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Nonlinear adaptive control based on fuzzy sliding mode technique and fuzzy-based compensator

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ABSTRACT

It is difficult to efficiently control nonlinear systems in the presence of uncertainty and disturbance (UAD). One of the main reasons derives from the negative impact of the unknown features of UAD as well as the response delay of the control system on the accuracy rate in the real time of the control signal. In order to deal with this, we propose a new controller named CO-FSMC for a class of nonlinear control systems subjected to UAD, which is constituted of a fuzzy sliding mode controller (FSMC) and a fuzzy-based compensator (CO). Firstly, the FSMC and CO are designed independently, and then an adaptive fuzzy structure is discovered to combine them. Solutions for avoiding the singular cases of the fuzzy-based function approximation and reducing the calculating cost are proposed. Based on the solutions, fuzzy sliding mode technique, lumped disturbance observer and Lyapunov stability analysis, a closed-loop adaptive control law is formulated. Simulations along with a real application based on a semi-active train-car suspension are performed to fully evaluate the method. The obtained results reflected that vibration of the chassis mass is insensitive to UAD. Compared with the other fuzzy sliding mode control strategies, the CO-FSMC can provide the best control ability to reduce unwanted vibrations.

1. Instruction

Efficient control of nonlinear systems in the presence of uncertainty and disturbance (UAD) is a difficult task. One of the outstanding issues is that the control effectiveness depends deeply on the unknown features of UAD as well as the ability of the control strategy to estimate accurately the control signal in the real time. In order to deal with this, plenty of approaches have been proposed via Fuzzy Logic (FL) [1–6], Sliding Mode Control (SMC) [1,7–14], or compensation solutions [15–17]. Reality has shown that an appropriate combination of these tools could create a novel model with improvable capabilities compared with that of the initial structures [18–23]. Fuzzy Sliding Mode Control (F-SMC) which derives from FL and SMC has been seen as one of the most typical combination models. In case the impact of UAD on the systems needs to be estimated as well, the design of the F-SMC system and compensator can be independently carried out [15]. Currently, F-SMC has gained wide popularity as a potential approach for nonlinear systems subjected to UAD.

The main advantages of the SMC are the simplicity in implementation, the robustness against uncertainty and the capability to deal with external disturbance. In addition, it is easy to co-ordinate with the other mathematical tools [14,24]. To exploit this, firstly, a switching surface or sliding surface, which reflects the specific control aim, needs to be established. The control strategy is then deployed so as to make the system dynamic response direct towards the sliding surface in the approaching phase and uphold the switching along it in the sliding phase. If the process is stable, state variables are almost kept on the switching surface [25,26] regardless of the inherent dynamics of the controlled plant. The capability to reach the sliding surface and keep the states on it without the chattering phenomenon expresses the quality of SMC. For the combination model F-SMC, in general, via the competence of FL, F-SMC can perform the above requisition more effectively than SMC only [27–31]. In F-SMC, the strong points of both, FL and SMC, can be exploited efficiently. FL can provide useful solutions for function approximation with a high degree of flexibility along with a vigorous tool for information inference [22]. While the sliding mode approach can establish adaptive control laws relied on its thorough stability-analysis ability [22,23,32]. As a nonlinear inversion control system with considerable advantages, F-SMC has been widely used in many fields [25,27–31,33].

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An adaptive F-SMC structure for active vehicle suspensions can be referred in [25]. In the paper, a T–S fuzzy model was built so as to handle uncertainty related to the sprung and unsprung mass. This is an appropriate selection. There is, however, a disadvantage coming from the dependence of the control signal on the time-varying masses. In fact, the time-varying load, including the impact of wind force, is difficult to estimate online accurately. Some more practical applications can be consulted in [1,12,18,23,31], where the control signals were relied on only the state variables and the constant design loads. In [12], Mohammad et al. showed an optimal adaptive sliding mode controller for a class of nonlinear systems subjected to UAD. An adaptive fuzzy structure was utilized to approximate the maximum boundary of uncertainty aspects. In this, however, a difficulty arises from the feedback linearization approach, which exists inherent uncertainty attributes. In [18,23,31], by using FL, the approximating unknown nonlinear functions depicting the plants was implemented. This is a reasonable solution for creating the adaptive competence, including the compensation for UAD. Nevertheless, there is not any tie to make sure that the approximated functions can remain regular during their operational process. The fuzzy-based function approximations in [12] and [18] are liable to appear the singular cases in the calculating process, which will be detailed in Section 2. Besides, the calculating cost is really also an outstanding issue for large network structures. FL system owns strong points as abovementioned, this, however, may increase the time delay due to the high calculating cost in various cases [32]. Although the fuzzy gains adopted in [12] and [18] are becoming to stamp out the chattering status, they take part in expanding time delay. In addition, another issue was addressed in [1] deriving from the limitation of the disturbance observer (DO). It was shown that when the time-varying rate of UAD increased, the quality of the DO became worse.

Consequently, in order to improve the control effectiveness, in this research, we propose a new controller named CO-FSMC for a class of nonlinear control systems subjected to UAD. The CO-FSMC is constituted of a fuzzy sliding mode controller (FSMC) and a fuzzy-based compensator (CO) for UAD. Firstly, the FSMC and CO are designed independently, and then an adaptive fuzzy structure for combining them is discovered based on analyzing the stability of a closed-loop control system. The design of the FSMC relies on Lyapunov stability theory with proposed solutions for avoiding the singular cases of the fuzzy-based function approximation and reducing the calculating cost. A closed-loop adaptive control law is proposed to make sure that the finite time convergence of the tracking error is a robustly stable process. In order to overcome partially the difficulty relative to the fact that the effectiveness of the compensation for UAD is quite sensitive to the time-varying rate of UAD, we separate UAD into two groups to estimate individually. The first one consists of model errors while the other relates to external disturbance. The lumped estimate method is employed to design the CO such that the convergence to zero of the estimation-error function is stable. Thus, external disturbance is then compensated by the CO, while the compensation for uncertainty has performed via the function approximation ability of the fuzzy system taking part in the FSMC. The effectiveness of the CO-FSMC is verified based on the vibration control of a semi-active train-car suspension system featuring a magnetorheological damper (MRD).

There are four main contributions of this work as follows.

1) The first one is solutions for relieving the negative impact of the time-varying rate of UAD on the control effectiveness, avoiding the singular cases during the operating process, and reducing the calculating cost. These will be presented in Section 2.
2) The second one is the design of the FSMC for the nonlinear systems without external disturbance presented in Section 3 and Theorem 1.
3) The third one is the design of a lumped-type disturbance observer (DO) and the mechanism of combination of the FSMC and DO in the form of the CO-FSMC such that the converging to zero of the tracking error of the closed-loop is stable. By this way, the CO-FSMC can deal with the nonlinear systems subjected to UAD. These will be presented in Section 4 and Theorem 2.
4) The real application of the CO-FSMC to the semi-active MRD train-car suspension is seen as the fourth contribution. The aim of this work is to fully evaluate the proposed method as well as clearly describe the way to exploit it. The content will be shown in Section 6.

2. Problem formulation and solutions

A general class of SISO n-th order nonlinear systems subjected to UAD is expressed by the differential equation with respect to time as in (1).

$$\begin{cases} x^{(n)} = f_0(x, \dot{x}, \dots, x^{(n-1)}, t) + g_{01}(x, \dot{x}, \dots, x^{(n-1)}, t)\, u(t) + g_{02}(t) D(t) \\ y = x \end{cases} \tag{1}$$

in which $f_0(.), g_{01}(.), g_{02}(.)$ are known functions; $u(t)$ is the control signal; $y(t)$ is the output;. is the state variable vector; $D(t)$ denotes UAD which is the unknown time-dependent parameter. Assuming that $g_{02}(.) > 0$; $\mathbf{x}(t)$ is observable and the upper bound of $D(t)$ exists, $|D(t)| \le D_0$. The control law $u(t)$ needs to be specified such that $\mathbf{x}(t)$ tracks stably the desired reference state $\mathbf{x}_d(t)$ in the presence of $D(t)$. In order to achieve well the aim, we pay attention to the two following issues.

The first one relates to the compensation for UAD. Reality has shown that the effectiveness of this work depends on the bounds [18] and the time-varying rate of $D(t)$ [1,33]. It becomes worse if the time-varying rate of $D(t)$ increases [1,33]. In order to overcome partly this difficulty, we separate $D(t)$ into two groups corresponding to external disturbances and uncertainties due to the model errors to estimate individually. Thus, Eq. (1) is re-expressed as follows:

$$\begin{cases} x^{(n)} = f(\mathbf{x}, t) + g_1(\mathbf{x}, t)\, u(t) + g_2(t)\, d(t) \\ y = x \end{cases} \tag{2}$$

where,$d(t)$ is the unknown time-dependent external disturbance. It is assumed that the upper bound exists, $|d(t)| \le d_0$. Without loss of generality, we can assume that $g_2(t)$ is known. In Eq. (1), the unknown model errors exist in $D(t)$, while in Eq. (2) it is approximated and compensated via $f(.)$ and $g_1(.)$. So, $f(.)$ and $g_1(.)$ become unknown nonlinear functions which need to be identified. By using such approach, instead of building the control law relied on the estimate $\hat{D}(t)$ of $D(t)$ in Eq. (1), a different control law is established via Eq. (2) using the estimates $\hat{d}(t)$ of $d(t)$, $\hat{f}(.)$ of $f(.)$ and $\hat{g}_1(.)$ of $g_1(.)$. The reason is that, in general, the time-varying rate of $d(t)$ only is lower than that of $D(t)$ and $d_0 \le D_0$.

The approach establishes two main parts to depict the closed-loop control system as in Fig. 1, which are the basic controller signed *B*-Controller for specifying the main control signal and the compensator for $d(t)$ signed CO. Generally, we can use any the well-known methods for designing them. In this paper, FL and SMC are employed to build the fuzzy-based compensator CO and the FSMC which works as the *B*-Controller. Thus, the unknown functions $f(.)$, $g_1(.)$ in Eq. (2) are approximated by the fuzzy structures $\hat{f}(.)$ and $\hat{g}_1(.)$ while the thorough stability analysis capability of SMC decisively takes park in establishing the control law. It is noted that although $d(t)$ is ignored when building the FSMC, the impact of the model errors on the system has been compensated by the fuzzy