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FUZZY SLIDING MODE CONTROL WITH ADDITIONAL FUZZY CONTROL COMPONENT

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Abstract. *A new control method is presented in this paper. The control employs a variant of fuzzy sliding mode, optimized by a genetic algorithm. Proposed controller has many advantages, such as satisfactory control performance under a wide range of operating conditions and parameter variations, a faster response than conventional controllers, suppressed chattering phenomenon and satisfactory control for nonlinear systems. The experimental results verify the efficiency, excellent performance, and robustness of such a control in the case of the experimental servo system.*

Key words: *sliding mode control, fuzzy control, genetic algorithm, DC servo motor*

1. INTRODUCTION

One of the possible approaches to the robust control of the uncertain systems has been found in variable structure systems and sliding mode control [1]. The principal goal of the sliding mode control technique is to force a system state to a certain prescribed manifold, known as the sliding hyper surface. Once the manifold is reached, the system is forced to remain on it thereafter. When in the sliding mode, the system is equivalent to an unforced system of lower order, which is insensitive to both parametric uncertainty and unknown disturbances that satisfy the matching condition. The main drawback of the sliding mode control is the requirement of a discontinuous control across the sliding manifold. In practical systems, this leads to a phenomenon termed chattering [2]. Chattering involves high-frequency control switching and may lead to excitation of unmodelled high-frequency system dynamics. Chattering also causes high heat losses in electronic systems and undue wear in mechanical systems. Smoothing techniques such as boundary layer [3] have been employed in order to prevent chattering. However, such an approach leads to a

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loss of asymptotic stability and a controller that can guarantee final tracking accuracy only to within a certain vicinity of the demand.

Over the last few years, the apparent similarities between the sliding mode and fuzzy controllers [4], [5] in diagonal form have been noticed. This fact has subsequently motivated considerable research effort in combining the two topologies [6] in a manner that serves to reduce the limitations of the sliding mode, while still maintaining the guarantees of global uniform stability and invariance to matched disturbances [7], [8]. In this paper, we propose additional fuzzy component [9] and additional control signal which is introduced to accelerate the reaching phase in sliding mode and to reduce chattering while maintaining sliding behavior.

The main difficulty in designing fuzzy controller is the acquisition of the controller parameters that are usually determined by human expert knowledge or trial and error method. It is a difficult problem to find optimal parameters of the controller in order to achieve maximum performance. Genetic algorithms [10], [11] are optimization technique based on simulation of the phenomena taking place in the evolution of species. They have demonstrated very good performances as global optimizers in many types of control applications [12]. They are good optimizers for fuzzy controllers, as well [13], [14]. In this paper, the genetic algorithm is applied to determine optimal values of the key parameters required for the two stage fuzzy sliding controller design [15]-[18].

To verify the efficiency of the proposed control method, experiments were performed on "Inteco" modular servo system [19]. The experimental results demonstrated the efficiency, excellent performance, and robustness of such a control in the case of the experimental DC servo drive.

2. SLIDING MODE CONTROL

Consider the system in the following form:

$$\boldsymbol{x}^{(n)} = f(\boldsymbol{x},t) + g(\boldsymbol{x},t)u + d \ , \tag{1}$$

where $\boldsymbol{x} = (x, \dot{x}, ..., x^{(n-1)})^T$ represents the state vector, d disturbances, u control input and f, g are nonlinear functions.

The tracking control problem is to find a control law such that given a desired trajectory $\boldsymbol{x_d}$, the tracking error $\boldsymbol{x}$-$\boldsymbol{x_d}$ tends to zero despite the presence of the model uncertainties, unmodelled frequencies and disturbances [2]. With the tracking error defined as:

$$\boldsymbol{e} = \boldsymbol{x} - \boldsymbol{x}_d = (e, \dot{e}, ..., e^{n-1})^T \ , \tag{2}$$

a sliding surface (sliding line for second order systems) $s(\boldsymbol{x},t) = 0$ is determined by:

$$s(\boldsymbol{x},t) = (d/dt + \lambda)^{n-1} e, \ \lambda \geq 0 \ . \tag{3}$$

In order to derive control law such that the state vector remains on the sliding surface, we define a Lyapunov function [2], [3]:

$$V = \frac{1}{2}s^2 . \tag{4}$$

Sufficient condition for the stability of the system (1) is:

$$\dot{V} = \frac{1}{2}\frac{d}{dt}(s^2) \le -\eta \,|\, s \,|, \quad \eta > 0 . \tag{5}$$

From (5) we can obtain so-called reaching condition that enables the system to reach the sliding surface in finite time interval:

$$\dot{s}\,\mathrm{sgn}(s) \le -\eta , \tag{6}$$

For the second order system:

$$\begin{aligned} s &= \lambda e + \dot{e} \\ \dot{s} &= \lambda\dot{e} + \ddot{e} = \lambda\dot{e} + \ddot{x} - \ddot{x}_d \end{aligned} . \tag{7}$$

From the reaching condition (7) we obtain:

$$s\dot{s} = s(\lambda\dot{e} + f(\boldsymbol{x},t) + g(\boldsymbol{x},t)u + d - \ddot{x}_d) \le -\eta \,|\, s \,| . \tag{8}$$

Following control can be used for establishing the sliding mode with respect to (8):

$$u = -g^{-1}(\hat{f} + \lambda\dot{e} + K(\boldsymbol{x},t)\mathrm{sgn}(s)), \;\; K(\boldsymbol{x},t) > 0 . \tag{9}$$

To avoid large changes of the control signal, boundary layer [3] can be introduced, which leads to the following control:

$$u = -g^{-1}\left(\hat{f} + \lambda\dot{e} + K(\boldsymbol{x},t)sat\left(\frac{s}{\Phi}\right)\right), \; \Phi > 0, \; K(\boldsymbol{x},t) > 0 . \tag{10}$$

3. TWO STAGE FUZZY SLIDING MODE CONTROL

Improvements in design of fuzzy sliding mode controller can be achieved by an additional fuzzy component which accelerates convergence toward sliding surface and decreases reaching phase time. First we define control u_0 which define equivalent dynamics (systems dynamic on the sliding surface) and satisfies the sliding mode existence conditions. This control also determines desired poles. Then we add switching control that guaranties sliding surface reaching in the presence of parameters fluctuation and external disturbances.

The next step in the control design is to define additional fuzzy control component. This control improves system performance by increasing control signal when the system state is far away from the sliding surface. In such a way, reaching time is decreased. On the other side, additional control decreases overall control when the system state is near the sliding surface and in such a way, chattering is decreased. So, now the overall control has the following form:

$$u = u_0 - u_{fuzz} . \tag{11}$$

Used approach in designing of fuzzy sliding mode control is to determine desired control not only on the basis of variable $s(\boldsymbol{x})$ for actual state vector but also on the basis of variable differential $\dot{s}(\boldsymbol{x})$. The goal is to establish the control that fulfills reaching condition $s(\boldsymbol{x})\dot{s}(\boldsymbol{x}) < 0$.

If we assume $g(\boldsymbol{x})>0$ in general equation of nonlinear system (1), then increase of u leads to increase of $\dot{s}(\boldsymbol{x})$, and vice versa. So, the following conclusions are valid:

- If $s>0$ and u decreases then $s\dot{s}$ also decreases
- If $s<0$ and u increases than $s\dot{s}$ also decreases

The logic for defining fuzzy controller rule base is based on idea that for systems state far away from the sliding surface, control signal should be larger (with appropriate sign that leads to the decrease of $s\dot{s}$). These conditions lead to parameters of fuzzy controller shown in Table 1 and Fig. 1. Formed control surface is given in Fig. 2.

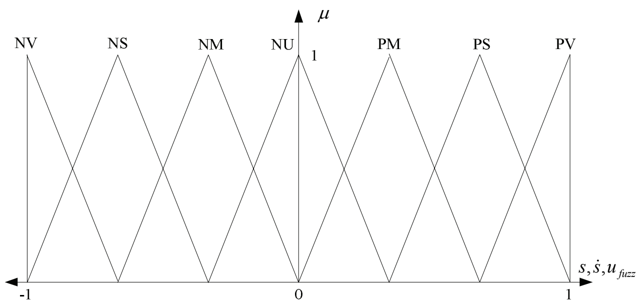

Fig. 1 Fuzzy controller membership functions for input and output variables

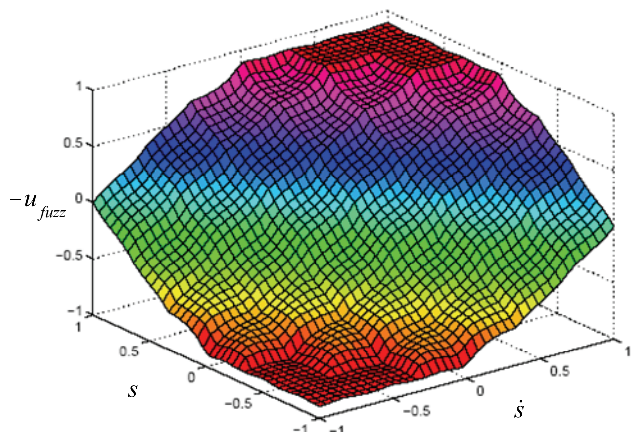

Fig. 2 Fuzzy controller control surface

Table 1 Fuzzy controller rule base

s \ $\dot{s}$	NL	NM	NS	ZE	PS	PM	PL
PL	ZE	NS	NM	NL	NL	NL	NL
PM	PS	ZE	NS	NM	NL	NL	NL
PS	PM	PS	ZE	NS	NM	NL	NL
ZE	PL	PM	PS	ZE	NS	NM	NL
NS	PL	PL	PM	PS	ZE	NS	NM
NM	PL	PL	PL	PM	PS	ZE	NS
NL	PL	PL	PL	PL	PM	PS	ZE

Further improvements in this method can be achieved by introducing two stage fuzzy control. The main idea behind the design is that large control switching signal leads to faster reaching of sliding surface but causes larger chattering. When the system state run away from the sliding surface ($s\dot{s} > 0$) for a large values of $|\dot{s}|$, system gain should increase in order to return the state toward the surface. When the system state approaches the sliding surface ($s\dot{s} < 0$) for a large values of $|\dot{s}|$, system gain should decrease in order to decrease chattering. If we introduce scaled absolute values for s and $\dot{s}$, then we have the following rules for the first stage of fuzzy control:

if $|s|$=Small *then* w_s=Small
if $|s|$=Large *then* w_s=Large

We can use exponential and singleton functions for the given fuzzy sets (Fig. 3) and gravitational method for defuzzyfication. In this case, auxiliary variable (weight factor) w_s can be calculated:

$$w_s = w_0\left(1-\exp\left(-\frac{|s|}{\sigma_s}\right)\right), \tag{12}$$

where w_0 represents preset weight.

After determining w_s, we can calculate final control u_{fuzz} in the second stage. In this stage fuzzy controller with similar fuzzy sets shown in Fig. 3 calculates control u_{fuzz} based on $|\dot{s}|$.

For $s\dot{s} > 0$, for determining u_{fuzz}, we can use the following rules:

if $|\dot{s}|$=Small *then* u_{fuzz}=Small
if $|\dot{s}|$=Large *then* u_{fuzz}=Large

For $s\dot{s} < 0$, rules are different:

if $|\dot{s}|$=Small *then* u_{fuzz}=Large
if $|\dot{s}|$=Large *then* u_{fuzz}=Small

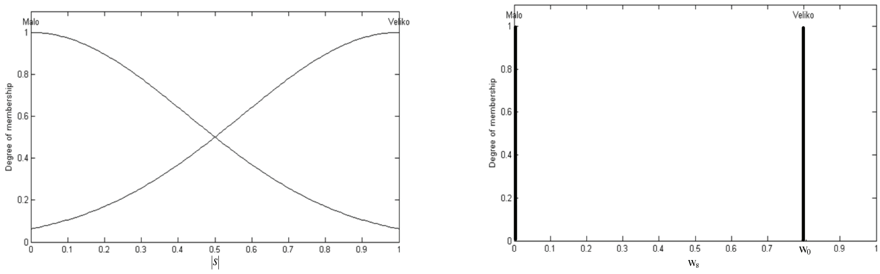

Fig. 3 Fuzzy sets $|s|$ and w_s

Finally, relations for control signal u_{fuzz} are the following:

$$u_{fuzz} = \begin{cases} w_0\left(1-\exp\left(-\dfrac{|s|}{\sigma_s}\right)\right)\left(1-\exp\left(-\dfrac{|\dot{s}|}{\sigma_{\dot{s}}}\right)\right), & s\dot{s} > 0 \\ w_0\left(1-\exp\left(-\dfrac{|s|}{\sigma_s}\right)\right)\exp\left(-\dfrac{|\dot{s}|}{\sigma_{\dot{s}}}\right), & s\dot{s} < 0 \end{cases}, \tag{13}$$

where $w_0, \sigma_s, \sigma_{\dot{s}}$ are controller parameters whose choice determine performances of designed system. In this paper, optimal values for these parameters will be determined by genetic algorithm.

4. CASE STUDY

For the purposes of the practical verification of proposed control method, modular servo drive shown in Fig. 4 is considered. The modular servo system [19] consists of the “Inteco” servomechanism and open-architecture software environment for real-time control experiments. The servo system supports the real-time design and implementation of advanced control methods using MATLAB and Simulink tools and extends the MATLAB environment in the solution of servomechanism control problems.

The integrated software supports: on-line process identification, control system modelling, design and simulation and real-time implementation of control algorithms. The modular servo system uses standard PC hardware platforms and Microsoft Windows operating systems.

The servo system setup (Fig. 4) consists of several modules mounted at the metal rail and coupled with small clutches. The modules are arranged in the chain. The DC motor together with tachogenerator opens the chain. The gearbox with the output disk closes the chain. The potentiometer module is located outside the chain. The DC motor can drive the following modules: inertia, backlash, encoder module, magnetic brake and the gearbox with the output disk.

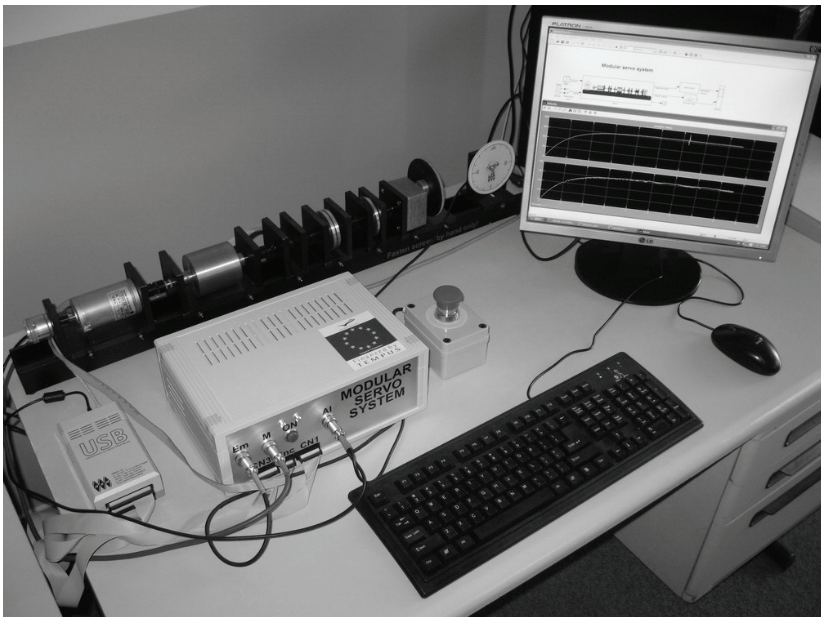

Fig. 4. The modular servo system setup

The rotation angle of the DC motor shaft is measured using an incremental encoder. A tachogenerator is connected directly to the DC motor and generates a voltage signal proportional to the angular velocity. The servomechanism is connected to a computer where a control algorithm is realized based on measurements of angle and angular velocity. All functions of the board are accessed from the Modular Servo Toolbox which operates directly in the MATLAB/Simulink environment. Modular servo drive is nonlinear due to some nonlinear static characteristics such as hysteresis and saturation, which may occur in the following devices: operational amplifiers, actuators, finite word length in A/D and D/A converters.

This servo motor has been used in our experiments with described control method employed. Figure 5 shows motor velocity and control signals for original sliding mode controller and Figure 6 shows the same variables for designed two stage fuzzy sliding mode control after optimization with genetic algorithm.

Control signal in experiment is limited to ±5V and response variations are results of previously described system nonlinearities. Performed experiments verify obtained mathematical background for our control method. Although our control method gives a little bit slower response comparing to the classical bang-bang control, its strength is obvious from the given control signals. Optimized two stage fuzzy sliding mode control has relatively low levels, and discontinuities of the control signal which results in lower heat losses and undue system wear.

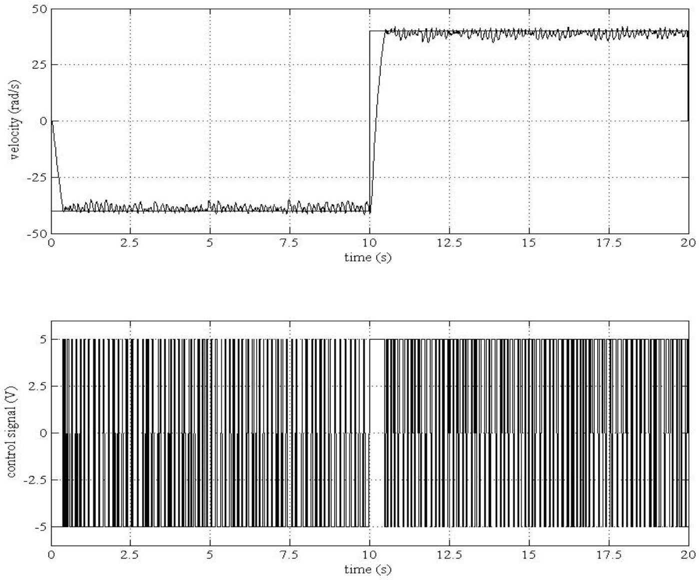

Fig. 5 Sliding mode control: a) reference and actual velocity; b) control signal

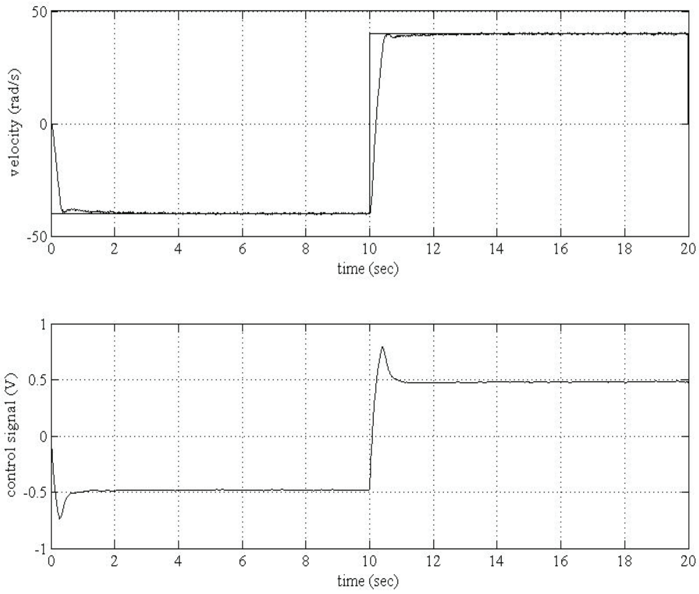

Fig. 6 Optimized two stage fuzzy sliding mode control:
a) reference and actual velocity; b) control signal

5. CONCLUSION

A new method for systems control based on genetic algorithms applied on two stage fuzzy sliding mode is realized in this paper. Illustration and verification of this new method is done by experiments on a DC servo drive system. The experimental results of the proposed controller, compared to the traditional variable structure controller and fuzzy sliding mode control verify the effectiveness of the introduction of two stage fuzzy logic and genetic algorithms in the variable structure control design. Fast system response, relatively low levels, and discontinuities of the control signal as well as suppressed chattering are achieved.

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UPRAVLJANJE U FAZI KLIZNOM REŽIMU SA DODATNOM FAZI UPRAVLJAČKOM KOMPONENTOM

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U ovom radu je predstavljen novi metod upravljanja. Upravljanje predstavlja varijantu fazi kliznog režima, optimizovanu genetičkim algoritmom. Predloženi regulator ima mnoge prednosti, kao što su zadovoljavajuće performanse u širokom opsegu uslova rada i varijacije parametara, brži odziv nego kod konvencionalnih regulatora, potisnuti problem četeringa i zadovoljavajuće upravljanje nelinearnim sistemima. Eksperimentalni rezultati potvrđuju efikasnost, dobre performanse i robusnost ove metode upravljanja u slučaju eksperimentalnog servo sistema.

Ključne reči: *klizni režim, fazi upravljanje, genetički algoritam, DC servo motor*