Design of a Fuzzy Logic Controller with a Variable Structure Based Supervisor

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Abstract

This paper presents a stable variable structure control scheme for achieving uniformly ultimately bounded control of a class of nonlinear systems. To reach a better performance, a generalized two-input single-output fuzzy controller is incorporated into the scheme to help improve dynamic responses when the trajectories enter into an ultimate bound. For practical consideration, we added a GA-based alpha-beta filter in front of the fuzzy controller to suppress noise and obtain smooth input signals. A force-adaptive robot effector acting on various profiles of surfaces has been used as a simulative example to demonstrate its effectiveness.

1 Introduction

Recently, treating fuzzy logic controllers (FLCs) as variable structure systems, [7], [6], [3] , some researchers have provided theoretical flameworks based on the theory of variable structure systems for the analysis and design of fuzzy sliding mode controllers , [5], [2]. In particular, Palm [5] presented two types of fuzzy controllers: the diagonal form FLC (DFLC) and the fuzzy sliding mode controller (FSMC). For a general $n^{\text{th}}-$order nonlinear system, a FSMC uses only the generalized error s as its input so that the number of fuzzy rules can be remarkably reduced. However, FSMCs relate the same value of $|s|$ to the same value of $|u|$, disregarding of the small or big error e. This could be a main drawback of FSMCs. To further improve the performance, some researchers introduced an additional degree of freedom for the state vector $\mathbf{e}$ in the fuzzy rules to form a two input single output (TISO) FSMC. Particularly, Huang [4] introduced $\dot{s}$ in the rules together with s to help determine a better control output u. Palm [5] defined an additional distance measure so that the region near the origin of the phase plane can be reached by the state vector $\mathbf{e}$ at a fast speed than before.However, the stability issues for these results seem not to be addressed rigorously in literature.

This paper presents a new approach to the design of a fuzzy logic controller for a general class of uncertain nonlinear systems. A variable structure control scheme is firstly established to achieve uniform ultimate boundedness of the closed-loop system. Then, a generalized two-input single-output fuzzy controller is incorporated into the scheme to help improve dynamic responses when the trajectories enter into an ultimate bound. To illustrate the effectiveness of the design, a robot effector control system will be taken as a simulated example.

2 Variable Structure Based Supervisor

Consider an $n^{\text{th}}-$order SISO nonlinear system described by

$$\overset{(n)}{y} = f\left(y, \dot{y}, \ldots, \overset{(n-1)}{y}, t\right) + g\left(y, \dot{y}, \ldots, \overset{(n-1)}{y}, t\right) u. \tag{1}$$

Assume that f is not known exactly but is bounded by a known function F, i.e., $|f(\mathbf{x},t)| \leq F(\mathbf{x},t)$,where $\mathbf{x} := [x_1, x_2, \ldots, x_n]^T = [y, \dot{y}, \ldots, \overset{(n-1)}{y}]^T$. The function g is unknown and is assumed to be positive for all $\mathbf{x}$. It has the following lower and upper bounds: $0 < \beta_{\min} \leq$

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$g(\mathbf{x}) \leq \beta_{\max}$ where $\beta_{\min}, \beta_{\max}$ may be constants, time-varying, or state-dependent time-varing functions. The control object is to find a control u such that the output y of (1) will approximately track a desired signal, y_d, which is assumed to be $n^{th}-$ order continuously differentiable and all of its derivatives are uniformly bounded. Given the tracking error $e(t) := y(t) - y_d(t)$, we define two generalized errors

$$s_1(t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \xi(t), \tag{2}$$

$$s_2(t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \tag{3}$$

with $\lambda > 0$, where $\xi(t) = \int^t e(\tau)\, d\tau$. In terms of s_1 and s_2 the system (1) can be transformed into the following equivalent $2^{nd}-$order stabilization problem

$$\dot{s}_1 = s_2 \tag{4}$$

$$\dot{s}_2 = f(\mathbf{x},t) + g(\mathbf{x},t)\, u + w(\mathbf{x}, t) \tag{5}$$

where $w(\mathbf{x}, t) = \sum_{k=1}^{n-1} \binom{n-1}{k-1} \lambda^{n-k} e^{(k)} - y_d^{(n)}$. Let

$$u = \frac{1}{\hat{g}} (\hat{u} + v) \tag{6}$$

where $\hat{g} = \sqrt{\beta_{\min}\beta_{\max}}$ and

$$\hat{u} = -\hat{w} \tag{7}$$

$$v = \begin{cases} -K_1 s_1 - \hat{K} s_1 & \text{if } s_1 s_2 \geq 0 \\ -K_2 s_1 + \hat{K} s_1 & \text{if } s_1 s_2 < 0 \end{cases} \tag{8}$$

We note that $\beta_m^{-1} = \sqrt{\frac{\beta_{\min}}{\beta_{\max}}} \leq \frac{g}{\hat{g}} \leq \sqrt{\frac{\beta_{\max}}{\beta_{\min}}} = \beta_m$. Let

$$V = \begin{cases} \frac{1}{2}\left(K_1 \beta_m^{-1} s_1^2 + s_2^2\right) & \text{for } \; s_1 s_2 > 0 \\ \frac{1}{2}\left(K_2 \beta_m s_1^2 + s_2^2\right) & \text{for } \; s_1 s_2 \leq 0 \end{cases}. \tag{9}$$

It can be shown that the control (6)(7) and (8) will render $\dot{V}$ negative definite with respect to the given nonlinear system (4)(5) provided the controller gains are taken to be

$$K_1 > \beta_m > 1, \; 0 < K_2 < \beta_m^{-1} < 1 \tag{10}$$

$$\hat{K} \geq \frac{(\beta_m - 1)|\hat{w}| + \beta_m F_m}{|s_1|} \tag{11}$$

It follows the trajectories of the system starting from any initial point in $(s_1, s_2)-$plane with $|s_1| > L$ will enter the region: $|s_1| \leq L$ in finite time. Moreover, the relationship between s_1 and s_2 leads to the following inequality: $\lim_{t\to\infty} \int_0^t s_2(\tau)\, d\tau \leq |s_1(0)| + L$ whenver in the region: $|s_1| \leq L$. By Barbalat's lemma, one can obtain

$$\lim_{t\to\infty} s_2(t) = 0 \tag{12}$$

.

3 Design of $\alpha\beta$ Filter Using Genetic Algorithm

In order to obtain better dynamical responses, we will design a TISO PD-type fuzzy controller insider the region $|s_1| \leq L$, $|s_2| \leq L$. For practical consideration, an $\alpha\beta$ filter is added to produce discrete smooth signals to the fuzzy controller. A schematic diagram is shown in Fig. 1.

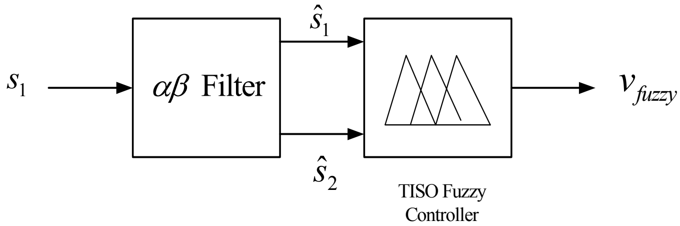

Figure 1. TISO Fuzzy Controller Preceded by an $\alpha\beta$ Filter

The filter produces smoothed estimates $\hat{s}_1$ and $\hat{s}_2$ from the observation s_1. Let T be the sampling interval. The time evolution of an $\alpha\beta$ filter from $(n-1)T$ to nT is described by the following equation

$$\begin{bmatrix} \hat{s}_1(n|n-1) \\ \hat{s}_2(n|n-1) \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{s}_1(n-1) \\ \hat{s}_2(n-1) \end{bmatrix} \tag{13}$$

where $\hat{s}_1(n|n-1)$ $(\hat{s}_2(n|n-1))$ is the prediction of the position (velocity) based on the observations up to the time instant $(n-1)T$. The estimations at the time instant nT, when the measurement $s_1(n)$ is performed and taken into consideration, are given by

$$\begin{bmatrix} \hat{s}_1(n) \\ \hat{s}_2(n) \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{s}_1(n-1) \\ \hat{s}_2(n-1) \end{bmatrix} + \hat{K}\left(s_1(n) - \hat{s}_1(n|n-1)\right)$$

where $(s_1(n) - \hat{s}_1(n|n-1))$ represents the prediction error, $\hat{K}$ is the Kalman gain. For $\alpha\beta$ filter, the Kalman gain $\hat{K}$ is fixed and taken to be $\hat{K} = \begin{bmatrix} \alpha & \beta/T \end{bmatrix}^T$, where α, β are to be designed to satisfy some performance requirements. The initializations are given as $\hat{s}_1(1) = \hat{s}_1(2|1) = s_1(1)$, $\hat{s}_2(1) = 0$, $\hat{s}_2(2) = \frac{s_1(2) - s_1(1)}{T}$. In general, noise is assumed to be a zero mean random process with variance equal to σ_v^2. It is shown [1] that the position and velocity variance reduction ration (VRR) ratios are, respectively, given by $(VRR)_1 = \frac{2\alpha^2 - 3\alpha\beta + 2\beta}{\alpha(4 - 2\alpha - \beta)}$ and $(VRR)_2 = \frac{1}{T^2}\frac{2\beta^2}{\alpha(4-2\alpha-\beta)}$. The reduction of measurement noise is normally determined by the VRR ratios. However, the maneuverability performance of the filter depends heavily on the choice of the parameter α and β. A special version of the filter was developed by Benedict and Bordner [1], who have shown that the optimal filter is coincident with an filter with the constraint

$$\beta = \frac{\alpha^2}{2 - \alpha} \tag{14}$$

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In this case, the position and velocity VRR ratios are, respectively, given by $(VRR)_1 = \frac{\alpha(6-5\alpha)}{\alpha^2-8\alpha+8}$ and $(VRR)_2 = \frac{2}{T^2}\frac{\alpha^3/(2-\alpha)}{\alpha^2-8\alpha+8}$. With the Eq. (14), the appropriate parameters of $\alpha\beta$ filter can be optimized by adjusting the value of α manually. This optimization process will be performed by genetic algorithms (GAs) which is briefly presented in the section.

3.1 Genetic Algorithms

Differing from the conventional search techniques, GAs start with an initial set of random solutions called population. Each individual in the population is called a chromosome, representing a solution to the problem at hand. The chromosomes evolve through successive iterations, called generations. During each generation, the chromosomes are evaluated with some measures of fitness. To create the next generation, new chromosomes, called offspring, are formed by either using a crossover operator or using a mutation operator. According to the fitness values, a new generation is formed by selecting some of the parents and offspring, and rejecting others so as to keep the population size constant. Fitter chromosomes have higher probabilities of being selected. After several generations, the algorithms converge to the best chromosome, which represents the optimal solution to the problem.

4 Numerical Example: a Robot Effector System

Keeping a constant desired force between the robot effector and the surface is one of major tasks of the manipulator, and we will examine this control problem in this section. A schematic diagram of the system is shown in Fig.2. Let the spring force F_F represent the sensor force. Then $F_F = K_1\left(y - y_0 - \tilde{D}\right)$; $\dot{F}_F = K_1(\dot{y} - \dot{y}_0)$; $\ddot{F}_F = K_1(\ddot{y} - \ddot{y}_0)$. We obtain the equation for F_F as follows

$$\ddot{F}_F = -\frac{c}{m}\cdot\dot{F}_F - \frac{K_1}{m}F_F + K_1 g - \frac{K_1}{m}F_O - K_1\ddot{y}_0 \quad (15)$$

where $F_O = K_2(y - y_c + r + A)$ is the reaction force within the surface. We note that $u = -K_1\ddot{y}_0$ is regarded as the input to the system (15). We want to design a TISO fuzzy sliding mode controller u for the system (15) so that F_F can approach a desired constant force F_d as soon as possible. The following model-specific parameters:$c = 50\,\mathrm{kg\,s^{-1}}$, $m = 0.05\,\mathrm{kg}$, $K_1 = 5000\,\mathrm{kg\,s^{-2}}$, $K_2 = 10000\,\mathrm{kg\,s^{-2}}$, $v = 0.2\,\mathrm{m\,s^{-1}}$, given in [5], were used in the controller design and simulations. The TISO FLC designed as follows. Taking $\hat{s}_1$ and $\hat{s}_2$ as inputs, we define a set of fuzzy rules

IF $\hat{s}_1$ is P and $\hat{s}_2$ is P then K is PB
IF $\hat{s}_1$ is P and $\hat{s}_2$ is Z then K is PS
IF $\hat{s}_1$ is P and $\hat{s}_2$ is N then K is ZO
IF $\hat{s}_1$ is Z and $\hat{s}_2$ is P thtn K is PS
IF $\hat{s}_1$ is Z and $\hat{s}_2$ is Z then K is ZO
IF $\hat{s}_1$ is Z and $\hat{s}_2$ is N then K is NS
IF $\hat{s}_1$ is N and $\hat{s}_2$ is P then K is ZO
IF $\hat{s}_1$ is N and $\hat{s}_2$ is Z then K is NS
IF $\hat{s}_1$ is N and $\hat{s}_2$ is N then K is NB

The inputs $\hat{s}_1$ and $\hat{s}_2$ have the same membership functions defined on the same normalized universe of discourse, shown in Fig.3, and the output has the membership functions depicted in Fig. 4. We take $\lambda = 5$, in all the simulations. Two kinds of surface along which the robot effector is supposed to slide are tested, as shown in Fig. 7. We considered respectively two constant desired effector forces: $F_d = 10\,\mathrm{N}$ and $F_d = 15\,\mathrm{N}$. Fig. 5 and Fig. 6 indicated the responses of the actual effector force F_F when $F_d = 10\,\mathrm{N}$ and $F_d = 15\,\mathrm{N}$, respectively. If the uneven surface is considered, the dynamic responses of F_F are depicted in Fig. 8 for the case, $F_d = 10\,\mathrm{N}$. As indicated in these figures, the performance of the proposed fuzzy control scheme is better than that of the conventional sliding mode control. Specifically, a rather better guaranteed steady-state tracking precision has been justified.

5 Conclusion

By introducing a new generalized error transformation, we have presented a novel variable structure control scheme in this paper, which was employed as a supervisor for the design of a fuzzy controller. With this control scheme, we have shown that it can result in a closed-loop system with better tracking performance. The design procedure was illustrated by a force-adaptive robot effector acting on various profiles of surfaces. As demonstrated from simulations, it appears that a comparatively good performance can be reached by the proposed fuzzy controller.

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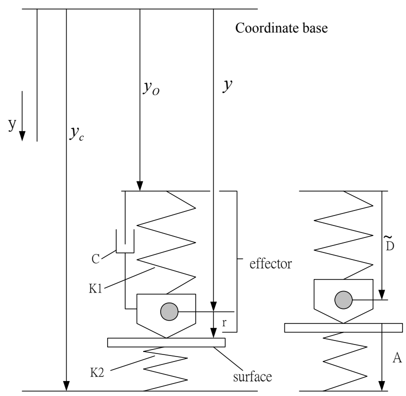

Figure 2. Simplified model of the robot effector

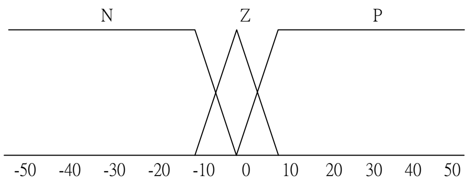

Figure 3. Membership functions of $\hat{s}_1$ and $\hat{s}_2$

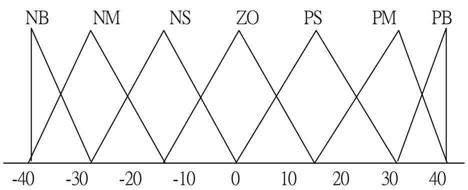

Figure 4. Membership functions of the output variable

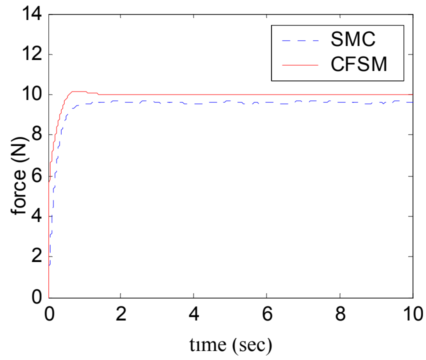

Figure 5. Force responses for a flat surface when $F_d = 10\,\mathrm{N}$

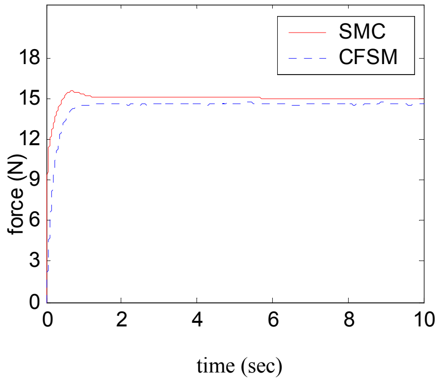

Figure 6. Force responses for a flat surface when $F_d = 10\,\mathrm{N}$

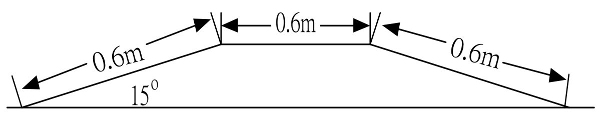

Figure 7. A surface having 3 different slopes

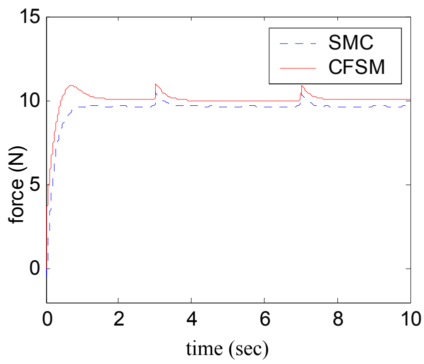

Figure 8. Force responses for a nonflat surface ($F_d = 10\,\mathrm{N}$)

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