A Appendices

Appendix A

Lyapunov Stability [1]

For all control systems and adaptive control systems in particular, stability is the primary requirement. Consider the time-varying system

$$\dot{x} = f(x, t) \tag{A.1}$$

where $x \in R^n$, and $f: R^n \times R_+ \to R^n$ is piecewise continuous in t and locally Lipschiz in x. The solution of (A.1) which starts from the point x_0 at time $t_0 \geq 0$ is denoted as $x(t; x_0, t_0)$ with $x(t_0; x_0, t_0) = x_0$. If the initial condition x_0 is perturbed to $\tilde{x}_0$, then, for stability, the resulting perturbed solution $x(t; \tilde{x}_0, t_0)$ is required to stay close to $x(t; x_0, t_0)$ for all $t \geq t_0$. In addition, for asymptotic stability, the error $x(t; \tilde{x}_0, t_0) \to x(t; x_0, t_0)$ is required to vanish as $t \to \infty$. So the solution $x(t; x_0, t_0)$ of (A.1) is

- *bounded*, if there exists a constant $B(x_0, t_0) > 0$ such that

$$|x(t; x_0, t_0)| < B(x_0, t_0), \quad \forall\ t \geq t_0;$$

- *stable*, if for each $\epsilon > 0$ there exists a $\delta(\epsilon, t_0) > 0$ such that

$$|\tilde{x}_0 - x_0| < \delta, \quad |x(t; \tilde{x}_0, t_0) - x(t; x_0, t_0)| < \epsilon, \quad \forall\ t \geq t_0;$$

- *attractive*, if there exists a $r(t_0) > 0$ and, for each $\epsilon > 0$, a $T(\epsilon, t_0) > 0$ such that

$$|\tilde{x}_0 - x_0| < r, \quad |x(t; \tilde{x}_0, t_0) - x(t; x_0, t_0)| < \epsilon, \quad \forall\ t \geq t_0 + T;$$

- *asymptotically stable*, if it is stable and attractive; and
- *unstable*, if it is not stable.

Theorem A.1 (Uniform Stability). Let $x = 0$ be an equilibrium point of (A.1) and $D = \{x \in R^n \mid |x| < r$. Let $V: \ D \times R^n \to R_+$ be a continuously differentiable function such that $\forall t \geq 0, \ \forall x \in D$, such that

$$\begin{aligned} \gamma_1(|x|) \leq V(x,t) &\leq \gamma_2(|x|) \\ \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} f(x,t) &\leq -\gamma_3(|x|) \end{aligned}$$

Then the equilibrium $x = 0$ is

- uniformly stable, if γ_1 and γ_2 are class κ functions on $[0, r)$ and $\gamma_3(.) \geq 0$ on $[0, r)$;
- uniformly asymptotically stable, if γ_1, γ_2 and γ_3 are class κ functions on $[0, r)$;
- exponentially stable, if $\gamma_i(\rho) = k_i \rho^\alpha$ on $[0, r), k_i > 0, \alpha > 0, i = 1, 2, 3$;
- globally uniformly stable, if $D = R^n$, γ_1 and γ_2 are class κ_∞ functions, and $\gamma_3(.) \geq 0$ on R_+;
- globally unifromly asymptotically stable, if $D = R^n$, γ_1 and γ_2 are class κ_∞ functions, and γ_3 is a class of κ function on R_+; and
- globally exponentially stable, if $D = R^n$ and $\gamma_i(\rho) = k_i \rho^\alpha$ on $R_+, k_i > 0, \alpha > 0, i = 1, 2, 3$.

Appendix B

LaSalle-Yoshizawa Theorem [1]

Theorem B.1 (LaSalle-Yoshizawa). Let $x = 0$ be an equilibrium point of (A.1) and suppose f is locally Lipschitz in x uniformly in t. Let $V: \ R^n \times R_+ \to R_+$ be a continuously differentiable function such that

$$\gamma_1(|x|) \leq V(x,t) \leq \gamma_2(|x|) \tag{B.1}$$

$$\dot{V} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} f(x,t) \leq -W(x) \leq 0 \tag{B.2}$$

$\forall \ t \geq 0, \ \forall \ x \in R^n$, where γ_1 and γ_2 are class k_∞ functions and W is a continuous function. Then, all solutions of (A.1) are globally uniformly bounded and satisfy

$$lim_{t \to \infty} W(x(t)) = 0 \tag{B.3}$$

In addition, if $W(x)$ is positive definite, then the equilibrium $x = 0$ is globally uniformly asymptotically stable.

Appendix C

Parameter Projection [1]

Defining the following convex set

$$II_\epsilon = \{\hat{\theta} \in IR^p | P(\hat{\theta}) \leq \epsilon\}, \quad II = \{\hat{\theta} \in IR^p | P(\hat{\theta}) \leq 0\} \tag{C.1}$$

which is a union of the set II and an $O(\epsilon)$-boundary layer around it. Let us denote the interior of II_ϵ by II^o and observe that $\nabla_{\hat{\theta}} P$ represents an outward normal vector at $\hat{\theta} \in \partial II_\epsilon$. The standard projection operator is

$$Proj\{\tau\} = \begin{cases} \tau & \hat{\theta} \in II^o \ or \ \nabla_{\hat{\theta}} P^t \tau \leq 0 \\ \left(I - c(\hat{\theta}) \Gamma \frac{\nabla_{\hat{\theta}} P \nabla_{\hat{\theta}} P^T}{\nabla_{\hat{\theta}} P^T \Gamma \nabla_{\hat{\theta}} P}\right)\tau & \hat{\theta} \in II_\epsilon / II^o \ and \ \nabla_{\hat{\theta}} P^T \tau > 0 \end{cases} \tag{C.2}$$

$$c(\hat{\theta}) = min\{1, \ \frac{P(\hat{\theta})}{\epsilon}\} \tag{C.3}$$

where Γ belongs to the set G of all positive definite symmetric $p \times p$ matrices. It is helpful to note that $c(\partial II_\epsilon) = 1$.

Theorem C.1 (Projection Operator). The following are the properties of the projection operator (C.2):

(i). The mapping $Proj$: $IR^p \times II_\epsilon \times G \to IR^p$ is locally Lipschiz in its arguments $\tau, \hat{\theta}, \Gamma$.

(ii). $Proj\{\tau\}^T \Gamma^{-1} Proj\{\tau\} \leq \tau^T \Gamma^{-1} \tau, \quad \forall \ \hat{\theta} \in II_\epsilon$.

(iii). Let $\Gamma(t), \tau(t)$ be continuously differentiable and $\dot{\hat{\theta}} = Proj\{\tau\}, \ \hat{\theta}(0) \in II_\epsilon$. Then, on its domain of definition, the solution $\hat{\theta}(t)$ remains in II_ϵ.

(iv). $-\tilde{\theta}^T \Gamma^{-1} Proj\{\tau\} \leq -\tilde{\theta}^T \Gamma^{-1} \tau$, $\forall \ \hat{\theta} \in II_\epsilon, \ \theta \in II$.

Appendix D

Internal Model Principle

Consider w generated by an exosystem

$$\dot{w} = Sw \tag{D.1}$$

where S is an unknown matrix having distinct eigenvalues with zero real parts. Such as

$$S = \begin{bmatrix} S_1 & \ldots & 0 \\ . & \ldots & . \\ 0 & \ldots & S_m \end{bmatrix}, \quad S_1 = \begin{bmatrix} 0 & \beta_1 \\ -\beta_1 & 0 \end{bmatrix} \quad \ldots \quad S_m = \begin{bmatrix} 0 & \beta_m \\ -\beta_m & 0 \end{bmatrix} \tag{D.2}$$

where $w = \text{col}(w_{11}, w_{12}, \ldots, w_{m1}, w_{m2})$, $\beta_1, \ldots, \beta_m$ are constants.

Lemma D.1. Let A be a $n \times n$ matrix having all eigenvalues with nonzero real part and S be a matrix which the eigenvalues are zero real parts and distinct as in (D.2). Let $\mathcal{P}$ denote the set of all homogeneous polynomials of degree p in $w_{11}, w_{12}, \ldots, w_{m1}, w_{m2}$ with coefficients in $\mathcal{R}$. For any $q(w) \in \mathcal{P}^n$, the equation

$$\frac{\partial \pi(w)}{\partial w} Sw = A\pi(w) + q(w) \tag{D.3}$$

has a unique solution $\pi(w)$, which is an element of $\mathcal{P}^n$.

Proof. Follows the proof as in [171]. $\mathcal{P}$ is indeed a vector space over $\mathcal{R}$, of finite dimension $d(p, m)$. Set

$$X_i = w_{i1} - jw_{i2}, \quad \bar{X}_i = w_{i1} + jw_{i2} \tag{D.4}$$

and note that any $b(w) \in \mathcal{P}$ can be written as

$$b(w) = \sum_{i_1+j_1+\ldots+i_m+j_m=p} b_{i_1 j_1 \ldots i_m j_m} X_i^{i_1} \bar{X}_1^{j_1} \ldots X_m^{i_m} \bar{X}_m^{j_m} \tag{D.5}$$

where $b_{i_1 j_1 \ldots i_m j_m}$ are unique determined and

$$b_{i_1 j_1 \ldots i_m j_m} = \bar{b}_{j_1 i_1 \ldots j_m i_m} \tag{D.6}$$

because the coefficients of $b(w)$ are real numbers. Choose any order for the set of indices $i_1 j_1 \ldots i_m j_m$ and write $b(w)$ in the form

$$b(w) = BW \tag{D.7}$$

where W is $d(p, m) \times 1$ vector consisting of all products of the form the $X_i^{i_1} \bar{X}_1^{j_1} \ldots X_m^{i_m} \bar{X}_m^{j_m}$, while B is a $1 \times d(p, m)$ vector consisting of the corresponding $b_{j_1 i_1 \ldots j_m i_m}$'s. In the notation thus established, elements $q(w)$ and $\pi(w)$ of $\mathcal{P}^n$ can be expressed in the form

$$q(w) = QW, \quad \pi(w) = \varPi W, \tag{D.8}$$

where Q and $\varPi$ are $n \times d(p, m)$ matrices.

Note that

$$\frac{\partial X_i^{i_1} \bar{X}_1^{j_1} \ldots X_m^{i_m} \bar{X}_m^{j_m}}{\partial w} Sw = \lambda_{i_1 j_1 \ldots i_m j_m} X_i^{i_1} \bar{X}_1^{j_1} \ldots X_m^{i_m} \bar{X}_m^{j_m}, \tag{D.9}$$

where

$$\lambda_{i_1 j_1 \ldots i_m j_m} = j((i_1 - j_1)\beta_1 + \ldots + (i_m - j_m)\beta_m). \tag{D.10}$$

Thus,

$$\frac{\partial W}{\partial w} Sw = \tilde{S} W \tag{D.11}$$

where $\tilde{S}$ is a $d(p, m) \times d(p, m)$ diagonal matrix having all the eigenvalues on the imaginary axis.

In the notation introduced above, the equation (D.3) becomes

$$\Pi \tilde{S} = A \Pi W + Q W \tag{D.12}$$

and this in turn reduces to the Sylvester equation

$$\Pi \tilde{S} = A \Pi + Q \tag{D.13}$$

Since the spectra of $\tilde{S}$ and A are disjoint, this equation has a unique solution Π.

$\triangleleft \triangleleft \triangleleft$

Using this property it is possible to prove the following result.

Proposition D.2. Let $F(x, u, w) = Ax + Bu + Dw$ and S as in (D.2). Assume that all matrices A_i have eigenvalues with negative real part. The the equation

$$\frac{\partial \pi(w)}{\partial w} S w = F(\pi(w), \alpha(w), w), \quad \pi(0) = 0 \tag{D.14}$$

having a globally defined solution $\pi(w)$, whose entries are polynomials, in the components of w.

Proof. Set $\pi(w) = \Pi w,\ \alpha(w) = \Lambda w$, where Π and Λ are matrices of appropriate dimensions. Then observe that the equation

$$\frac{\partial \pi(w)}{\partial w} S w = A \pi(w) + B \Lambda w + D w \tag{D.15}$$

reduces to a Sylvester equation of the form

$$\Pi S = A \Pi + B \Lambda + D \tag{D.16}$$

which indeed has a unique solution Π because the spectra of S and A are disjoint.

Thus according to Lemma D.1, It is easy to show the existence and uniqueness of the solution $\pi(w)$ of (D.14), whose entries are homogeneous polynomials.

$\triangleleft \triangleleft \triangleleft$

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