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Time Delay MIMO Decoupling Control based on DOB-SVM Inverse System

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Abstract

The formation of potentially harmful trihalomethanes (THM) when using chlorine as a sanitizer in water supplies has led to a need for better control algorithm. Sanitizer dosing is a system with large time delay, non-linear, time-varying and multi models, also couple is introduced to the system because of multi tunnels multi pools structure (MTMP). Improved time-delay DOB based on SVM inverse system is proposed in this paper. Support Vector Machine (SVM) is used to identify the inverse system due to that the mathematical model will not be known precisely, then this inverse system cascades the original system so that time-delay pseudo-linearization system can be obtained. Meanwhile improved time-delay DOB is designed to overcome model mismatch, disturbance and time delay. Application results in waterworks at Suzhou (China) show that the method is able to resist the disturbance and improve the robustness; also the lower unit consumption (more than 9%) of sanitizer is obtained.

Keywords: *sanitizer dosing system, decoupling, inverse system, time-delay DOB, support vector machine*

1. Introduction

A typical Multi tunnels multi pools structure sanitizer dosing system is shown in Figure 1. It is a system with larger time-delay, coupling, time-varying and multi models.

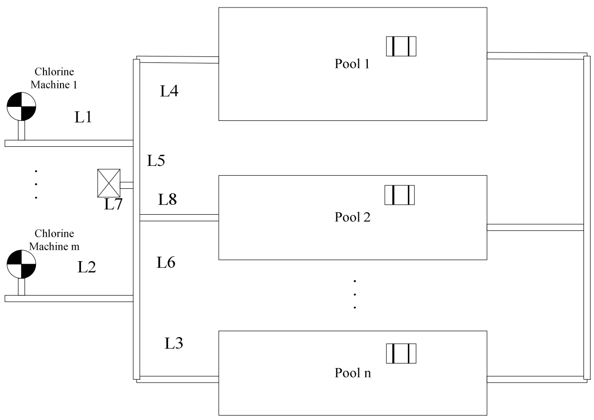

Figure 1. Multi Tunnels Multi Pools Structure Sanitizer Dosing System

There are some papers on MIMO system with coupling, simplified dynamic or static decoupling matrix methods are widely used in application of multi-variable decouple control, while the precision model is needed and its effect is not satisfactory in high-frequency domain. The generalized inverse system theory is the improvement of the inverse system theory. Compared with the inverse system, the generalized inverse system can constitute open-loop stable subsystem with the original system, and the obtained subsystem is a linear transfer

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function of which poles and zeros can be assigned. However, attributed to the complexity of the MTMP sanitizer dosing system, the mathematical model will not be known precisely. So the purpose of decoupling and linearization is hard to achieve by only using the inverse system theory. The other method is needed to combine with the generalized inverse system theory to realize the decoupling control.

Recently neural networks method is introduced to decouple control. In paper [1] double –neuron adaptive predictive decouple algorithm is used to solve a kind of MIMO decouple control system, in paper [2] neural networks and adaptive PID is designed for nonlinear and time-varying MIMO system. However, the neural network suffers from the problems in over-learning, local minima or slow learning speed, support vector machine (SVM) can achieve good performances even in small samples [3-6]. The disadvantages of these methods are that time delay and model mismatch does not take into account, leading to that these methods are not suitable for MTMP structure sanitizer dosing control system.

For the purpose of improving the robustness of the whole system DOB theory is utilized to design the extra controllers to construct close-loop control. Disturbance and model mismatch is unavoidable, DOB is well known that it can estimate the difference between the real model output and internal model output caused by external disturbances and model error. DOB controller can be regarded as one kind of robust control algorithm because of its ability to compensate the lumped disturbance [7-10]. However DOB approaches have been limited to minimum phase systems or systems having no zero dynamics. Most systems have nonlinear characteristics [11], and the inverse system of non minimum phase system is unstable, leading to that its application of DOB is limited. In paper [12] a novel robust nonlinear motion controller with disturbance observer is proposed, in paper [13, 14] some methods of time delay DOB are proposed, but these methods are based on precision model. In paper [11, 15] inverse system based on neural networks are proposed, but large time delay can not be overcome.

In this paper, a method of time-delay DOB based on pseudo-linearization system using LS-SVM is proposed. First α order inverse system is identified using LS-SVM, after that this inverse system cascades the original system so that time-delay pseudo-linearization system can be obtained, this MIMO system will be transformed to SISO system with no coupling. Improved time-delay DOB is proposed to solve the problems of match disturbance and mismatch disturbance.

2. Least Square Support Vector Machine

Support Vector Machine is a new learning machine based on statistical learning theory, which is a small sample statistical learning algorithm based on structure risk minimization principle (SRM) and Vapnik-Chervonenkis (VC) dimension conception.

Let $S = \{(x_1, y_1), (x_2, y_2), \cdots (x_n, y_n)\}$ is a training sample set, where $x_i \in R^{n+m}$, $y_i \in R$, $i = 1, 2, \cdots, l$. The nonlinear regression function can be given as:

$$f(x) = <\omega, x> + b \tag{1}$$

Where $\omega \in R^{n+m}$ is the weight in high-dimensional space, $<\omega, x_i>$ is the inner product, and $b \in R$ is the threshold.

According to the SRM principle, after introducing the insensitive coefficient ε, the nonnegative variables ζ_i, ζ_i^*, the solution of the regression function can be expressed as:

$$\min_{\omega,b} P = \frac{1}{2}\omega^T\omega + C\sum_{i=1}^{l}(\zeta_i + \zeta_i^*) \tag{2}$$

$$\text{s.t. } y_i - (\omega^T\phi(x_i) + b) \le \varepsilon + \zeta_i$$
$$(\omega^T\phi(x_i) + b) - y_i \le \varepsilon + \zeta_i^*$$

$$\zeta_i, \zeta_i^* \geq 0, i = 1,2,\cdots l$$

Where C is a positive number.

Using Least Squares SVM (LS-SVM), the nonlinear regression function can be given as:

$$\min_{\omega,b,e} Q = \frac{1}{2}\|\omega\|^2 + \frac{C}{2}\sum_{i=1}^{l} e_i^{\,2}$$

s.t. $y_i = \omega\phi(x_i) + b + e_i$

To resolve the optimization problem, we introduce the following Lagrange function:

$$L = Q - \sum_{i=1}^{l} \alpha_i [\omega\phi(x_i) + b + e_i - y_i] \quad (3)$$

The optimal solution is:

$$\begin{cases} \frac{\partial L}{\partial \omega} = 0 \Rightarrow \omega - \sum_{i=1}^{l} \alpha_i \phi(x_i) = 0 \\ \frac{\partial L}{\partial b} = 0 \Rightarrow \sum_{i=1}^{l} \alpha_i = 0 \\ \frac{\partial L}{\partial e_i} = 0 \Rightarrow Ce_i - \alpha_i = 0 \\ \frac{\partial L}{\partial \alpha_i} = 0 \Rightarrow \omega\phi(x_i) + b + e_i - y_i = 0 \end{cases} \quad (4)$$

It can be rewritten as a matrix function:

$$\begin{bmatrix} 0 & e^T \\ e & \Omega + C^{-1}I \end{bmatrix}_{(l+1)\times(l+1)} \begin{bmatrix} b \\ \alpha \end{bmatrix} = \begin{bmatrix} 0 \\ Y \end{bmatrix} \quad (5)$$

Where $e = [1,\cdots 1]_{l\times 1}^T$ $\Omega_{ij} = K(x_i, x_j) = \phi(x_i)^T \phi(x_j)$ $\alpha = [\alpha_1,\cdots \alpha_l]^T$ $Y = [y_1,\cdots y_l]^T$.

The output of the SVM can be deduced as:

$$f(x) = \sum_{i=1}^{l} \alpha_i K(x, x_i) + b$$

3. Multi Tunnels Multi Pools Structure Sanitizer Dosing System

Liquid chlorine is the common sanitizer; there are some papers about the decay law of residual-chlorine in water [16, 17]. The process can be divided into two parts, one is the rapid process and the other is the slow process. During the rapid process, chlorine injects to the after-filter-water, the consumption of chlorine is very large, it is related to the initial dosage and the amount of NH3. Then during the slow process, the speed of consumption obviously slow down. Based on the theory, combined to the experiment, the approximate model can be acquired.

Without considering coupling, the structure of single tunnel single pool chlorine dosing process model is shown in Figure 2.

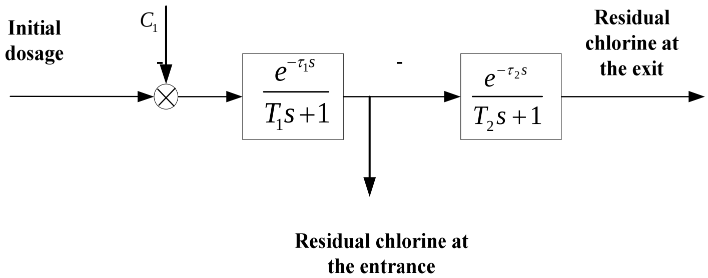

Figure 2. Single Tunnel Single Pool Chlorine Injection Process Model

C_1 is the difference between initial dosage and the residual-chlorine at 0 minute (actually some seconds later). The model can be treated as first-order inertial model with time-delay approximately. T_1, τ_1, T_2, τ_2 are coefficients of first-order inertial model and coefficients of pure time delay, C_1 and T_1, τ_1, T_2, τ_2 are related to many factors and also they are time-varying.

In this paper, the residual-chlorine at the entrance of pools is the main purpose, so the model of multi tunnels multi pools structure chlorine injection system as follows:

$$\begin{cases} y_1 = \eta_{11}(X_1 - C_1)\frac{e^{-\tau_{11}s}}{T_{11}s+1} + \eta_{21}(X_2 - C_2)\frac{e^{-\tau_{21}s}}{T_{21}s+1} + \cdots + \eta_{m1}(X_m - C_m)\frac{e^{-\tau_{m1}s}}{T_{m1}s+1} \\ y_2 = \eta_{12}(X_1 - C_1)\frac{e^{-\tau_{12}s}}{T_{12}s+1} + \eta_{22}(X_2 - C_2)\frac{e^{-\tau_{22}s}}{T_{22}s+1} + \cdots + \eta_{m2}(X_m - C_m)\frac{e^{-\tau_{m2}s}}{T_{m2}s+1} \\ \vdots \\ y_n = \eta_{1n}(X_1 - C_1)\frac{e^{-\tau_{1n}s}}{T_{1n}s+1} + \eta_{2n}(X_2 - C_2)\frac{e^{-\tau_{2n}s}}{T_{2n}s+1} + \cdots + \eta_{mn}(X_m - C_m)\frac{e^{-\tau_{mn}s}}{T_{mn}s+1} \end{cases} \quad (6)$$

4. α Order SVM Inverse System

Definition 1: Σ is a system with p order input $u(t) = (u_1, u_2, \cdots, u_p)^T$ and q order output $u(t) = (y_1, y_2, \cdots, y_p)^T$, suppose Π_α is a q order input and p order output system with mapping function $u = \overline{\theta}\varphi$. Where $\varphi_t = (\varphi_1, \varphi_2, \cdots, \varphi_q)^T$ is a random differential vector that meet the requirement of initial value of system Σ, $u(t) = (u_1, u_2, \cdots, u_p)^T$ is the output vector. If the operator meet the requirement as follows:

$$\theta\overline{\theta}_\alpha\varphi = \theta[\overline{\theta}_\alpha(y_d^\alpha)] = \theta u = y_d$$

Then system Π_α is defined as the α order inverse system of the system Σ.

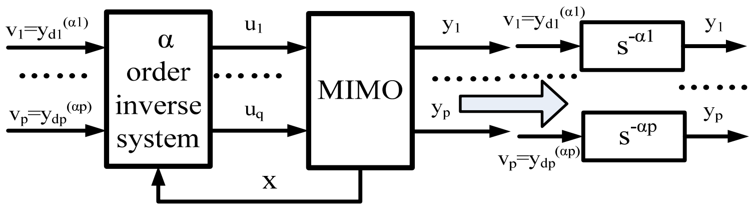

Figure 3. Pseudo-linearization System

The inverse system cascades the original system so that pseudo-linearization system can be obtained, this MIMO system can be transformed to SISO system with no coupling, as is shown in Figure 3.

The application of direct inverse system control is not very common, because of some fatal weakness such as no feedback, can not resist the disturbance and etc. The other method is needed to combine with the pseudo-linearization system theory to realize the decoupling control. Improved DOB can be designed based on pseudo-linearization system so that the controller is able to resist the disturbance and improve the robustness.

5. Design of Improved Time-delay DOB Based on Pseudo-linearization System

The case study in this paper (waterworks at Suzhou in China) is a complicated MIMO system with large time delay, nonlinear and couple. It is a non-minimum phase system, and the original DOB can not deal with non-minimum phase system. Because of time delay, the inverse system can not be achieved due to advanced arguments. SVM is proposed to identify the time-delay inverse system, and then this inverse system cascades the original system so that time-delay pseudo-linearization system can be obtained, after that this MIMO system can be transformed to time-delay SISO system without coupling. There are two disturbances, one is the mismatch disturbance, and the other is match disturbance. The DOB based on pseudo-linearization system can deal with the two disturbances and the time delay. 1 Block of time-delay DOB based on pseudo-linearization system.

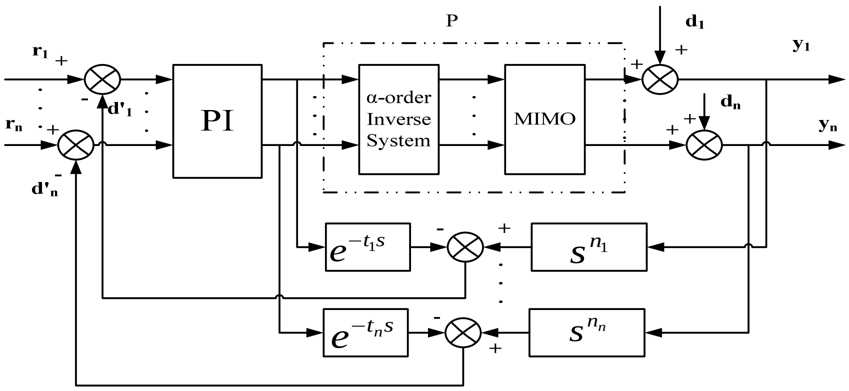

Figure 4. Block of DOB based on Pseudo-linearization System

The structure of time-delay DOB based on pseudo-linearization system is shown in Figure 4. P is the pseudo-linearization system consists of SVM inverse system and the original system. P is considered as follows:

$$P_i = s^{-n_i} e^{-t_i s}$$

Where n_i is the order degree of SVM input i. t_i is the minimum time delay of Channel i.

$$Y_i(s) = G(s)R(s) + G_d(s)D_i(s)$$

$$G(s) = \frac{G_p(s)G_c(s)}{1 + G_p(s)G_n(s)G_c(s) - e^{-t_i s}G_c(s)}$$

$$G_d(s) = \frac{1 - e^{-t_s s}G_c(s)}{1 + G_p(s)G_n(s)G_c(s) - e^{-t_i s}G_c(s)}$$

Where $G_p(s)$ is the pseudo-linearization system, $G_n(s) = s^{n_i} = (G_p(s)/e^{-t_i s})^{-1}$, $G_c(s)$ is the transfer function of PI controller.

Thus, $d_i(s)$ can be rejected by improved DOB based on pseudo-linearization system using SVM.

6. Case Study

In this paper, the parameters of the case study are shown as follows:

m=2, n=2. $C = [C_1, C_2]$ is a vector of difference between initial dosage and the residual-chlorine at 0 minute, its value can be obtained by experiments.

$\eta = \begin{bmatrix} \eta_{11} & \eta_{12} \\ \eta_{21} & \eta_{22} \end{bmatrix} = \begin{bmatrix} 0.85 & 0.1 \\ 0.15 & 0.9 \end{bmatrix}$ is a matrix of flux ratio into pools from tunnels. $\tau = \begin{bmatrix} \tau_{11} & \tau_{12} \\ \tau_{21} & \tau_{22} \end{bmatrix} = \begin{bmatrix} 11 & 13 \\ 16 & 13 \end{bmatrix}$ is a matrix of time delay. $T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} 1.8 & 2.2 \\ 2.4 & 1.8 \end{bmatrix}$ is a matrix of parameters of inertial. Sample time T=0.3s, N= 300.

(1) Simulation results of pseudo-linearization system open-loop control

Test of SVM of α order inverse system is shown in Figure 5. Good results are obtained without disturbance. While open-loop control based on pseudo-linearization system control can not get ideal results because of disturbance and model mismatch, even unstable results will be obtained.

(2) Simulation of no disturbance with the algorithm proposed in this paper

Good results can be obtained with the algorithm using DOB based on SVM inverse system as is show in Figure 6.

(3) Simulation of mismatch disturbance

The result is shown in Figure 7, the controller designed using improved DOB based on SVM is able to resist the disturbance caused by mismatching disturbance or matching disturbance.

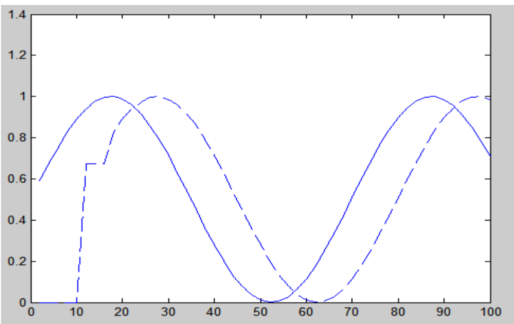

Figure 5. Test of SVM of α Order Inverse System

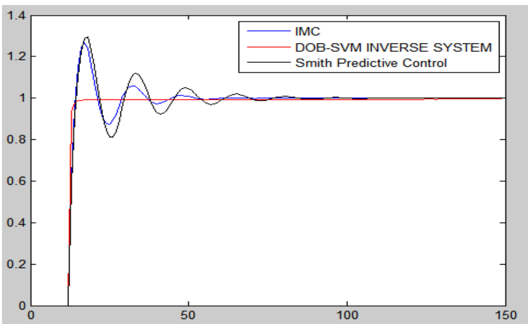

Figure 6. Simulation of no Disturbance

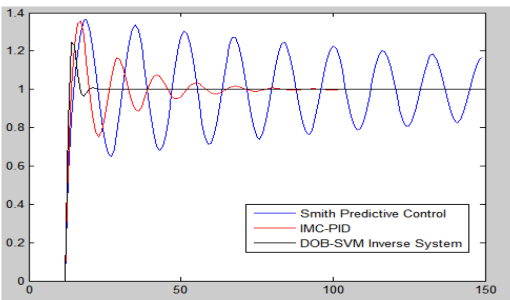

Figure 7. Simulation of Disturbance

(4) Application of algorithm in tap-waterworks

Table 1. Comparing with other Algorithm

Month	Unit Consumption without decoupling	Unit Consumption with decoupling	Saving
1-3	1.8328(mg/L)	1.6289(mg/L)	9.46%
3-9	1.7828(mg/L)	1.5731(mg/L)	11.76%
9-12	1.7763(mg/L)	1.5625(mg/L)	12.03%

Due to that the residual-chlorine is stable using the algorithm, and it has the ability to resist the disturbance and improve the robustness, the lower unit consumption of chlorine is obtained as is shown in Table 1.

7. Conclusion

The formation of potentially harmful trihalomethanes when using chlorine as a sanitizer in potable water supplies has led to tighter regulatory controls and hence a need for better control algorithm. Because of multi tunnels multi pools structure brings coupling, decouple control method is also needed. SVM inverse system is designed to identify the inverse system, and then this inverse system cascades the original system so that time-delay pseudo-linearization system can be obtained, after that this MIMO system can be transformed to SISO system without coupling. There are model mismatch, disturbance and time delay, improved time-delay disturbance observer (DOB) is proposed to overcome the disadvantages. Simulations and application of the algorithm shows that the algorithm has the ability to resist the disturbance and improve the robustness; meanwhile the lower unit consumption of chlorine (more than 9%) is obtained.

References

[1] Geng Liang, Guotian Yang. *A Kind of MIMO Decouple Control System Based on Double-Neuron Adaptive Predictive And Static Decouple Algorithm*. IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application. 2008; 360-364.

[2] Geng Liang. *A Kind of Fault-tolerant Decouple and Control Algorithms for Non-linear and Time-varying MIMO System Based on Neuron Adaptive PID and Neural network.* Proceedings of the 2007 International Conference on Wavelet Analysis and Pattern Recognition. 2007; 677-682.

[3] Guohai Liu, Lingling Chen. Internal Model Control of Permanent Magnet Synchronous Motor Using Support Vector Machine Generalized Inverse. *IEEE Transaction on Industrial Informatics*. 2013; 9(2): 890-899.

[4] Sun Qiaomei, Ren Guang. SVM Inverse Model-based Heading Control of Unmanned Surface Vehicle. *Information Computing and Telecommunications (YC-ICT*). 2010; 138-141.

[5] Lu Rongxiu, Yang Hui, Zhang Kunpeng. Component Content Soft-Sensor of SVM Based on Ions Color Characteristics. *TELKOMNIKA*. 2012; 10(6): 1445-1452.

[6] Fengqing Han, Hongmei Li, Cheng Wen, Wenjuan Zhao. A New Incremental Support Vector Machine Algorithm. *TELKOMNIKA*. 2012; 10(6): 1171-1178.

[7] Bong Keun Kim, Wan Kyun Chung, Kohtaro Ohba. Design and Performance Tuning of Sliding-Mode Controller for High-Speed and High-Accuracy Positioning Systems in Disturbance Observer Framework. *IEEE Transactions on Industrial Electronics*. 2009; 56(10): 3798-3809.

[8] Jingang Yi, Steven Chang, Yantao Shen. Disturbance-Observer-Based hysteresis compensation for piezoelectric actuators. *IEEE/ASME Transactions on Mechatronics*. 2009; 14(4): 456-464.

[9] Rong-Hwang Horng, Heng-Lung Chou, and An-Chen Lee. Rejection of Limit Cycles Induced From Disturbance Observers in Motion Control. *IEEE Transactions on Industrial Electronics*. 2006; 53(6): 1770-1780.

[10] Bong Keun Kim, Wan Kyun Chung. Advanced Disturbance Observer Design for Mechanical Positioning Systems. *IEEE Transactions on Industrial Electronics*. 2003; 50(6): 1207-1216.

[11] LI Juan, YANG Jun, LI Shihua, CHEN Xisong. *Design of Neural Network Disturbance Observer using RBFN for Complex Nonlinear Systems*. Proceedings of the 30th Chinese Control Conference. 2011; 6187-6192.

[12] Zi-Jiang Yang, Hiroshi Tsubakihara, etc. A Novel Robust Nonlinear Motion Controller with Disturbance Observer. *IEEE Transactions on Control Systems Technology*. 2008; 16(1): 137-147.

[13] Seul Jung. *On the unified approach to the disturbance observer*. International Conference on Control. Automation and Systems. 2012: 573-578.

[14] Aryabhima A. Rahman, Kouhei Ohnishi. *Robust Time Delayed Control System Based on Communication Disturbance Observer with Inner Loop Input.* IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society. 2010; 1621-1626.
[15] S Zhao, J Yuh. *Adaptive DOB Control of Underwater Robots. Proceedings of the 2003 IEEE/RSJ Intl.* Conference on Intelligent Robots and Systems. 2003; 571-576.
[16] Feben D, Taras MJ. Studies on Chlorine Demand Constants. *Journal of American Water Works Association*. 1951; 43(11): 922–932.
[17] Qualls RG, Johnson JD. Kinetics of the Short-term Consumption of Chlorine by Fulvic Acid. *Environmental Science & Technology*. 1983; 17(11): 692-698.