非線性未知系統之適應性模糊－類神經控制研究(3/3)

計畫編號：NSC90-2213-E-009-067

執行期間：民國 90 年 8 月 1 日起至 91 年 7 月 31 日止

計畫主持人：李祖添 國立交通大學電機與控制工程學系 講座教授

一、 摘要

A new hybrid direct/indirect adaptive FNN controller with state observer and supervisory controller for a class of uncertain nonlinear dynamic systems is developed in this paper. The hybrid adaptive FNN controller, whose free parameters can be tuned on-line by observer-based output feedback control law and adaptive law, is a combination of direct and indirect adaptive FNN controllers. A weighting factor, which can be adjusted by the trade-off between plant knowledge and control knowledge, is adopted to sum together the control efforts from indirect adaptive FNN controller and direct adaptive FNN controller. Also a supervisory controller is appended into the FNN controller to force the state to be within the constraint set. Therefore, if the FNN controller cannot maintain the stability, the supervisory controller starts working to guarantee stability. On the other hand, if the FNN controller works well, the supervisory controller will be de-activated. The overall adaptive scheme guarantees the global stability of the resulting closed-loop system in the sense that all signals involved are uniformly bounded. Two nonlinear systems, i.e., inverted pendulum system and Chua's chaotic circuit are fully illustrated to track sinusoidal signals. The resulting hybrid direct/indirect FNN control systems show better performances, i.e., tracking error and control effort can be made smaller and it is more flexible during the design process.

二、 計畫緣由與目的

Recently, an important adaptive FNN control system has been proposed to incorporate with the expert information systematically and the stability can be guaranteed by universal approximation theorem. For systems with high degree of nonlinear uncertainty, such as chemical process, aircraft, and so on, they are very difficult to control using the conventional control theory. But human operators can often successfully control them. Based on the fact that FNN logic systems are capable of uniformly approximating a nonlinear function over a compact set to any degree of accuracy, a globally stable adaptive FNN controller is defined as an

FNN logic system equipped with an adaptation algorithm. Moreover, FNN is constructed from a collect of fuzzy IF-THEN rules using fuzzy logic principles, and the adaptation algorithm adjusts the free parameters of the FNN based on the numerical experiment data. Like the conventional adaptive control, the adaptive FNN control has direct and indirect FNN adaptive control categories. Based on the Lyapunov synthesis approach, the free parameters of hybrid direct/indirect adaptive FNN controller can be tuned on-line by an observer-based output feedback control law and adaptive law. Also a supervisory controller is designed to cascade with FNN controller. If the nonlinear system tends to unstable by the FNN controller, especially in the transient period, the supervisory controller will be activated to work with the FNN controller to stabilize the whole system. On the other hand, if the FNN controller works well, the supervisory controller will be deactivated. This will result in a smaller control effort (energy). Therefore, the overall adaptive scheme guarantees that the global stability of the resulting closed-loop system in the sense that all signals involved are uniformly bounded. We have successfully designed the FNN adaptive controllers with supervisory control to control the inverted pendulum and Chua's chaotic circuit to track reference sinusoidal signals. The resulting hybrid direct/indirect FNN control systems show better performances, i.e., both tracking error and control effort can be made smaller.

三、 研究方法與成果

An adaptive fuzzy system is a fuzzy logic system equipped with a training algorithm to maintain a consistent performance under plant uncertainties. The most important advantage of the adaptive FNN control over conventional adaptive control is that adaptive FNN controllers are capable of incorporating linguistic fuzzy information from human operator, whereas conventional adaptive controller is not. The adaptive FNN control is divided into two categories. One is called the indirect adaptive FNN control and the other is called direct adaptive FNN control.

To summarize the above analysis, the design algorithm for observer-based hybrid direct/indirect adaptive FNN control is proposed as follows:

[Step 1]:

Specify the feedback and observer gain vector $\underline{k}_c$ and $\underline{k}_o$, such that the characteristic matrices $A - B\underline{k}_c^T$ and $A - \underline{k}_o C^T$ are strictly Hurwitz matrices, respectively.

[Step 2]:

Specify a positive definite $n \times n$ matrix Q and solve the Lyapunov equation $\Lambda_o^T P + P\Lambda_o = -Q$ to obtain a positive definite symmetric $n \times n$ matrix P.

[Step 3]:

Solve the state error equation

$\dot{\underline{\hat{e}}} = A\underline{\hat{e}} - B\underline{k}_c^T\underline{\hat{e}} + \underline{k}_o(e_1 - \hat{e}_1)$; $\hat{e}_1 = C^T\underline{\hat{e}}$ to obtain estimate state vector $\underline{\hat{x}} = \underline{y}_r - \underline{\hat{e}}$.

[Step 4]:

Specify the parameters M_f, M_g, M_D, $M_{\underline{\hat{x}}}$, $¥_1$, $¥_2$, $¥_3$, $£$ and $\bar{V}$ based on the practical constraints. Although $\bar{V}$ is any given constant, but we let $\bar{V}$ be the same as $\bar{V}_{\underline{\hat{e}}}$, which can be determined from $M_{\underline{\hat{x}}}$, $|y_r|$ and $a_{\hat{P}\min}$ of $\hat{P}$ in (3.1).

$$|\underline{\hat{x}}(t)| \le \left[|\underline{y}_r| + \left(\frac{2\bar{V}_{\underline{\hat{e}}}}{a_{\hat{P}\min}}\right)^{\frac{1}{2}}\right] = M_{\underline{\hat{x}}} \text{ and}$$

$$|u| \le \frac{\sim}{£}\left[M_{f\underline{\hat{x}}} + |y_r^{(n)}| + |\underline{k}_c|\left(\frac{2\bar{V}_{\underline{\hat{e}}}}{a_{\hat{P}\min}}\right)^{\frac{1}{2}}\right] + (1-\sim)M_{D\underline{\hat{x}}} +$$

$$\frac{1}{g_L(\underline{x})}\left\{\left(1 + \frac{g^U(\underline{x}) + M_{g\underline{\hat{x}}}}{£}\right)\left[M_{f\underline{\hat{x}}} + |y_r^{(n)}| + |\underline{k}_c|\left(\frac{2\bar{V}_{\underline{\hat{e}}}}{a_{\hat{P}\min}}\right)^{\frac{1}{2}}\right]\right.$$

$$\left. + 2f^U(\underline{x}) + g^U(\underline{x})M_{D\underline{\hat{x}}} + d_m\right\} \quad (3.1)$$

This is to match the magnitude scale of the system so that the designer is free from supplying $\bar{V}$ at random to the system.

[Step 5]:

Define the membership function $«_{F_i^l}(\underline{\hat{x}})$ for $i = 1, 2, \cdots, M$ and compute the fuzzy basis functions $\underline{¶}(\underline{\hat{x}})$. Then fuzzy logic control systems are constructed as

$$\hat{f}(\underline{\hat{x}} \mid \overline{\_}_f) = \underline{¶}^T(\underline{x})\,\overline{\_}_f ; \hat{g}(\underline{x} \mid \overline{\_}_g) = \underline{¶}^T(\underline{\hat{x}})\overline{\_}_g$$

Similarly, define the other membership functions and compute $\underline{!}(\underline{\hat{x}})$. Then fuzzy logic control system is constructed as $u_D(\underline{\hat{x}} \mid \overline{\_}_D) = \underline{!}^T(\underline{x})\overline{\_}_D$

[Step 6]:

Obtain the control and apply it to the plant, then compute the adaptive laws (3.2)-(3.8) to adjust the parameter vectors $\overline{\_}_f$, $\overline{\_}_g$ and $\overline{\_}_D$. Following Remark I, we let the unknown $g(\underline{x})$ to be $g_0(\underline{x})$ in (3.7) and (3.8).

- Use the following adaptive law to adjust the parameter vector $\overline{\_}_f$:

$$\dot{\overline{\_}}_f = \begin{cases} -¥_1\underline{¶}(\underline{\hat{x}})B^T P\underline{\tilde{e}} \quad if\ (|\overline{\_}_f| < M_f) \\ or\ \ (|\overline{\_}_f| = M_f \\ and\ \underline{\tilde{e}}^T PB\underline{¶}^T(\underline{\hat{x}})\overline{\_}_f \ge 0) \\ \Pr oj\{-¥_1\underline{¶}(\underline{\hat{x}})B^T\underline{\tilde{e}}\} \\ if\ \ (|\overline{\_}_f| = M_f \\ and\ \underline{\tilde{e}}^T PB\underline{¶}(\underline{\hat{x}})\overline{\_}_f < 0) \end{cases} \quad (3.2)$$

where the projection operator $Proj\{*\}$ is defined as:

$$\Pr oj\{-¥_1\underline{¶}(\underline{\hat{x}})B^T P\underline{\tilde{e}}\} =$$

$$-¥_1\underline{¶}(\underline{\hat{x}})B^T P\underline{\tilde{e}} + \quad (3.3)$$

$$¥_1\underline{\tilde{e}}^T PB\frac{\overline{\_}_f\overline{\_}_f^T\underline{¶}^T(\underline{\hat{x}})}{|\overline{\_}_f|^2}$$

- Use the following adaptive law to adjust the parameter vector $\overline{\_}_g$:

Whenever an element q_{gi}^l in (1)[1] of $\overline{\_}_g = £$, use

$$\dot{q}_{gi}^l = \begin{cases} -¥_2¶^l(\underline{\hat{x}})B^T P\underline{\tilde{e}}u_I & if\ \underline{\tilde{e}}^T PB¶^l(\underline{x})u_I < 0 \\ 0 & if\ \underline{\tilde{e}}^T PB¶^l(\underline{\hat{x}})u_I \ge 0 \end{cases}$$

(3.4)

---

[1] $R^{(l)}$: IF x_1 is F_1^l, and $\cdots$, and x_n is F_n^l, THEN $y_l = q_0^l + q_1^l x_1 + \cdots + q_n^l x_n = \underline{\grave{e}}_l^T[1\ \underline{x}^T]^T$ (1)

where $\P^{l}(\hat{\underline{x}})$ is the l^{th} component of $\underline{\P}^{T}(\hat{\underline{x}})$.

Otherwise, use

$$\dot{\bar{\underline{\ }}}_{g}=\begin{cases}-¥_{2}\underline{\P}(\hat{\underline{x}})B^{T}P\tilde{\underline{e}}u_{I} \;\; if \;\; (|\bar{\underline{\ }}_{g}|<M_{g}) \;\; or \;\; (|\bar{\underline{\ }}_{g}|=M_{g} \;\; and \;\; \tilde{\underline{e}}^{T}PB\underline{\P}^{T}(\underline{x})\bar{\underline{\ }}_{g}u_{I}\geq 0)\\ \Pr oj\{-¥_{2}\underline{\P}(\hat{\underline{x}})B^{T}P\tilde{\underline{e}}u_{I}\} \;\; if \;\; (|\bar{\underline{\ }}_{g}|=M_{g} \;\; and \;\; \tilde{\underline{e}}^{T}PB\underline{\P}^{T}(\underline{x})\bar{\underline{\ }}_{g}u_{I}<0)\end{cases} \tag{3.5}$$

where the projection operator $Proj\{*\}$ is defined as:

$$Proj\{-¥_{2}\underline{\P}(\hat{\underline{x}})B^{T}P\tilde{\underline{e}}u_{I}\}=-¥_{2}\underline{\P}(\hat{\underline{x}})B^{T}\tilde{\underline{e}}u_{I}+¥_{2}\tilde{\underline{e}}^{T}PB\frac{\bar{\underline{\ }}_{g}\bar{\underline{\ }}_{g}^{T}\underline{\P}^{T}(\hat{\underline{x}})u_{I}}{|\bar{\underline{\ }}_{g}|^{2}} \tag{3.6}$$

- Use the following adaptive law to adjust the parameter vector $\bar{\underline{\ }}_{D}$:

$$\dot{\bar{\underline{\ }}}_{D}=\begin{cases}¥_{3}\underline{¦}(\hat{\underline{x}})g(\underline{x})B^{T}P\tilde{\underline{e}} \;\; if \;\; (|\bar{\underline{\ }}_{D}|<M_{D}) \;\; or \;\; (|\bar{\underline{\ }}_{D}|=M_{D}\\ \qquad and \;\; \tilde{\underline{e}}^{T}PBg(\underline{x})\underline{¦}^{T}(\hat{\underline{x}})\bar{\underline{\ }}_{D}\geq 0)\\ Proj\{¥_{3}\underline{¦}(\hat{\underline{x}})g(\underline{x})B^{T}P\tilde{\underline{e}}\} \;\; if \;\; (|\bar{\underline{\ }}_{D}|=M_{D} \;\; and \;\; \tilde{\underline{e}}^{T}PBg(\underline{x})\underline{¦}^{T}(\hat{\underline{x}})\bar{\underline{\ }}_{D}<0)\end{cases} \tag{3.7}$$

where the projection operator $Proj\{*\}$ is defined as:

$$Proj\{¥_{3}\underline{¦}(\hat{\underline{x}})g(\underline{x})B^{T}P\tilde{\underline{e}}\}=¥_{3}\tilde{\underline{e}}^{T}PBg(\underline{x})\underline{¦}(\hat{\underline{x}})-¥_{3}\tilde{\underline{e}}^{T}PBg(\underline{x})\frac{\bar{\underline{\ }}_{D}\bar{\underline{\ }}_{D}^{T}\underline{¦}^{T}(\tilde{\underline{x}})}{|\bar{\underline{\ }}_{D}|^{2}} \tag{3.8}$$

四、 結論與討論

An observer-based hybrid direct/indirect adaptive FNN controller appended with a supervisory controller for a class of unknown nonlinear dynamical systems is proposed in this paper. It is a flexible design methodology by the trade-off between plant knowledge and control knowledge using a weighting factor α adopted to sum together the control effort from indirect adaptive FNN controller and direct adaptive FNN controller. If the fuzzy descriptions of the plant are more important and viable, then choose large α, otherwise, choose small α. Based on the Lyapunov synthesis approach, the free parameters of the adaptive FNN controller can be tuned on-line by an observer-based output feedback control law and adaptive law. Also, it is a valuable idea that the supervisory control is appended into the FNN controller. The supervisory controller will be activated to force the state to be within the constraint set as long as the system tends to be unstable controlled only by the FNN controller. On the other hand, if the FNN controller works well, the supervisory controller will be deactivated. The simulation results show explicitly the tracking error of larger á is less than smaller á, i.e., the plant knowledge is more important and viable, and the supervisory controller only works in the beginning period and after that the FNN controller is a main controller. Two nonlinear systems, i.e., inverted pendulum system and Chua's chaotic circuit are fully illustrated to track sinusoidal signals. Moreover it is obvious to see that the control effort is much less and tracking performance is better than those in previous works.

五、 參考文獻

[1] S. S. Sastry and A. Isidori, "Adaptive control of linearization systems," *IEEE Trans. Automat. Contr.*, vol. 34, pp. 1123-1131, 1989.

[2] R. Marino and P. Tomei, "Globally adaptive output-feedback control on nonlinear systems, part I: Linear parameterization," *IEEE Trans. Automat. Contr.*, vol. 38, pp. 17-32, 1993.

[3] R. Marino and P. Tomei, "Globally adaptive output-feedback control on nonlinear systems, part II: Nonlinear parameterization," *IEEE Trans. Automat. Contr.*, vol. 38, pp. 33-48, 1993.

[4] B. S. Chen, C. H. Lee, and Y. C. Chang, " H^{∞} tracking design of uncertain nonlinear SISO systems: Adaptive fuzzy approach," *IEEE Trans. Fuzzy Syst.* vol. 4, pp. 32-43, Feb. 1996.

[5] G. A. Rovithakis and M. A. Christodoulou, "Adaptive control of unknown plants using dynamical neural networks," *IEEE Trans. Syst., Man, Cybern.*, vol. 24, pp. 400-412, Mar. 1994.

[6] G. A. Rovithakis and M. A. Christodoulou, "Direct Adaptive Regulation of Unknown Nonlinear Dynamical Systems via Dynamic Neural Networks," *IEEE Trans. Syst., Man, Cybern.*, vol. 25, pp. 1578-1594, Dec. 1995.

[7] L. X. Wang, "Stable adaptive fuzzy control of nonlinear systems," *IEEE Trans. Fuzzy Syst.*, vol. 1, pp.146-155, May, 1993.

[8] J. T. Spooner and K. M. Passino, "Stable adaptive control using fuzzy systems and neural networks," *IEEE Trans. Fuzzy Syst.*, vol. 4, pp.339-359, Aug., 1996.

[9] A. S. Poznyak, W. Yu, E. N. Sanchez and J. P. Perez, "Nonlinear adaptive tracking using dynamic neural networks," *IEEE Trans. Neural Networks*, vol. 10, pp. 1402-1411, Nov., 1999.

[10] Y. G. Leu, T. T. Lee and W. Y. Wang, "Observer-based adaptive fuzzy-neural control for unknown nonlinear dynamical systems," *IEEE Trans. Syst., Man, Cybern.*, vol. 29, pp. 583-591, Oct., 1999.

[11] C. H. Wang, W. Y. Wang, T. T. Lee and P. S. Tseng, "Fuzzy B-spline membership function (BMF) and its applications in fuzzy-neural control," *IEEE Trans. Syst., Man, Cybern.*, vol. 25, pp. 841-851, May., 1995