A simple robust fuzzy-logic sliding-mode controller of the diagonal type

S.G. Tzafestas and G.G. Rigatos

Intelligent Robotics and Automation Laboratory

Department of Electrical and Computer Engineering

National Technical University of Athens

Zografou, 15773, Athens, Greece

Abstract

The paper presents a reduced-complexity sliding-mode fuzzy-logic controller (RC-SMFCL) of the diagonal type which keeps the system under control on the sliding surface, thus assuring stability of the closed-loop system. This controller does not need the prior knowledge of the system or the prior design of the rule base , or the prior selection of the shape of the membership functions. Simulation results obtained for both linear and nonlinear systems showed the excellent performance of the controller.

Keywords

Fuzzy logic controller, sliding-mode controller, fuzzy rule base , sliding surface , boundary layer.

1 INTRODUCTION

For a large class of second-order systems fuzzy logic controllers (FLCs) are designed using the fuzzy phase plane which is defined by the fuzzy values of e and $\dot{e}$ (Palm, Driankov and Hellendoorn ,1996). The usual heuristic approach for the derivation of these control laws is to separate the fuzzy phase plane into two semi-planes with a sliding line. This means that the FLC will have a “ diagonal” form. Each semi-plane is used to define only positive or only negative values of the fuzzy control signal u . This method of design is similar to the design of conventional Sliding-Mode Control (SMC) with Boundary Layer (BL) which is a technique of robust control (Slotine and Li, 1991) .

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In this paper a modified approach to the design of Sliding-Mode Fuzzy-Logic Controllers (SMFLC) will be presented. The proposed controller, named Reduced Complexity - SMFLC (RC-SMFLC) is characterized by its simplicity, and can facilitate significantly the solution of control problems for nonlinear systems with model uncertainties, parameter fluctuations, and disturbances.

2 SLIDING MODE CONTROL

2.1 The SMC controller

Consider the nonlinear and non-autonomous open-loop system :

$$\dot{\mathbf{x}}^{(n)}(t) = \mathbf{f}(\mathbf{x}, t) + \mathbf{b}(\mathbf{x}, t) \cdot \mathbf{u} + \tilde{\mathbf{d}}, \quad (\mathbf{x}^{(n)} = d^n \mathbf{x} / dt^n) \quad (1)$$

where $\mathbf{x}(t) = (x, \dot{x}, \dots, x^{(n-1)})^T$ is the state vector, $\tilde{\mathbf{d}}(x, t)$ is a time-dependent disturbance with known upper bound, and $\mathbf{f}(x, t)$ and $\mathbf{b}(x, t)$ are nonlinear functions. Assume also that v_u are the unmodelled frequencies of the system.

The tracking error of the state vector is :

$$\mathbf{e}(t) = \mathbf{x}(t) - \mathbf{x}_d(t) = (e, \dot{e}, \dots, e^{(n-1)})^T.$$

Defining a sliding surface $s(x, t) = 0$, where

$$s(x, t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e = \sum_{k=0}^{n-1} \binom{n-1}{k} \lambda^k e^{(n-1-k)}, \quad e(0) = 0 \quad (2)$$

the problem reduces to that of finding an appropriate control rule so as to keep the state vector $\mathbf{e}$ on the sliding surface $s(x, t) = 0$. To this end, a Lyapunov

function $V = \frac{1}{2} s^2$, with $V(0) = 0$ and $V(s) > 0$ for $s > 0$, is defined.

An efficient condition for the stability of the system is (Slotine and Li, 1991) :

$$\dot{V} = \frac{1}{2} \frac{d}{dt} s^2 \leq -\eta |s|$$

which leads to the convergence condition :

$$s \dot{s} \leq -\eta |s| \Rightarrow \dot{s} s \leq -\eta \operatorname{sgn}(s) s \Rightarrow \dot{s} \operatorname{sgn}(s) \leq -\eta \quad (3)$$

If $\eta > 0$, then the system is driven to the *sliding mode*. This means that, if the state trajectory $[e, \dot{e}]^T$ has reached the sliding surface $s=0$, then it remains on it while at the same time it slides to the origin $e=0$ independently of the system's parametric uncertainties and disturbances.

The parameter λ must be selected such that the unmodelled frequencies of the system to be rejected. A sufficient condition for frequency rejection is $\lambda \ll \nu_{\min}$ where $\nu_{\min}$ is the lower bound of the system's unmodelled frequencies ν_u .

The next step is to find the control law that will keep the system in sliding mode.

To this end, the derivative $\dot{s}$ is computed from (2) and introduced into (3) to give, using (1) :

$$([f(x,t) + b(x,t)u + d] - x_d^{(n)} + \sum_{k=1}^n \binom{n-1}{k} \lambda^k e^{(n-k)} \text{sgn}(s)) \quad (4)$$

The sliding-mode control law is now defined via the following equations :

$$u = \hat{b}^{-1} (\hat{u} - \hat{f}), \quad \hat{u} = G(\hat{u} - K(x,t) \text{sgn}(s)), \quad \hat{u} = x_d^{(n)} - \sum_{k=1}^{n-1} \binom{n-1}{k} \lambda^k e^{(n-k)} \quad (5)$$

where $K(x,t) > 0$, and $\hat{f}$ and $\hat{b}$ are estimates of the functions f and b respectively. To choose the multiplicative coefficient (gain) G , the following bounds are defined:

$$0 \leq \beta^{\min} \leq \hat{b} \hat{b}^{-1} \leq \beta^{\max}. \text{ Then } G \text{ is defined as } G = (\beta^{\min} \beta^{\max})^{-1/2}, \text{ and the gain margin } \beta \text{ as } \beta = \left(\frac{\beta^{\max}}{\beta^{\min}} \right)^{1/2}.$$

It now remains to find $K(x,t)$ so as to satisfy equation (3) : $\dot{s} \text{sgn}(s) \leq -\eta$. The above inequality is satisfied if (Slotine and Li, 1991) :

$$K(x,t) \geq \beta(|\Delta f| + (1 - \beta^{-1})|\hat{u}| + |d|) + \eta, \quad \Delta f = f - \hat{b} \hat{b}^{-1} f \quad (6)$$

The upper bounds $\tilde{F}$, $\tilde{D}$ and $\tilde{U}$: $|\Delta f| < \tilde{F}$, $|\tilde{d}| < \tilde{D}$, and $|\tilde{u}| < \tilde{U}$ are supposed to be known from the system's analysis. Thus, a sufficient condition for the control law to make the sliding surface $s=0$ a domain of attraction, is

$$K(x,t) \geq \beta(\tilde{F} + (1 - \beta^{-1})U) + D + \eta \quad (7)$$

2.2 SMC with reduced chattering

An essential drawback of SMC is that, owing to the "signum" term $K(x,t)\text{sgn}(s)$, it causes abrupt changes (chattering) to the control signal u . However this can be avoided by introducing a Boundary Layer (BL) from both sides of the sliding surface $s=0$. If the term $K(x,t)\text{sgn}(s)$ exceeds the width of the BL, then it becomes saturated, and is assigned the maximum (minimum) permissible value. The width of BL is selected to be 2Φ .

Assume that $|s|$ is the distance between the state vector $\mathbf{e}$ and the sliding surface $s=0$. Then, the state $\mathbf{e}$ is inside the boundary layer if $|s| < \Phi$, and is outside the BL if $|s| > \Phi$. If the BL is imported in the control law (5) one gets :

$$u = b^{-1}(\tilde{u} - \hat{f}), \quad \tilde{u} = G(\hat{u} - K(x,t)\text{sat}(s/\Phi)), \quad \hat{u} = x_d^{(n)} - \sum_{k=1}^{n-1} \binom{n-1}{k} \lambda^k e^{(n-k)} \quad (8)$$

where the saturation function "sat(.)" is defined as

$$\text{sat}(z) = \begin{cases} z & \text{if } |z| < 1 \\ \text{sgn}(z) & \text{if } |z| > 1 \end{cases} \quad (9)$$

3 ANALOGY BETWEEN FLC AND SMC

3.1 FLC of the diagonal type

Consider a second-order SISO nonlinear and non-autonomous system. In the case of a diagonal-type FLC the controller inputs are the error e and the rate of change of error $\dot{e}$, while the controller output is u . The ranges of the fluctuation of e , $\dot{e}$ and u are E , $\dot{E}$ and U , respectively, which are domains around zero. The fuzzy values of e , $\dot{e}$ and u belong to the fuzzy sets TE , $\dot{TE}$ and TU respectively, where :

$$TE = \{NLE_1, NLE_2, \dots, NLE_m, ZLE_{m+1}, PLE_{m+2}, \dots, PLE_m\}$$

$$\dot{TE} = \{\dot{NLE}_1, \dot{NLE}_m, \dots, \dot{NLE}_m, \dot{ZLE}_{m+1}, \dot{PLE}_{m+2}, \dots, \dot{PLE}_n\}$$

$$TU = \{NLU_1, NLU_2, \dots, NLU_m, ZLU_{m+1}, PLU_{m+2}, \dots, PLU_n\}$$

The regions where the controller output becomes zero lie on the diagonal that separates the fuzzy phase plane into two semi-planes. For all the fuzzy regions below the diagonal the controller output takes a positive fuzzy value with a magnitude that depends on the distance between this fuzzy region and a particular zero-region on the diagonal, below which the given fuzzy region is located. In Figures 1 and 2 are illustrated the set of all fuzzy regions below and above the diagonal :

Figure1 Fuzzy regions below the diagonal

Figure 2 Fuzzy regions above the diagonal

As distance between a "fuzzy region below (above) the diagonal and the diagonal" is defined the distance between the "center of this region and the center of the zero region below (above) which the given fuzzy region is located". For all the fuzzy regions below (above) the diagonal, the controller output is assigned positive (negative) values with magnitude depending on the distance between the fuzzy region and the diagonal.

3.2 SMC with BL for a second-order system

To show the similarity between the diagonal-type FLC and SMC with BL the latter control method is applied here to a second-order system where the sliding

line is $\dot{s} = \lambda e + \dot{e}$.

The control law is described by (see (8)) :

$$u = \hat{b}^{-1} (-\hat{f} + G(\ddot{x}_d - \lambda \dot{e}) - GK(x,t) \text{sat}(s/\Phi)) \quad (10)$$

This control law involves the following terms :

$$1. \text{ Compensation term : } u_{comp} = -\hat{b}^{-1} \hat{f} \quad (11)$$

$$2. \text{ Filtering term : } u_{flt} = -\hat{b}^{-1} G \lambda \dot{e} \quad (12)$$

This term rejects the unmodelled frequencies of the system

$$3. \text{ Feedforward term : } u_{ff} = \hat{b}^{-1} G \ddot{x}_d \quad (13)$$

$$4. \text{ Feedback control term : } u_c = -\hat{b}^{-1} GK(x,t) \text{sat}(s/\Phi) \quad (14)$$

This term prevents the state vector e from moving away from the sliding surface $s=0$. The negative sign indicates that the control action takes always place in the direction of error's decrease. The part $-K(x,t) \text{sat}(s/\Phi)$ is of diagonal form, with $s=0$ being the diagonal line. Examining the diagonal part of u_c one gets :

$$u_{diag} = -K(x,t) \text{sat}(s/\Phi) \quad (14')$$

where $u_{diag} > 0$ for $s < 0$, $u_{diag} = 0$ for $s = 0$, $u_{diag} < 0$ for $s > 0$

Assuming that K is constant, and that the state error vector e lies inside the BL, then

$$u_{diag} = -K \frac{s}{\Phi} = K \frac{|s|}{\Phi} \text{sgn}(s) \quad (15)$$

3.3 Analysis of a diagonal-type FLC

The diagonal for a second-order system is described by the equation

$s = \lambda \dot{e} + \ddot{e} = 0$. Here, the rules of the diagonal-type FLC are selected such that:

1. the states e and $\dot{e}$ are bounded as : $-e_{\max} \leq e \leq +e_{\max}$ and

$$-\dot{e}_{\max} \leq \dot{e} \leq \dot{e}_{\max}$$

2. the control signal u is bounded as : $-u_{\max} \leq u \leq u_{\max}$

3. the states e and $\dot{e}$ that are located on the diagonal produce zero control signals,
4. the states e and $\dot{e}$ that are located below the diagonal produce positive control signals,
5. the states e and $\dot{e}$ that are located above the diagonal produce negative control signals,
6. the magnitude of the control signal $|u|$ increases when the distance from the diagonal increases, and vice-versa.

The analytical representation of a diagonal-type FLC is :

$$u_{fuzz} = -K_{fuzz}(e, \dot{e}, \lambda) \text{sgn}(s) \quad (16)$$

$$\text{with } K_{fuzz}(e_1, \dot{e}_1, \lambda) \leq K_{fuzz}(e_2, \dot{e}_2, \lambda) \text{ for } |\lambda e_1 + \dot{e}_1| \leq |\lambda e_2 + \dot{e}_2|,$$

which means that the greater the distance of $(e, \dot{e})$ from the sliding surface is, the greater the control signal becomes.

4 RC-SMFLC DESIGN

4.1 The concept of RC-SMFLC

To design a *Reduced-Complexity SMFLC*, the basic conditions that assure the convergence of a system to the desirable set-point are taken into account.

Denoting the tracking error by $e(t) = x(t) - x_d(t)$, and the rate of error change by $\dot{e}(t) = \dot{x}(t) - \dot{x}_d(t)$, the convergence conditions are expressed as follows

$$\bullet \text{ If } e(t)\dot{e}(t) < 0 \text{ then } x(t) \rightarrow x_d(t), \text{ i.e. } e(t) \rightarrow 0 \quad (17)$$

$$\bullet \text{ If } e(t)\dot{e}(t) > 0 \text{ then } x(t) \text{ deviates from } x_d(t) \quad (18)$$

The same conditions could have been derived from the Lyapunov function $V = (1/2) \cdot e^2$ for which $\dot{V} = e\dot{e}$. Define now the sliding surface $s(x, t)$:

$s(x, t) = e(t)\dot{e}(t) < 0$. Then, the control law can be expressed as follows :

- If $\text{sgn}(e(t)\dot{e}(t)) < 0$, then the control action leads to convergence and should be maintained.
- If $\text{sgn}(e(t)\dot{e}(t)) > 0$, then the control action leads to divergence and should be altered.

Once the state vector $[e(t), \dot{e}(t)]^T$ is found in the semi-plane $s(x,t) = e(t)\dot{e}(t) < 0$, it gradually approaches the null vector $[0,0]^T$. Thus, the goal is to find a control law u that will be able to keep the state vector in the semi-plane $s(x,t) = e(t)\dot{e}(t) < 0$.

4.2 The rule base of RC-SMFLC

There are two possible control actions : increase or decrease the control signal u . Thus the rule base of RC-SMFLC is

R_1 : IF $\text{sgn}(e(t)\dot{e}(t)) < 0$ AND $\Delta u_k > 0$ THEN $\Delta u_{k+1} > 0$

R_2 : IF $\text{sgn}(e(t)\dot{e}(t)) < 0$ AND $\Delta u_k < 0$ THEN $\Delta u_{k+1} < 0$

R_3 : IF $\text{sgn}(e(t)\dot{e}(t)) > 0$ AND $\Delta u_k > 0$ THEN $\Delta u_{k+1} < 0$

R_4 : IF $\text{sgn}(e(t)\dot{e}(t)) > 0$ AND $\Delta u_k < 0$ THEN $\Delta u_{k+1} > 0$

where Δu_k is the change in the control signal at the k-th iteration of the algorithm.

To ensure that the control signal is increased with the use of the FLC, the following rules are employed

IF u_k is U_1 THEN u_{k+1} is U_2 , ..., IF u_k is U_{n-1} THEN u_{k+1} is U_n

To ensure that the control signal is decreased with the use of the FLC the rules that must be used are :

IF u_k is U_2 THEN u_{k+1} is U_1 , ..., IF u_k is U_n THEN u_{k+1} is U_{n-1}

where $U_1, U_2, \dots, U_{n-1}, U_n$ are the fuzzy subsets in which the fuzzy phase plane U of the control input is divided.

If the fuzzy phase plane U is partitioned by n triangular membership functions with equal widths and slopes, it can easily be verified that the above rule base can lead the system to oscillations around the desirable set-point. Consequently, in order to achieve convergence, the nonlinear transfer characteristic of the fuzzy controller should be such that the smaller the distance from the setpoint is, the smaller the change of the control signal becomes.

4.3 Analytical description of the RC-SMFLC

In this case $e=0$ plays the role of the diagonal. Therefore there are two requirements for the control law in RC-SMFLC :

1. To keep the error state vector $[e(t), \dot{e}(t)]^T$ inside the sliding surface $s(x,t) = e(t) \dot{e}(t) < 0$
2. Its magnitude to be proportional to the distance from the diagonal $e = 0$

The RC-SMFLC has similar properties to the ones of a diagonal-type FLC as described in the section 3.3 (properties 1 through 5). To show that RC-SMFLC also satisfies the property 6, the desirable control law should be similar to the one of a diagonal-type FLC : $u_{fuzz} = -K_{fuzz}(\dot{e}, e, \lambda) \text{sgn}(s)$ or to the control law of SMFLC : $u_{fuzz} = -K(|s| \text{sgn}(s))$, where $|s|$ is the distance from the diagonal.

The use of membership functions with the same shape (e.g. triangular with the same width and slopes) produces a control law of the form : $u_{fuzz} = -K \text{sgn}(s)$, where K is constant. To overcome this problem, the width of the membership functions should be modified at every crossing of the diagonal $e = 0$. The last two control signals u_{k-1} and u_k are taken into account, namely : u_{k-1} is the last control signal below (above) the diagonal and u_k is the last control signal above (below) the diagonal.

Recalling the bisection method, the control signal u^* that will produce zero error should be searched in the range $[u_{k-1}, u_k]$. The new fuzzy subsets $U_1, U_2, \dots, U_{n-1}, U_n$ correspond to the division of the interval between these two control signals $[u_{k-1}, u_k]$ in n equal segments.

Thus the centers of the fuzzy subsets U_i are in this case moving, and the nonlinear transfer characteristic $u = f(s)$ of the fuzzy controller changes. As the diagonal is approached, the width of the membership functions is reduced, and consequently the control gain K is reduced too. In this way a control law of the form

$$u_{fuzz} = -K_{fuzz}(\text{sgn}(e_k e_{k+1}))\text{sgn}(s), \quad (s = \dot{e}e) \quad (19)$$

where, e_k is the error at the k -th step of the algorithm, and e_{k+1} is the error at the $(k+1)$ -th step of the algorithm, is derived, and the similarity between RC-SMFLC and the diagonal-type FLC or the conventional SMFLC becomes clear.

4.4 Design of an RC-SMFLC

The control law in RC-SMFLC will be the same as that of SMC, with only one change concerning the control term $K(x,t)\text{sat}(s/\Phi)$ which now becomes

$$K(\text{sgn}(e_k e_{k+1}))\text{sgn}(\dot{e}_k e_k), \text{ i.e. } u = \hat{b}^{-1}(\tilde{u} - \hat{f}), \text{ where } \\ \tilde{u} = G(\hat{u} - K(\text{sgn}(e_k e_{k+1}))\text{sgn}(\dot{e}_k e_k)) \text{ and } \hat{u} = x_d^{(n)} - \sum_{k=1}^{n-1} \binom{n-1}{k} \lambda^k e^{(n-k)}$$

Is a previous estimation of the system parameters $f(x,t)$ and $b(x,t)$ always necessary? Assume that the system is stable and $\hat{b}^{-1} = 1$ and $\hat{f} = 0$. Assume also that G and $\hat{u}$ are selected as : $G=1$ and $\hat{u} = u_0$, where u_0 is a randomly selected value in the interval of the permitted input values. Introducing this selection in the above RC-SMFLC equations yields :

$$u = \tilde{u}, \quad \tilde{u} = \hat{u} - K(\text{sgn}(e_k e_{k+1}))\text{sgn}(\dot{e}_k e_k) \text{ and } \hat{u} = u_0 \quad (20)$$

The absence of estimation of the system's parameters $f(x,t)$ and $b(x,t)$ means that RC-SMFLC will have to handle additional parameter uncertainties. However, this additional uncertainty can be viewed as a perturbation that can be compensated by the robustness property possessed by the fuzzy controller.

Neglecting the filtering term $u_{filt} = -\hat{b}^{-1} G \sum_{k=1}^{n-1} \binom{n-1}{k} \lambda^k e^{(n-k)}$, makes the system susceptible to unmodeled high frequencies and consequently this should be done with caution.

5 SIMULATION RESULTS

The RC-SMFLC was applied to the linearized problem of arc-welding. The tests were also expanded to systems of high order and nonlinear systems. The following systems were considered :

1. Welding systems (Tzafestas, Kyriannakis and Rigatos , 1997)

$$G_m(z) = \frac{0.11(z+1)^2}{(z-0.96)(z-0.63)} \quad (\text{input : thermal power } Q ; \text{ output cooling rate CR})$$

2. 3rd order linear system $G_m(z) = \frac{0.5(z+1)^2(z-0.4)}{(z-0.5)(z-0.6)(z-0.7)}$

3. The nonlinear system : $y(k+1) = 0.95y(k) + 0.025y^2(k) + 0.05u(k)$

The system models are assumed to be unknown, and the RC-SMFLC had to operate under total parametric uncertainty. The first system was derived from the linearized model of the arc-welding process while the other two systems were introduced in order to prove the controller efficiency in compensating successfully nonlinear and high-order systems. Moreover, the tracking capability of RC-SMFLC was evaluated in the case of the second-order linear model (a) where the aim was to follow a ramp set-point with either positive or negative slope.

Due to space limitations only the results concerning the nonlinear system, and the tracking of a positive slope are given.

Figure 3 Control of nonlinear system

Figure 4 Tracking of a ramp setpoint

6 CONCLUSIONS

A new approach of Sliding-Mode Fuzzy Control was presented in this paper. It combines the basic principles of diagonal-type fuzzy controllers with sliding mode theory, and has the additional advantage that no prior design of the rule base is required. The control law that satisfies the above requirements is described by the rules :

IF $\text{sgn}(e(t)\dot{e}(t)) < 0$ THEN maintain (change) the control action

IF $\text{sgn}(e(t)\dot{e}(t)) > 0$ THEN change the control action

where the control action can be either an increase or a decrease of the control signal. The increase or decrease of the control signal is realized via the use of fuzzy linguistic rules.

Then, the problem was to determine changes in the control signal that will become smaller as the system output approaches the diagonal $e = 0$. This was achieved by changing the widths of the fuzzy subsets in which the control signal can be analyzed. The adaptation of the widths was performed each time the system output crossed the diagonal $e = 0$, either in a positive or a negative direction.

In contrast to the conventional SMFLC, there was no need to design in advance the shape of the membership functions. All membership functions are identical triangular functions, and therefore the transfer characteristic of RC-SMFLC is roughly approximated by a first-order linear function. Unlike diagonal type FLC, in RC-SMFLC no previous existence of a rule base, connecting the error output to the control signal, is necessary. Thus the problem of unavailable expert's knowledge is solved.

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7 BIOGRAPHY

Spyros G. Tzafestas received : B.Sc. in Physics and Postgraduate Diploma in Electronics (Athens University 1963;1964) ; D.I.C. and M.Sc. in Control (Imperial College, London Univ., 1966); Ph.D. (1969) and D.Sc. (1978) in systems and Control (Southampton University). From 1969 to 1973 he was research leader at the Nuclear Research Center "Democritos" (Athens), and from 1973 to 1984 he was Professor of systems and control engineering at Patras University, Greece. Since 1985 he is Professor of robotics and control at the National Technical University of Athens, Greece. He has published 30 research books and over 500 technical papers. He has organized and/or chaired many international conferences. His research interests include intelligent systems, knowledge-based systems , robotics, CIM, control , and fault diagnosis. He is a fellow of IEEE and IEE, Honorary President of the Society of Intelligent Robotics and Expert Systems (SIRES) , and a member of ASME and the New York Academy of Sciences.. He is an Honorary Doctor of Engineering of the Technical University of Munich , and an Honorary Doctor of Science of the International University Foundation.

Gerasimos G. Rigatos received a degree in Electrical and Computer Engineering from the National Technical University of Athens (NTUA) , Greece. Currently he is a Ph.D. student at the Intelligent Robotics and Automation Laboratory of NTUA. His current work is mainly concerned with neural and fuzzy based control and hybrid intelligent control systems. He has published four papers and is a member of the Technical Chamber of Greece.