「系统工程理论与应用 2」

——贵州省系统工程学会第三届学术年会论文集

SYSTEMS ENGINEERING THEORY AND APPLICATION Ⅱ

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贵州省系统工程学会

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图书在版编目(CIP)数据

系统工程理论与应用 2 / 王红蕾，陈建中主编. --贵阳：贵州大学出版社，2012.11

ISBN 978-7-81126-549-1

Ⅰ. ①系… Ⅱ. ①王… ②陈… Ⅲ. ①系统工程-文集 Ⅳ. ①N945-53

中国版本图书馆 CIP 数据核字(2012)第 260635 号

系统工程理论与应用 2

主　　编:王红蕾　陈建中
责任编辑:滕　芸
出版发行:贵州大学出版社有限责任公司
印　　刷:贵阳海印印刷有限公司
开　　本:787 毫米×1092 毫米　1/16
印　　张:16
字　　数:210 千
版　　次:2012 年 11 月第 1 版　第 1 次印刷
书　　号:ISBN 978-7-81126-549-1
定　　价:38.00 元

序

自从1978年钱学森、许国志、王寿云联合署名的《组织管理的技术——系统工程》一文在《文汇报》上发表以来，开启了系统工程理论与方法在经济管理领域应用的新纪元。中国的系统工程的创建、推广、应用和深入的理论研究，已经走过30余年的历程。

当前，全世界的系统化趋势与工程化趋势越来越明显，越来越加强。前者所言的是世界上已经没有孤立于系统之外的事物了，后者强调的是世界上的工程项目越来越多，不但工程问题作为工程项目来处理，且社会经济系统的各种问题也越来越作为工程项目来处理。在中国，历届高层领导经常把一些复杂的、庞大的事说成是一项系统工程，也有不少中高层领导学过或听说过系统工程方面的知识。

2012年是贵州省系统工程学会成立三周年的日子，也是贵州省贯彻落实国务院《关于进一步促进贵州经济社会又好又快发展的若干意见》（以下简称《意见》）的第一年。文件中指出，“贵州发展既存在着交通基础设施薄弱、工程性缺水严重和生态环境脆弱等瓶颈制约，又拥有区位条件重要、能源矿产资源富集、生物多样性良好、文化旅游开发潜力大等优势；既存在着产业结构单一、城乡差距较大、社会事业发展滞后等问题和困难，又面临着深入实施西部大开发战略和加快工业化、城镇化发展的重大机遇；既存在着面广量大程度深

的贫困地区，又初步形成了带动能力较强的黔中经济区，具备了加快发展的基础条件和有利因素，正处在实现历史性跨越的关键时期。”显然，实现贵州又好又快的发展就是一项系统工程和长期任务，其不仅涉及经济社会发展的方方面面，而且涉及经济活动、社会活动和自然界的复杂关系，涉及人与经济社会环境、自然环境的相互作用。贯彻落实《意见》既要有紧迫感，又必须统筹规划，突出重点，分步实施，防止一哄而起，要用系统工程的方法来分析、解决问题。

我国系统工程与国际上有一些不同之处，那就是力图与国内当前形势紧密结合。鉴于此，贵州省系统工程学会决定2012年在贵州民族大学举办第三届学术年会，继续由贵州大学资助出版学术年会论文集。论文集分为理论篇和应用篇，既要结合贵州发展的主线，又要顾及系统工程在各个领域中的不同方法，因此我们在投稿的论文中遴选了27篇比较具有代表性的结集出版，以供读者参考。

今后，我们将继续组织出版这样的论文集，不但在应用领域方面要不断扩大，而且在理论与方法的研究上也要更多、更新。此外，论文集为系统工程学会的会员提供了一个平台，展露他们的才华，感受到“系统工程，责任重大；系统工程，大有可为”。

由于编者水平所限，在组织编排方面难免有不妥之处，欢迎读者提出宝贵意见，以利今后改进。

王红蕾　陈建中

2012年10月

目　录

Nash 平衡点存在性定理等价于 Brouwer 不动点定理

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【摘要】本文应用 Nash 平衡点存在性定理直接证明了 Brouwer 不动点定理。

【关键词】Nash 平衡点存在性定理；Brouwer 不动点定理

以下是著名的 Brouwer 不动点定理[1]。

定理 1. 设集合 X 是 n – 维欧式空间 R^n 的一个非空凸紧集，映射 $\varnothing: X \to X$ 连续。则存在 $x^* \in X$，使得 $\varnothing(x^*) = x^*$。

Geanakoplos [2] 曾应用 Brouwer 不动点定理直接证明了如下的 Nash 平衡不动点存在性定理（不妨设局中人为 2 个）。

定理 2. 设集合 X, Y 分别是 m、n – 维欧式空间 R^m、R^n 中的非空凸紧集，实函数 $f, g: X \times Y \to R$ 均连续，且满足：$\forall y \in Y, x \to f(x, y)$ 是凹的；$\forall x \in Y, y \to g(x, y)$ 是凹的。则存在 $x^* \in X, y^* \in Y$ 使得

$$f(x^*, y^*) = \max_{x \in X} f(x, y^*), g(x^*, y^*) = \max_{y \in X} f(x^*, y)$$

下面，我们将应用 Nash 平衡不动点定理（定理 2）来直接证明 Brouwer 不动点定理（定理 1）。

证明:设 X 是 $n-$维欧式空间 R^n 的一个非空凸紧集,映射 $\emptyset:X\to X$ 连续。我们现在来构造一个 2 人博弈:

设 $Y=X$. $\forall x,y\in X$ 定义

$$f(x,y)=-\|x-y\|,\quad g(x,y)=-\|y-\emptyset(x)\|$$

这里,$\|.\|$ 表示 $n-$维欧式空间 R^n 的范数。

容易验证,$f,g:X\times Y\to$ 连续,且满足:$\forall y\in Y, x\to f(x,y)$ 是凹的;$\forall x\in YX, y\to g(x,y)$ 是凹的。

由定理 2,存在 $x^*\in X, y^*\in Y$,使得

$$f(x^*,y^*)=-\|x^*-y^*\|=\max_{x\in X}\{-\|x-y^*\|\}=-\min_{x\in X}\|X-y^*\|$$

$$g(x^*,y^*)=-\|y^*-\emptyset(x^*)\|=\max_{y\in Y}\{-\|y-\emptyset(x^*)\|\}=-\min_{y\in Y}\|y-\emptyset(x^*)\|$$

所以,$x^*=y^*, y^*=\emptyset(x^*)$。从而,$\emptyset(x^*)=x^*$,定理 1 成立。

应用 Nash 平衡存在性定理(即定理 2),还可以直接证明 KKM 引理,Walras 经济平衡点存在性定理以及变分不等式解的存在性定理。

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BIBO Stabilization of Delayed System with Sector and Slope Restricted Nonlinear Perturbation

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[**Abstract**] This paper addresses the Bounded-Input Bounded-Output (BIBO) stabilization problem of a class of delayed systems with sector and slope restricted nonlinear perturbation. Sector bounds and slope bounds are used on a convex combination representation of the nonlinear function. By using Finsler's Lemma and double integral Jensen inequality, a tripe integral Lyapunov functional is constructed to derive some new BIBO stability criteria. One numerical example is presented to illustrate the validity of the main results.

[**Keyword**] BIBO stabilization; convex combination; nonlinear perturbation

1. PRELIMINARIES

Consider the delayed control system with sector and slope restricted nonlinear perturbation given by

$$\begin{cases} y\&(t) = Ay(t) + By(t-\tau(t)) + Cu(t) + Df(y(t)), \\ x(t) = Ey(t), \\ y(t) = \varphi(t), \forall t \in [t_0 - \tau, t_0], \end{cases} \quad (1)$$

where $y(t) \in R^n$ denotes the state vector; $u(t)$ and $x(t)$ are the control input and control output vectors; $\tau(t)$ is the time-varying delay satisfying $0 < \tau_1 \leqslant \tau(t)$ $\tau_u, u\&(t) \leqslant \tau < 1$, where τ_1, τ_2, τ are the lower and upper bound of $\tau(t)$ and $u\&$ (t) respectively; $\varphi(t)$ is a continuous vector-valued initial function and $\| \varphi(t) \|_\tau$ is defined by $\| \varphi(t) \|_\tau = \sup_{-\tau \leqslant \theta \leqslant 0} \| \varphi(t_0 + \theta) \|$; and are constant matrices; $f(y(t))$ denotes the nonlinear perturbation which is restricted by the sector bounds $[l_i^-, l_i^+]$, i. e

$$l_i^- \leqslant \frac{f_i(y_i(t))}{y_i(t)} \leqslant l_i^+, i = 1, 2, \mathrm{L}, \mathrm{n}.$$

Notice that the nonlinear function $f_i(\cdot)$ can be written as a convex combination of the sector bounds as follows: $f_i(y_i(t)) = (\lambda_i(y_i(t)) l_i^- + (1 - \lambda_i(y_i(t)))$ $l_i^+) y_i(t), i = 1, 2, \mathrm{L}, n$ where $\lambda_i(y_i) = \dfrac{f_i(y_i(t)) - l_i^- y_i(t)}{(l_i^+ - l_i^-) y_i(t)}$ *satisfying* $0 \leqslant \lambda_i(y_i)$ $\leqslant 1$. *Namely*, $f_i(y(t)) = \Lambda_i(y_i(t)) y_i(t)$, where $\Lambda_i(y_i(t))$ is an element of a convex hull $Co\{l_i^-, l_i^+\}$. Similarly, $f_i(y_i(t - \tau(t)))$ can also be expressed as a convex combination of the sector bounds l_i^- and l_-^+ as $f_i(y_i(t - \tau(t)))$ $= \bar{\Lambda}_i(y_i(t - \tau(t))) y_i(t - \tau(t))$, *where* $\bar{\Lambda}_i(y_i(t - \tau(t))) \in Co\{l_i^-, l_i^+\}$.

Let us define

$$\Lambda = \mathrm{diag}\{\Lambda_1(y_1(t)), \Lambda_2(y_2(t)), \cdots, \Lambda_n(y_n(t))\},$$

$$\Delta_1 = \mathrm{diag}\{l_1^-, l_2^-, \cdots, l_n^-\}, \Delta_2 \mathrm{diag}\{l_1^+, l_2^+, \cdots, l_n^+\}$$

$$\bar{\Lambda} = \mathrm{diag}\{\bar{\Lambda}_1(y_1(t - \tau(t))), \bar{\Lambda}_2(y_2(t - \tau(t))), \cdots, \bar{\Lambda}_n(y_n(t - \tau(t)))\}.$$

Then, nonlinearities $f(y(t))$ and $f(y(t-\tau(t)))$ can be expressed as $f(y(t))=\Lambda y(t)$, $f(y(t-\tau(t)))$. Set$\Omega=\{\mathrm{diag}(\Lambda,\bar{\Lambda})\mid\Lambda,\bar{\Lambda}\in Co\{\Delta_1,\Delta_2\}\}$. To obtain the control law of tracking out the reference input of the system, we define$u(t)=Kx(t)+r(t)$, where K is the feedback gain matrix, and $r(t)$ is the reference input. Substituting $u(t)=Kx(t)+r(t)$ into system (1), we can obtain

$$\begin{cases}\dot{y}(t)=(A+CK)y(t)+By(t-\tau(t))+Cr(t)+Df(y(t)),\\ x(t)=Ey(t),\end{cases}\tag{2}$$

Before deriving the main results, the following definition and lemmas are needed.

Definition 1. [1] A real-valued vector $r(t)\in L_\infty^n$, if $\|r\|_\infty=\sup_{t_0\leqslant t<\infty}\|r\|<+\infty$.

Definition 2. [1] The control system with reference input $r(t)$ is BIBO stable if there exist some positive constants θ_1 and θ_2 satisfying $\|x(t)\|\leqslant\theta_1\|r\|_\infty+\theta_1$ for every reference input $r(t)\in L_\infty^n$.

Lemma 1. [2] For any positive definite symmetric constant matrix Q and scalar $\tau>0$, such that the following integrations are well defined, then

$$-\int_{-\tau}^{0}\int_{t+\theta}^{t}y^T(s)Qy(s)\,ds\,d\theta\leqslant-\frac{1}{\tau^2}\left(\int_{-\tau}^{0}\int_{t+\theta}^{t}y(s)\,ds\,d\theta\right)^TQ\int_{-\tau}^{0}\int_{t+\theta}^{t}y(s)\,ds\,d\theta).$$

Lemma 2. [3] Let a matrix F, a symmetric matrix $Q=Q^T$ and a compact subset of real matrices h be given. The following statements are equivalent:

(1) *Foreach* $H\in h,\xi^TQ\xi<0$, *for all* $\xi\neq0$ such that $HF\xi\neq0$.

(2) *Thereexists*$\Theta=\Theta^T$ such that $Q+F^T\Theta F<0,\Psi_n^T\Theta\Psi_n\geqslant0$, for all $H\in h$, where Ψ_h is a matrix belong to a null space of H.

2. BIBO STABILIZATION

In this section, we attempt to establish some new practically computable BI-

BO stable criteria for closed-loop system (2). By constructing a new Lyapunov functional including tripe integral item, we obtain the following BIBO stability result.

Theorem 1. For given scalars $\tau_1 > 0$, $\tau_u > 0$, $\tau > 0$, $L^- diag\{l_1^-, l_2^-, \cdots, l_n^-\}$, $L^+ = diag\{l_1^+, l_2^+, \cdots, l_n^+\}$, the control system (2) with feedback gain matrix is BIBO stable, if there exist positive definite diagonal matrices $\widetilde{D} = \mathrm{diag}\{d_1, d_2, \cdots, d_n\}$, $\Lambda_1 = diag\{\lambda_1, \lambda_2, \cdots, \lambda_n\}$, $\Lambda_2 = diag\{\alpha_1, \alpha_2, \cdots, \alpha_n\}$, $\Gamma = diag\{\gamma_1, \gamma_2, \cdots, \gamma_n\}$, $\widetilde{\Gamma} = diag\{\widetilde{\gamma}_1, \widetilde{\gamma}_2, \cdots, \widetilde{\gamma}_3\}$, symmetric positive definite matrices P, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, symmetric matrix Θ, and arbitrary matrices $F_1, F_2, N_1, N_2, M_1, M_2, M_3$ of appropriate dimensions such that the following condition holds:

$$\begin{bmatrix} \Xi_1 + \Xi_2^T \Theta \Xi_2 & F^T & \widetilde{F}^T \\ & -\frac{\tau_l^2}{4} Q_3 & 0 \\ & * & -\frac{\tau_u^2}{4} Q_4 \end{bmatrix} < 0, \begin{bmatrix} I \\ \omega \end{bmatrix}^T \Theta \begin{bmatrix} I \\ \omega \end{bmatrix} \geq 0, \forall \omega \in \Omega,$$

where $\Xi_1 = (\Xi_{ij})\ i, j = 1, 2, \mathrm{L}\ , 12$, and

$$\Xi_{11} = (P - L^- \Lambda_1 + L^+ \widetilde{D})(A + CK) + (A + CK)^T (P - L^- \Lambda_1 + L^+ \widetilde{D})^T + Q_5,$$
$$+(\tau_l^2 + \tau_u^2)\Lambda_2 (L^+ - L^-) + 2\tau_l Q_1 + 2\tau_u Q_2 - 2L^- \Gamma L^+,$$
$$\Xi_{12} = (A + CK)^T M_2^T, \quad \Xi_{13} = (P - L^- \Lambda_1 + L^+ \widetilde{D})B, \quad \Xi_{14} = (P - L^- \Lambda_1 + L^+ \widetilde{D})C + (A + CK)^T M_3^T,$$
$$\Xi_{15} = (P - L^- \Lambda_1 + L^+ \widetilde{D})D + (A + CK)^T (\Lambda_1 - \widetilde{D}) + (A + CK)^T M_1^T + \Gamma(L^+ + L^-),$$
$$\Xi_{22} = \frac{\tau_l^2}{2} Q_2 + \frac{\tau_u^2}{2} Q_3 - M_2 - M_2^T,$$
$$\Xi_{23} = M_2 B, \Xi_{24} = M_2 C - M_3^T, \Xi_{25} = M_2 D - M_1^T,$$
$$\Xi_{33} = -(1 - \tau)Q_5 - 2L^- \widetilde{\Gamma} L^+, \Xi_{34} = B^T M_3^T,$$
$$\Xi_{35} = B^T (M_1^T + \Lambda_1 - \widetilde{D}), \Xi_{36} = \widetilde{\Gamma}(L^+ + L^-),$$
$$\Xi_{44} = M_3 C + C^T M_3^T, \Xi_{45} = M_3 D + C^T (M_1^T + \Lambda_1 - \widetilde{D}),$$
$$\Xi_{55} = M_1 D + D^T M_1^T - \Gamma - \Gamma^T + 2(\Lambda_1 - \widetilde{D})D + Q_6,$$

$$\Xi_{66} = -(1-\tau)Q_6 - \widetilde{\Gamma} - \widetilde{\Gamma}^T, \Xi_{77} = -\frac{1}{\tau_l}Q_1, \ \Xi_{88} = -\frac{1}{\tau_u}Q_2,$$

$$\Xi_{99} = -[\frac{2}{\tau_l^2}\Lambda_2(L^+ - L^-) + \frac{2}{\tau_l^3}Q_1], \ \Xi_{11,11} = -\frac{1}{2\tau_l^2}Q_3 - F_1,$$

$$\Xi_{10,10} = -[\frac{2}{\tau_u^2}\Lambda_2(L^+ - L^-) + \frac{2}{\tau_u^3}Q_2], \ \Xi_{12,12} = -\frac{1}{2\tau_u^2}Q_4 - F_2,$$

$$F = [0,0,0,0,0,0,0,0,0,0,F_1,0], \hat{F} = [0,0,0,0,0,0,0,0,0,0,0,F_2],$$

$$\Xi_2 = \begin{bmatrix} I + N_1\tau_u & 0 & 0 & 0 & 0 & 0 & 0 & -N_1 & 0 & 0 & 0 & -N_1 \\ N_2\tau_l & 0 & I & 0 & 0 & 0 & -N_2 & 0 & 0 & 0 & -N_2 & 0 \\ 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Proof. Choose a new class of Lyapunov functional candidate as follows:

$$V(y(t)) = V_1(y(t)) + V_2(y(t)) + V_3(y(t)) + V_4(y(t)),$$

where

$$V_1(y(t)) = y^T(t)Py(t) + 2\sum_{i=1}^{n}\{\int_0^{y_i(t)}\lambda_i(f_i(s) - l_i^- s)ds$$
$$+\int_0^{y_i(t)} d_i(l_i^+ s - f_i(s))ds + \int_{t-\tau(t)}^{t} y^T(s)Q_5 y(s)ds\}$$

$$V_2(y(t)) = 2\sum_{i=1}^{n}\{\int_{-\tau_l}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t}\alpha_i y_i(s)[f_i(y_i(s)) - l_i^- y_i(s)]dsd\mu d\theta\}$$
$$+2\sum_{i=1}^{n}\{\int_{-\tau_l}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t}\alpha_i y_i(s)[l_i^+ y_i(s) - f_i(y_i(s))]dsd\mu d\theta\}$$
$$+2\sum_{i=1}^{n}\{\int_{-\tau_u}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t}\alpha_i y_i(s)[f_i(y_i(s)) - l_i^- y_i(s)]dsd\mu d\theta\}$$
$$+2\sum_{i=1}^{n}\{\int_{-\tau_u}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t}\alpha_i y_i(s)[l_i^+ y_i(s) - f_i(y_i(s))]dsd\mu d\theta\}$$
$$+2\int_{-\tau_l}^{0}\int_{t+\theta}^{t} y^T(s)Q_1 y(s)dsd\theta + 2\int_{-\tau_u}^{0}\int_{t+\theta}^{t} y^T(s)Q_2 y(s)dsd\theta,$$

$$V_3(y(t)) = \int_{-\tau_l}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t} y^T\&(s)Q_3y\&(s)dsd\mu d\theta$$
$$+\int_{-\tau_u}^{0}\int_{\theta}^{0}\int_{t+\mu}^{t} y^T\&(s)Q_4y\&(s)dsd\mu d\theta,$$
$$V_4(y(t)) = \int_{t-\tau(t)}^{t} f^T(y(s))Q_6f(y(s))ds.$$

By lemma 1, lemma 2, free weighting technique, and Schur complement, similar to the proof of [4], if the conditions in Theorem 1 are satisfied, then $V\&(y(t)) < 0$. From Lyapunov stable theory, we can get that the control system (2) with feedback gain matrix K is BIBO stable. This completes the proof.

3. ILLUSTRATIVE EXAMPLE

In this section, one numerical example will be presented to show the validity of the main result derived in this paper.

Example 1. In order to compare with previews results easily, consider the delayed system (2) with parameters given by[4]

$$C=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, A=\begin{bmatrix}-2 & 0\\ 1 & -1\end{bmatrix}, B=\begin{bmatrix}-1 & 0\\ -1 & -1\end{bmatrix}, D=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}.$$

In [5], Li and Zhong researched the BIBO problem of this system, and gave a BIBO criterion, which represented by Riccati matrix equation. The criterion derived in [5] is a delay-independent one, and before solving the Riccati matrix equation, two scalars must be given previously and artificially, there is no rule to find these scalars, it needs experience. However, the criteria established in this paper can be solved more easily, and there is no scalar need to be given previously. This implies that the results obtained in this paper are more practice that the result established in [5].

Additional, to stabilize the delayed system (2), the stabilizing feedback gain matrix computed by the criterion established in [5] is $K=\begin{bmatrix} 2.1117 & -0.2532 \\ -0.2532 & 2.7689 \end{bmatrix}$.

By using Theorem1 derived in this paper, we can solve the matrix condition like [6], and the stabilizing feedback gain matrices are

$$K=\begin{bmatrix} 2.0101 & -0.1752 \\ -0.1752 & 2.1401 \end{bmatrix}, and\ K=\begin{bmatrix} 1.8402 & 0.1134 \\ -0.1134 & 1.9407 \end{bmatrix}, respectively.$$

From the elements of K, we can see that the criteria established in this paper are less conservative that the conclusion derived in [5].

4. CONCLUSIONS

Combined with Lyapunov stable theory and double integral inequality, we researched the BIBO problem for a class of delayed systems. Different from previous work on this topic, the property of convex function is introduced to research the BIBO stability of delayed system, and a new Lyapunov functional including triple integral has been proposed to derive some less conservative delay-dependent BIBO stability criteria. Numerical example shows that the new criteria derived in this paperare more practical and less conservative than some previous results obtained in the references cited therein.

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