-1}(r)$ – class K

Function $\alpha(r) = r^k$ – class K_∞

Definition. A function $\beta : [0, \delta) \times [0, \delta) \to [0, \infty)$ is "class KL if it is continuous , $\beta(\cdot, s) \in K$ for all fixed s, and for each fixed r, $\beta(r, \cdot)$ is strictly decreasing: $\lim_{s \to \infty} \beta(r, s) = 0$

Example. Function $\beta(x, s) = max(r, r^2)e^s$ belong class KL.

Properties of compasion functions:

- If $\alpha \in K$ on $[0, \delta)$, then α^{-1} is defined on $[0, \alpha(\delta))$ and $\alpha^-1 \in K$.
- If $\alpha \in K_\infty$, then $\alpha^{-1} \in K_\infty$
- If $\alpha_1, \alpha_2 \in K$, then $\alpha_1 \circ \alpha_2 \in K$ (same for K_∞
- If $\alpha_1, \alpha_2 \in K$, $\beta \in KL$ then $\alpha_1(\beta(\alpha_2(r), s)) \in KL$

Now we conseider comparsion funcctions and stability definitions.

Lemma 3. The equilibrium $x^* = 0$ of $\dot{x}(t) = f(t, x(t))$ is uniformly stable iff $\exists \alpha \in K$ and $c > 0$ s.t. $\forall t \geq t_0$, $\forall ||x(t_0)|| < c$ and $||x(t)|| \leq \alpha(||x(t_0)||)$.

(only sufficiency). Given $\epsilon > 0$ choose $\delta < \min(c, \alpha^{-1}(\epsilon))$. Then from $||x(t_0)|| < \delta$ follows $||x(t)|| \leq \alpha(||x(t_0)||) < \alpha(\alpha^{-1}(\epsilon)) = \epsilon$. □

Lemma 4. The equilibrium $x^* = 0$ of $\dot{x}(t) = f(t, x(t))$ is uniformly asymptotically stable iff $\exists \beta \in KL$ and $c > 0$ s.t. $\forall t \geq t_0$, $\forall ||x(t_0)|| < c$ and $||x(t)|| \leq \beta(||x(t_0)||, t - t_0)$.

(only sufficiency). Let $\|x(t_0)\| < c$. Then $\|x(t)\| \leq \beta(\|x(t_0)\|, t - t_0) < \beta(c, t - t_0)$. This mean uniform convergence. $\|x(t)\| \leq \beta(\|x(t_0)\|, t - t_0) < \beta(\|x_{t_0}\|, 0)$. This gives us uniform stability. □

Lemma 5. The equilibrium $x^* = 0$ of $\dot{x}(t) = f(t, x(t))$ is uniformly asymptotically stable iff $\exists \beta \in KL$ and $c > 0$ s.t. $\forall t \geq t_0$, $\forall ||x(t_0)|| < c$ and $||x(t)|| \leq \beta(||x(t_0)||, t - t_0)$.

(only sufficiency). Let $||x(t_0)|| < c$. Then $||x(t)|| \leq \beta(||x(t_0)||, t - t_0) < \beta(c, t - t_0)$. This mean uniform convergence. $||x(t)|| \leq \beta(||x(t_0)||, t - t_0) < \beta(||x_{t_0}||, 0)$. This gives us uniform stability. □

Lemma 6. The equilibrium $x^* = 0$ of $\dot{x}(t) = f(t, x(t))$ is globally uniformly asymptotically stable iff previous lemma holds for all $x_0 \in R^n$.

Now consider comparsion functios and Lyapunov functions

If $W : R^n \to R$ is continuous and positive definite, then $\forall r > 0 \;\; \exists \alpha_1, \alpha_2 \in K$ s.t. $\alpha_1(||x||) \leq W(x) \leq \alpha_2(|x||)$ for all $x \in B_r(0) = \{x|||x|| \leq r\}$.

If W is radially unbounded, then $\exists \alpha_1, \alpha_2 \in K_\infty$ s.t. $\alpha_1(||x||) \leq W(x) \leq \alpha_2(|x||)$ for all $x \in R^n$.

Lemma 7 (Auxility)**.** Consider $\dot{y} = \alpha(y), \;\; y(t_0) = y_0 > 0, \; \alpha \in K$. Then $\exists \beta \in KL$ s.t. $y(t) = \beta(y_0, t - t_0)$.

Sketch of proof of Lyapunov's direct method:

$$\begin{cases} W_1(x) \leq V(t,x) \leq W_2(x) \\ \dot{V} \leq -W_3(x) \end{cases}$$

Where W_1, W_2, W_3 – continuous and positive defined.

Then $\exists \alpha_1, \alpha_2, \alpha_3 \in K$ such that $\alpha_1(||x||) \leq V(t,x) \leq \alpha_2(||x||)$ and $\dot{V}(t,x) \leq -\alpha_3(||x||)$.

Proof uniform stability:

$||x(t)|| \leq \alpha_1^{-1}(V(t,x(t)) \leq [\alpha_1 inK] \leq \alpha_1^{-1}(V(t_0,x(t_0)) \leq \alpha_1^{-1}(\alpha_2(||x(t_0)||))$.

Proof uniform convergence

$\dot{V} \leq -\alpha_3(||x||) \leq -\alpha_3(\alpha_2^{-1}(V))$. We know, that $\alpha_3 \circ \alpha_2^{-1} \in K$. By comparsion lemma, $V(t,x(t)) \leq W(t)$, where W solves $\dot{W} = -\alpha_3(\alpha_2^{-1}(W))$ with $W(t_0) = V(t_0, x(t_0))$. By auxility lemma $\exists \beta \in KL$ s.t. $V(t,x(t)) \leq \beta(V(t_0,x(t_0)), t - t_0)$, then $||x(t)|| \leq \alpha_1^{-1}(V(t,x(t))) \leq \alpha_1^{-1}(\beta(V(t_0,x(t_0)), t-t_0)) \leq \alpha_1^{-1}(\beta(\alpha_2(||x(t_0)||), t - t_0)) =: \bar{\beta}(||x(t_0)||, t - t_0)$. From this follows uniform asymptotic stability since $\bar{\beta} \in KL$.

2.4 Converse theorems

Theorem 2.3. Let $X^* = 0$ be an EP of $\dot{x}(t) = f(t, x(t))$ with $f : [0, \infty) \times R^n \to R^n$ continously differentiable and $\frac{\partial f}{\partial x}$ bounded in R^n, uniformly in t $(||\frac{\partial f}{\partial x}(t,x)|| \leq L$ for all $x \in R^n, \; t \geq 0, \; L > 0$.

If $x^* = 0$ is globally exponentially stale, then exists differentiable $V : [0, \infty) \times R^n \to R$ and $c_1, c_2, c_3, c_4 > 0$ s.t. $c_1||x||^2 \leq V(t,x) \leq c_2||x||^2$, $\dot{V}(t,x) \leq -c_3||x||^2$ and $\left\|\frac{\partial V}{\partial x}\right\| \leq c_4||x||$.

Proof. Let $\Phi(\tau; t, x)$ – solution to $\dot{x}(t) = f(t, x(t))$ which static at (t, x).

$V(t,x) = \int_t^{t+\delta} \Phi^T(\tau;t,x)\Phi(\tau;t,x)d\tau, \quad \delta > 0$. Upper bound: $V(t,x) = \int_t^{t+\delta} ||\Phi(\tau;t,x)||_2^2 d\tau \leq$ [*exponential stability*] $\leq \int_t^{t+\delta} k^2 e^{-2\lambda(\tau - t)} d\tau ||x||_2^2 = \frac{k^2}{2\lambda}(1 - e^{-2\lambda\delta})||x||_2^2$.

Lower bound: since $\left\|\frac{\partial V}{\partial x}\right\| \leq L$, then $||f(t,x)||_2 \leq L||x||_2$. Thus by comparation lemma $||\Phi(\tau;t,x)||_2^2 \geq ||x||_2^2 e^{-2L(\tau - t)}$. Set it in $V(t,x) \geq \int_t^{t+\delta} e^{-2L(\tau-t)} d\tau ||x||_2^2 = \frac{1}{2L}(1 - e^{-2L\delta})||x||_2^2$.

Decrease conditions: $\dot{V}(t,x) = \dots \leq -(1-k^2 e^{-2\lambda\delta})||x||_2^2$. $\square$

3 System with inputs

Consider equation:

$$\dot{x}(t) = f(x(t), u(t)), \quad x(0) = x_0 \tag{4}$$

where $f : R^n \to R^n$.

Assumption: f in localy Lipschitz.

Exageneous signa $u : R \to R^n$.

Input can be "bad" (disturbance) or "good" (control).

3.1 Input-to-state stability

Motivation: LTI system $\dot{x} = Ax + Bu, \quad x(0) = x_0$.

Solution: $x(t) = e^{At}x_0 + \int_0^t e^{A(t-\tau)}Bu(\tau)d\tau$. If A is Hurwitz, then $||e^{At}|| \leq ce^{-\lambda t}$ for some $c, \lambda > 0$.

How large can x grow for some bounded u? $||x(t)|| \leq ||e^{At}||||x_0|| + \int_0^t ||e^{A(t-\tau)}||||B||||u(\tau)||d\tau \leq e^{-\lambda t}c||x_0|| + \int_0^t e^{-\lambda(t-\tau)}c||B||||u(\tau)||d\tau = ce^{-\lambda t}||x_0|| + (1-e^{-\lambda t})\ \frac{c}{\lambda}||B|| \sup_{\tau\in[0,t]} ||u(\tau)||$.

- $ce^{-\lambda t}||x_0||$ class KL in $(||x_0||, t)$
- $(1-e^{-\lambda t})$ less than 1
- $\frac{c}{\lambda}||B|| \sup ||u(\tau)||$ class K

If $\sup_{\tau\in[0,t]} ||u(\tau)||$ is bounded than $\dot{x}$ remains bounded. Even more: the smaller $\sup_{\tau\in[0,t]} ||u(\tau)||$, the smaller $||x(t)||$.

Definition. System (4) is input-to-state stable (ISS) if $\exists \beta \in KL$, $\gamma \in K$ s.t. $\forall x_0 \in R^n$, $\forall t \geq 0$ follows $||x(t)|| \leq \beta(||x_0||, t) + \gamma(\sup_{\tau\in[0,t]} ||u(\tau)||)$.

Remarks:

- From ISS follows O-GAS (global assymptotical stability of $x = 0$ for $\dot{x} = f(x, 0)$
- γ can be interpreted as "gain" w.r.t. u

- if $\lim_{t\to\infty} u(t) = 0$ then $\lim_{t\to\infty} x(t) = 0$

Example. Consider equation $\dot{x} = -x + xu$. System is O-GASS, not ISS (for example $u \equiv \alpha \Rightarrow \dot{x} = x(\alpha - 1)$ all solution diverge).

Example. Consider equation $\dot{x} = -3x + (1 + 2x^2)u$. System is O-GASS, not ISS (for example $u \equiv 1$, $x_0 = 2$, $x(t) = \frac{3-e^t}{3-2e^t}$ has a finite escape time.

Theorem 3.1. Suppose that there exists a continuously differentiable function $V : R^n \to R$ and $\alpha_1, \alpha_2 \in K_\infty$ and $\alpha_3, \rho \in K$ such that $\alpha_1(||x||) \leq V(x) \leq \alpha_2(||x||)$, $\forall x \in R^n$ and $\frac{\partial V}{\partial x} f(x,u) \leq -\alpha_3(||x||)$, $\forall x : ||x|| \geq \rho(||u||)$. Then (4) is ISS with $\gamma = \alpha_1^{-1} \circ \alpha_2 \circ \rho$

Proof. Idea: same as Lyapunovs direct method when x is "outside" of ball $\{x|||x|| \leq \rho(||u||)\}$

TODO Picture □

Example. Consider equality $\dot{x} = -x^3 + u$. Let $V(x) = \frac{1}{2}x^2$, then $\dot{V} = -x^4 + xu = [0 < \Theta < 1] = -(1-\Theta)x^4 - \Theta x^4 + xu \leq -(1-\Theta)x^4$ for all $x : ||x|| \geq \left(\frac{||u||}{\Theta}\right)^{\frac{1}{3}}$. Thus, system is ISS with $\gamma(v) = \rho(v) = \left(\frac{v}{\Theta}\right)^{\frac{1}{3}}$.

4 Backstepping

These remarks from the last lecture, so should be added to the last chapter

$$\forall x \neq 0 : \inf_u \frac{\partial V}{\partial x} f(x,u) < 0 \; \dot{x} = f(x) + G(x)u$$

So this leads to

$$\forall x \neq 0 L_G V(x) = 0 \Rightarrow L_f V(x) \neq 0$$

Remark: The last formula is "optimal" if minimize:

$$\int_0^\infty \frac{1}{2} p(x) b(x)^T b(x) + \frac{1}{2p(x)} u^T u dt$$

$b(x) := (L_G V(x))^T$

where $c > 0$

$$p(x) = \begin{cases} c + \frac{a(x) + \sqrt{a(x)^2 + (b(x)^T b(x))^2}}{b(x)^T b(x)} & b(x) \neq 0 \\ c & b(x) = 0 \end{cases}$$

It still works if $u = \lambda h(x)$ with $\lambda \in [\frac{1}{2}; \infty)$ is applied (large "gain margin")

This is Backstepping

Integrator backstepping

$$\dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 \tag{5}$$
$$\dot{x}_2 = u$$

where $x_1 \in \mathbb{R}^m,\ x_2,\ u \in \mathbb{R}$ (single input)

image to be inserted

Assumption: we know (smooth) "feedback" $\alpha_1 : \mathbb{R}^n \to \mathbb{R}$, and positive definite, differentiable $v_1 : \mathbb{R}^m \to \mathbb{R}$

s.t. $L_{f_1+g_1\alpha_1}V_1(x)$ is negative definite $\Rightarrow$ origin of $\dot{x_1} = f_1(x_1) + g_1(x_1)\alpha_1(x_1)$ is asymptotically stable

Goal: Compute feedback $u = k(x)$ which stabilises (5). Backstepping constructs $u = \alpha_2(x_1, x_2)$ s.t. $(e_1, e_2) = (x_1 - 0, x_2 - \alpha_1(x_1)) = 0$ error coordinates

Rewrite (5) :

$$\dot{x}_1 = f_1(x_1) + g_1\alpha_1(x_1) + g_1(x_1)(x_2 - \alpha_1(x_1))$$
$$\dot{x}_2 = u$$

image to be inserted

In error coordinates

$$\dot{e}_1 = f_1(e_1) + g_1(e_1)\alpha_1(e_1) + g_1(e_1)e_2 \tag{6}$$
$$\dot{e}_2 = u - \dot{\alpha_1} = u - \frac{\partial \alpha_1}{\partial e_1}\dot{e_1} = u - \frac{\partial \alpha_1}{\partial e_1}$$

"backstepping" α_1 through the integrator

Define $V_2(e_2) := \frac{1}{2}e_2^2$, and

$$V(e_1, e_2) = V_1(e_1) + V_2(e_2)$$
$$\dot{V}(e_1, e_2) = \frac{\partial V_1}{\partial e_1}(f_1(e_1) + g_1(e_1)\alpha_1(e_1)) + \frac{\partial V_1}{\partial e_1}g_1(e_1)e_2 + \frac{\partial V_2}{\partial e_2}(u - \dot{\alpha_1})$$

as far as $L_{f_1+g_1\alpha_1}V_1$ -negative definite and $\frac{\partial V_2}{\partial e_2} \to e_2$

Choose

$$u = (-\frac{\partial V_1}{\partial e_1}g_1(e_1) + \dot{\alpha_1})(\text{"}\textit{canaling terms}\text{"}) - k_2e_2(\text{"}\textit{stabilizing term}\text{"})k_2 > 0 \tag{7}$$

$\Rightarrow$ Then $\dot{V}(e_1, e_2) = L_{f_1+g_1\alpha_1}V_1(e_1) - k_2e_2^2 < 0,\ \forall(e_1, e_2) \neq 0$

$\Rightarrow$ Then $\dot{V}(e_1, e_2) = L_{f_1+g_1\alpha_1}V_1(e_1) - k_2e_2^2 < 0 \; \forall (e_1, e_2) \neq 0$

$\Rightarrow (e_1, e_2) = (0, 0)$ is an asymptotically stable EP for (6) with u as in (7)

Remark: $(e_1, e_2) \to (0, 0)$ doesnot necessarily imply that $(x_1, x_2) \to 0$ for $u = \alpha_2(x_1, x_2) = -\frac{\partial V_1}{\partial x_1}g_1(x_1) + \dot{\alpha_1} - k_2(x_2 - \alpha_1(x_1))$

where $u \leftarrow$ (7) the original coordinates and $\dot{\alpha_1} \leftarrow \frac{\partial \alpha_1}{\partial x_1}(f_1(x_1) + g_1(x_1)x_2)$

But $(x_1, x_2) = (0, 0)$ is asymptotically stable if $\alpha_1(0) = 0$ why? $(e_1, e_2) \to 0 \Rightarrow x_1 \to 0 \; x_2 \to \alpha_1(0) = 0$

Example.

$$\dot{x_1} = x_1x_2$$
$$\dot{x_2} = u$$

Choose $\alpha_1(x_1) = -k \; (k > 0) \to \dot{x_1} = -kx_1 \Rightarrow V_1(x_1) = \frac{1}{2}x_1^2$

Then:

$$e_1 = x_1 - 0 \; \dot{e_1} = e_1(e_2 - k)$$
$$e_2 = x_2 + k \; e_2 = u$$

Backstepping yields: $u = -e_1^2 - k_2e_2 \; k_2 > 0 \Rightarrow (e_1, e_2) = (0, 0)$ is asymptotically stabilized

$(x_1, x_2) = (0, -k)$ is asymptotically stabilized

Can we choose different α_1 s.t. $(x_1, x_2) = (0, 0)$ is stabilized?

Yes, e.g.

$$\alpha_1(x_1) = -x_1^2 \Rightarrow \dot{x_1} = -x_1^3 \; V_1(x_1) = \frac{1}{2}x_1^2$$

So we have equations

$$e_1 = x_1 - 0 \; \dot{e_1} = e_1(e_2 - e_1^2)$$
$$e_2 = x_2 + x_1^2 \; \dot{e_2} = u + 2e_1^2(e_2 - e_1^2)$$

Backstepping results in

$$u = -e_1^2 - 2e_1^2(e_2 - e_1^2) - k_2e_2, \; k_2 > 0 \Rightarrow (e_1, e_2) \to (0, 0), \; (x_1, x_2) \to (0, 0)$$

Generalization-1

$$\dot{x_1} = f_1(x_1) + g_1(x_1)x_2$$

$$\dot{x_2} = f_2(x_1, x_2) + g_2(x_1, x_2)u$$

Assumption: $g_2(x_1, x_2) \neq 0 \forall x_1, x_2 \Rightarrow$ Input transformation: $u = \frac{1}{g_2(x_1,x_2)}(V - f_2(x_1, x_2)) \Rightarrow \dot{x_1} = f_1(x_1) + g_1(x_1)x_2 \; \dot{x_2} = V \Rightarrow$ can apply integrator backstepping to determine V results in

$$u = \alpha_2(x_1, x_2) = \frac{1}{g_2(x_1, x_2)}(-\frac{\partial V_1}{\partial x_1} g_1(x_1) + \dot{\alpha_1} - k_2(x_2 - \alpha_1(x_1)) - f_2(x_1, x_2))$$