A new robust adaptive fuzzy synergetic control for nonlinear systems with an application to an inverted pendulum

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Abstract: This paper deals with a nonlinear adaptive control design based on synergetic control, which also uses fuzzy systems to approximate the dynamics of nonlinear systems. The stability of the closed-loop system is ensured by the Lyapunov synthesis in the sense that all the signals are bounded, and the controller parameters adjusted by adaptation laws. The proposed algorithm is applied to an inverted pendulum to track a sinusoidal reference trajectory. Simulations and discussion are presented to illustrate the new robust adaptive fuzzy synergetic control described in this work.

Keywords: adaptive control; fuzzy adaptive control; fuzzy systems; Lyapunov; nonlinear systems; synergetic control.

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1 Introduction

Modelling, identification and control are important research topics in control systems engineering (Kang et al., 2018; Azar and Serrano, 2018; Han et al., 2018; Rajani et al., 2018; Benamor and Messaoud, 2018; Chibani et al., 2018; Lien et al., 2019; Vaidyanathan et al., 2019).

Unlike linear automation, nonlinear automation does not have universal solutions for either system analysis or controller design. Most nonlinear control approaches require knowledge of a mathematical model of the system.

The performances guaranteed will be directly linked to the accuracy of the model used. Indeed, obtaining a mathematical model that is precise, relevant and simple to use, is sometimes difficult and complex. To solve these problems, the use of controllers based on human expertise can be a reliable alternative.

Among these approaches is the fuzzy logic control which does not require knowledge of the mathematical model of the process to be controlled, so it exploits the information linguistic skills of the human expert. In addition, fuzzy systems have the ability to approximate any unknown nonlinear function with a given degree of precision (Wang, 1994). Most often fuzzy controllers are used in systems that have unknown intrinsic variations. The goal is therefore to maintain good overall system performance by adapting the controller according to system variations.

This goal can be achieved by so-called intelligent control whose fuzzy logic has been applied in many fields in the control of nonlinear systems. An adaptive fuzzy system is used to approximate the unknown system dynamics and the system stability is analysed by Lyapunov stability theory (Khalil, 2002).

Synergetic control has evolved only in recent years, which is similar in its conceptual approach to sliding mode control. Synergetic control is seen as a powerful methodology for robust control design (Rebai et al., 2016). Synergetic control technique has been successfully applied in the field of power electronics where, for example, its application to a boost converter has been studied (Kolesnikov et al., 2002), and some practical aspects concerning simulation and hardware have been discussed (Kondratiev et al., 2004; Monti et al., 2003). Some of the successful practical applications of synergetic control in industry are battery chargers (Jiang and Dougal, 2004).

Like the fuzzy adaptive control (Li et al., 2017, 2018; Chen et al., 2014, 2015), we develop the design and implementation of the adaptive fuzzy synergetic control in this work. Fuzzy type-1 systems are initially used to approximate the dynamics of unknown nonlinear systems. Then type-2 fuzzy systems (Theodoridis et al., 2010; Bounemeur et al., 2018; Chemachema, 2012) are used in our new design.

The stability of the closed-loop system is ensured by the synthesis of Lyapunov in the sense that all the signals are bounded and the parameters of the controller adjusted by an adaptation law provided with a projection algorithm. Control laws and adaptation laws are obtained using the Lyapunov method.

This research work is organised as follows. Section 2 describes the problem formulation and control objective of adaptive fuzzy synergetic control design. Section 3 details the construction of adaptive fuzzy synergetic control. Section 4 discusses the adaptation laws. Section 5 illustrates an application of the proposed fuzzy synergetic control to an inverted pendulum and discusses the numerical simulations in detail. Section 6 draws the main conclusions of this work.

2 Problem formulation and control objective

In this section, we describe the problem formulation and control objective for the adaptive fuzzy synergetic control. We first use the objectives of the command to develop synergistic adaptive controllers based on fuzzy systems to achieve these same goals (Rebai et al., 2016).

Consider the single-input single-output (SISO) system of the *n*th order:

$$\begin{cases} x^{(n)} = f(x,\dot{x},\ldots,x^{(n-1)}) + g(x,\dot{x},\ldots,x^{(n-1)})u \\ y = x \end{cases} \tag{1}$$

In system form, the ODE (1) can be expressed in the Isidori-Byrnes normal form (Isidori, 1989) as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \quad \vdots \quad \vdots \\ \dot{x}_n = f(x_1,x_2,\ldots,x_n) + g(x_1,x_2,\ldots,x_n)u \\ y = x_1 \end{cases} \tag{2}$$

In the system (2), f and g are continuous and unknown functions, $u \in R$ and $y \in R$ are the input and output of the system (2) respectively and

$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$ is the state vector of the system (2).

We can also write the output y as $y = c^T x$, where

$$c = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

For the control system (2) be controllable and feedback linearisable, it is required that $g(x) \neq 0$ for x in certain controllability region $U_c \subset R^n$. Without loss of generality, the following assumption is made (Wang et al., 2002):

Assumption A: $g(x) \succ 0$ for all $x \in U_c$.

It is worth noting that several nonlinear systems can be given the form (2) and satisfy the Assumption A, e.g., Duffing chaotic system, Chua's circuit, aircraft wing rock, induction servo-motor drive, inverted pendulum, and many others (Boulkroune et al., 2008).

The control objective is to regulate the output y of the system (2) to track the bounded reference signal y_m under the constraint that any signal involved is bounded.

This is determined by a status feedback control $u = u(x/\theta)$ and an adaptation law for adjusting the parameter vector such that the following conditions are satisfied.

- The system to evolve with a dynamic chosen in advance by the designer.
- The macro-variable $\psi(e)$ must be as small as possible under the constraint indicated by the following equation: $T\psi + \psi = 0, \quad (T \succ 0).$

3 Construction of adaptive fuzzy synergetic control

We start by defining a macro-variable $\psi(e)$ in the error state space, which is usually defined as:

$$\psi(e) = c^T e \tag{3}$$

It is desired to complete a zero error between the output of the system and the reference signal by forcing the system to evolve towards a domain chosen by the designer to know:

$$\psi(e) = 0$$

One of the simplest methods to achieve this is to choose the dynamics of evolution of the macro-variable using a constraint such as:

$$T\psi(e) + \psi(e) = 0$$

where $e = y_m - x$ is the error, and c is chosen so that all the roots of the polynomial $h(\lambda) = \lambda^{n-1} + c_{n-1}\lambda^{n-1} + \cdots + c_1$ are in the left half-plane of the complex space. T is a control parameter that indicates the rate of convergence of the closed-loop system to the indicated domain.

We consider the system (2). If the functions *f* and *g* are known, then the control law solving the output regulation problem is given by:

$$u = \frac{1}{g(x)}\left[-f(x) + y_m^{(n)} - e^{(n)}\right] \tag{4}$$

According to the equation $T\dot{\psi}(e) + \psi(e) = 0,$ we have:

$$e^{(n)} = -\sum_{1}^{n-1} c_i e^{(i)} - \frac{1}{T}\psi(e) \tag{5}$$

The substitution of equation (5) in equation (4) makes it possible to write:

$$u = \frac{1}{g(x)}\left[-f(x) + y_m^{(n)} + \sum_{i=1}^{n-1} c_i e^{(i)} + \frac{1}{T}\psi(e)\right] \tag{6}$$

However, in the general case, the functions f and g are unknown, which makes the approximation of f and g necessary. For this purpose, we use the fuzzy systems which are universal approximators (Wang and Mendel, 1992).

Next, we describe the design of fuzzy systems used in this work.

In our study we will approximate the functions f and g by fuzzy systems that allow us to write in the following form:

$$y(x) = \theta^T \xi(x) \tag{7}$$

In equation (7),

$$\theta = \begin{bmatrix} \bar{y}^1 \\ \bar{y}^2 \\ \vdots \\ \bar{y}^M \end{bmatrix}$$

is a vector of parameters and

$$\xi(x) = \begin{bmatrix} \xi^1(x) \\ \xi^2(x) \\ \vdots \\ \xi^M(x) \end{bmatrix}$$

is the basic fuzzy function vector that is calculated as follows.

For fuzzy systems of type-1, the fuzzy basic functions (FBF) are given by the following equations:

$$\xi^1(x) = \frac{\prod_{i=1}^{n} u_{F_i^l}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n} u_{F_i^l}(x_i)\right)} \tag{8}$$

The functions $\hat{f}$ and $\hat{g}$ are estimates given by:

$$\begin{cases} \hat{f}(x/\theta_f) = \theta_f^T \xi_f(x) \\ \hat{g}(x/\theta_g) = \theta_g^T \xi_g(x) \end{cases} \tag{9}$$

For fuzzy systems of type-2, the FBF are given by the following equations:

$$\xi_{f_l}^i = \frac{w_{f_l}^i}{\sum_{i=1}^{M} w_{f_l}^i} \tag{10}$$

$$\xi_{f_r}^i = \frac{w_{f_r}^i}{\sum_{i=1}^{M} w_{f_r}^i} \tag{11}$$

$$\xi_{g_l}^i = \frac{w_{g_l}^i}{\sum_{i=1}^{M} w_{g_l}^i} \tag{12}$$

$$\xi_{g_r}^i = \frac{w_{g_r}^i}{\sum_{i=1}^{M} w_{g_r}^i} \tag{13}$$

where w_f^i and w_g^i are the activation intervals (degree of membership) corresponding to the same rule of fuzzy systems type-2 $\hat{f}$ and $\hat{g}$, respectively, θ_f^i and θ_g^i are the centres of consistent sets that also represent the adjustable parameters of our adaptive control.

The functions $\hat{f}$ and $\hat{g}$ are estimates given by:

$$\hat{f} = \frac{\theta_f^T \xi_{f_l} + \theta_f^T \xi_{f_r}}{2} = \theta_f^T \left[\frac{\xi_{f_l} + \xi_{f_r}}{2} \right] = \theta_f^T \xi_f(x) \quad (14)$$

$$\hat{g} = \frac{\theta_g^T \xi_{g_l} + \theta_g^T \xi_{g_r}}{2} = \theta_g^T \left[\frac{\xi_{g_l} + \xi_{g_r}}{2} \right] = \theta_g^T \xi_g(x) \quad (15)$$

where $\xi_f = (\xi_{f_l} + \xi_{f_r})/2$ is the average vector of FBF of $\hat{f}$ and $\xi_g = (\xi_{g_l} + \xi_{g_r})/2$ is the average vector of FBF of $\hat{g}$.

The algorithm of Karnik and Mendel (Karnik et al., 1999) is used to calculate $w_{f_r}^i, w_{f_l}^i, w_{g_r}^i, w_{gl}^i$ and allows to build the FBF $\xi_{f_r}, \xi_{f_l}, \xi_{g_r}, \xi_{gl}$.

4 Adaptation laws

The next task is to replace $\hat{f}$ and $\hat{g}$ by the specific formula of fuzzy systems (9) and to develop adaptation laws to adjust the parameters for the purpose to ensure the convergence of the closed-loop system.

First, we define:

$$\theta_f^* = \arg\min_{\theta_f \in \Omega_f} \left[\sup_{x \in U_C} \left| \hat{f}(x/\theta_f) - f(x) \right| \right] \quad (16)$$

$$\theta_g^* = \arg\min_{\theta_g \in \Omega_g} \left[\sup_{x \in U_C} \left| \hat{g}(x/\theta_g) - g(x) \right| \right] \quad (17)$$

where Ω_f and Ω_g are sets of constraints for θ_f and θ_g respectively, specified by the expert. These sets are defined as follows:

$$\Omega_f = \left\{ \theta : \left| \theta_f \right| \le M_f \right\} \quad (18)$$

$$\Omega_g = \left\{ \theta : \left| \theta_g \right| \le M_g \right\} \quad (19)$$

where M_f and M_g are positive constants specified by the expert.

The minimum approximation error is defined by

$$w = (\hat{f}(x/\theta_f^*) - f(x)) + (\hat{g}(x)/\theta_g^*) - g(x))u \quad (20)$$

Then the equation of the macro-variable (3) can be rewritten as:

$$\dot{\psi}(e) = (\theta_f^T - \overset{*}{\theta}_f^T)\xi(x) + (\theta_g^T - \overset{*}{\theta}_g^T)\xi(x)u - \frac{1}{T}\psi(e) + w \quad (21)$$

Here, $\varphi_f = \theta_f - \overset{*}{\theta}$, $\varphi_g = \theta_g - \overset{*}{\theta}_g$ and ξ is the basic fuzzy function.

$$\dot{\psi}(e) = (\theta_f^T \xi(x) + \theta_g^T \xi(x)u - \frac{1}{T}\psi(e) + w \quad (22)$$

Now, we consider the following candidate Lyapunov function:

$$V = \frac{1}{2}\psi(e)^2 + \frac{1}{2\gamma_1}\varphi_f^T \varphi_f + \frac{1}{2\gamma_2}\varphi_g^T \varphi_g \quad (23)$$

where γ_1 and γ_2 are positive constants.

The derivative of V with respect to time is given by:

$$\begin{aligned} \dot{V} &= \frac{1}{\gamma_1}\varphi_f^T(\gamma_1 \psi(e)\xi(x) + \dot{\theta}_f) \\ &+ \frac{1}{\gamma_2}\varphi_g^T(\gamma_2 \psi(e)\xi(x)u + \dot{\theta}_g) \\ &- \frac{1}{T}\psi(e)^2 + \psi(e) \end{aligned} \quad (24)$$

If we choose the following adaptation laws:

$$\begin{aligned} \dot{\theta}_f &= -\delta_1 \psi(e)\xi(x) \\ \dot{\theta}_g &= -\delta_2 \psi(e)\xi(x)u \end{aligned} \quad (25)$$

Then from equation (25) we will have:

$$\dot{V} = -\frac{1}{T}\psi(e)^2 + \psi(e)w \quad (26)$$

The influence of the term $\psi(e)w$ is minimal in the order of the minimal approximation error which is too small, since the fuzzy systems $\hat{f}$ and $\hat{g}$ have an ability to approximate nonlinear functions f and g with great precision because they are universal approximators that can approximate any continuous real function with arbitrary precision.

So, using sufficient rules to build $\hat{f}$ and $\hat{g}$ allows us to have w very small. When w tends to 0, the inequality (26) becomes:

$$\dot{V} \le -\frac{1}{T}\psi(e)^2 \le 0 \quad (27)$$

This guarantees the convergence of the closed-loop system by Lyapunov stability theory (Khalil, 2002).

5 Application to an inverted pendulum

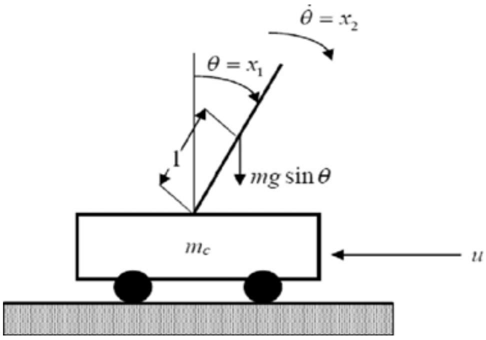
This involves applying the adaptive controller fuzzy developed to an inverted pendulum shown on Figure 1.

The dynamics of this pendulum is described by the differential equation (28) (Slotine and Li, 1991):

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{g\sin(x_1) - \dfrac{mlx_2^2\cos(x_1)\sin(x_1)}{m_c + m}}{l\left(\dfrac{4}{3} - \dfrac{m\cos^2(x_1)}{m_c + m}\right)} + \frac{\dfrac{\cos(x_1)}{m_c + m}}{l\left(\dfrac{4}{3} - \dfrac{m\cos^2(x_1)}{m_c + m}\right)}u \end{aligned} \quad (28)$$

where $x_1 = \theta$ is the angle of rotation, $\dot{x}_2 = \theta$ speed angular, $g = 9.8\ \text{m/s}^2$ the acceleration of gravity, m_c the mass of the trolley, m the mass of the beam, $2l$ the length of the beam and u applied force.

Figure 1 Diagram of an inverted pendulum



The goal of the controller is to force the angle of the pendulum θ to follow the desired trajectory defined by:

$$y_m(t) = \frac{\pi}{30}\sin(t)$$

The parameters of the pendulum are: $m_c = 1\,\text{kg}$, $m = 0.1\,\text{kg}$, $l = 0.5\,\text{m}$.

The design parameters of the proposed controller are thus chosen:

$$Q = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}, \quad k_1 = 2, \quad k_2 = 1, \quad \gamma_1 = 50, \quad \gamma_2 = 1,$$
$$M_f = 16, \quad M_g = 1{,}6 \text{ and } \varepsilon = 0.7$$

5.1 *Fuzzy adaptive synergistic control type-1*

We choose $m_1 = m_2 = 5$ since $|x_i| \le \pi/6$ with $i = 1, 2$. We consider the membership functions defined on the universe $[-\pi/6, \pi/6]$ We will take $\gamma_1 = 50$ and $\gamma_2 = 1$.

Table 1 gives the inference matrices for both functions $f(x_1, x_2)$ and $g(x_1, x_2)$.

Table 1 Inference matrices for $f(x_1, x_2)$ and $g(x_1, x_2)$

$g(x_1, x_2)$

x_2					
F_2^1	1.26	1.36	1.46	1.36	1.26
F_2^2	1.26	1.36	1.46	1.36	1.26
F_2^3	1.26	1.36	1.46	1.36	1.26
F_2^4	1.26	1.36	1.46	1.36	1.26
F_2^5	1.26	1.36	1.46	1.36	1.26
	F_1^1	F_1^2	F_1^3	F_1^4	F_1^5

x_1

$f(x_1, x_2)$

x_2					
F_2^1	-8	-4	0	4	8
F_2^2	-8	-4	0	4	8
F_2^3	-8	-4	0	4	8
F_2^4	-8	-4	0	4	8
F_2^5	-8	-4	0	4	8
	F_1^1	F_1^2	F_1^3	F_1^4	F_1^5

x_1

5.1.1 *Simulation results*

The simulation results of fuzzy adaptive synergistic control type-1 are obtained for two cases, first in the absence of disturbances with the initial state

$$x(0) = \begin{bmatrix} -\pi/60 \\ 0 \end{bmatrix}$$

and then in the presence of a strong constant amplitude disturbance $d = 2$ at the instant $t = 14$ s.

Without disturbance:

Figures 2 and 3 show that the output of the system $y(t)$ follows its reference $y_r(t)$ for the two initial conditions.

Figure 2 Response in system position

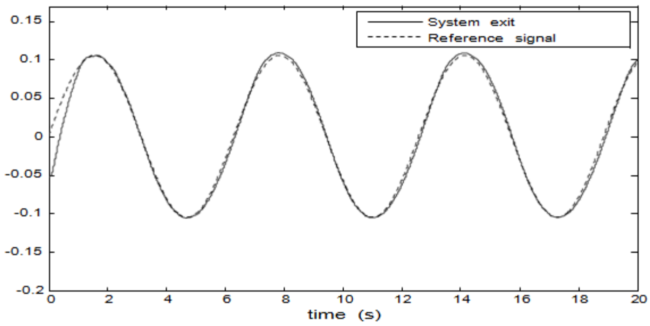
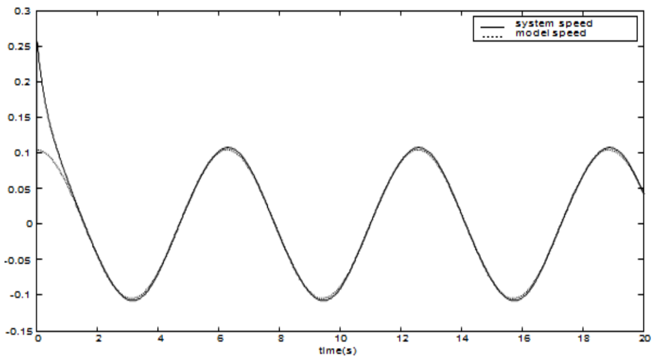


Figure 3 Speed response of the system



Figures 4 and 5 give the appearance of the overall control of the system for the two initial conditions. The control signal has switching in the transient regime in the case where the initial condition is far from that of the reference signal.

$$x(0) = [-\pi/10, 0]^T$$

These switches are due to the activation of the supervisory command u_s which is not enabled (null) in the case of the initial condition $x(0) = [-\pi/60, 0]^T$

Figure 4 Control signal

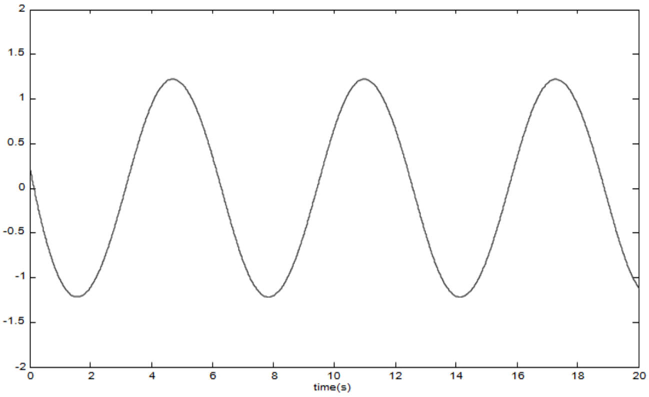
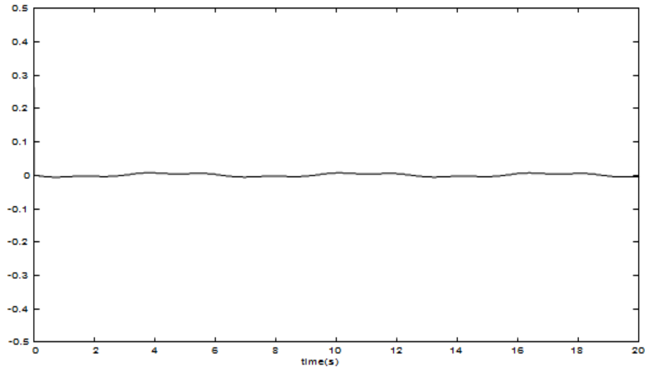


Figure 5 Signal of the macro-variable



With disturbance:

Figure 6 Response in system position

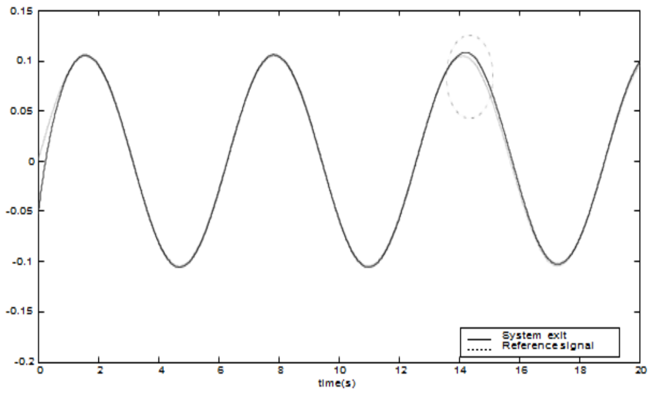
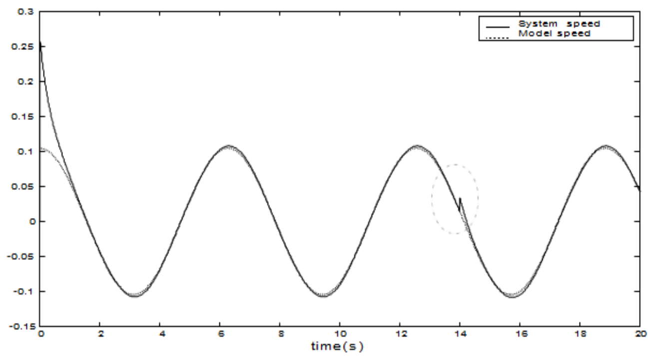


Figure 7 Speed response of the system



Figures 6–9 shows the output of the system $y(t)$ which achieves an acceptable tracking of the reference signal $y_m(t)$ despite the presence of external disturbances.

Figure 8 Control signal

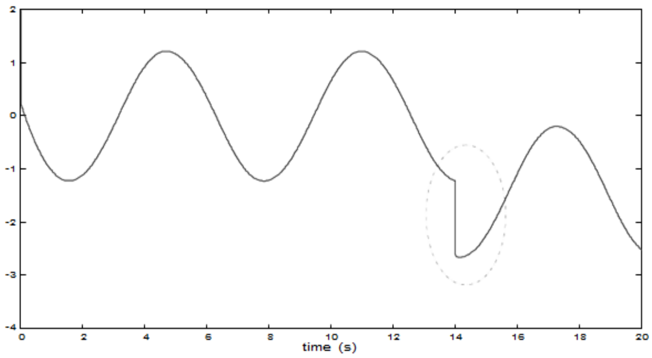
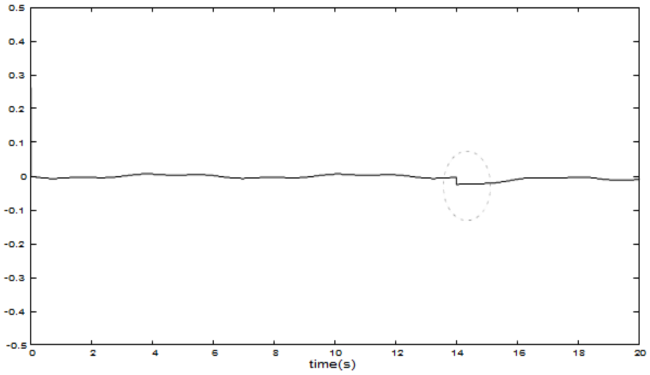


Figure 9 Signal of the macro-variable



5.2 *Fuzzy adaptive synergistic control type-2*

The design steps for this control remain the same as for type-1 except that $\hat{f}$ and $\hat{g}$ are obtained by fuzzy type-2 systems.

- In this case we choose $m_i = 3(i = 1, 2)$ fuzzy sets type-2, on the discourse universe $\left[-\frac{\pi}{6}, \frac{\pi}{6}\right]$, these fuzzy sets type-2 are constructed from the type-1 antecedents, adding to them a region of uncertainty represented by the variation of the mean $M \in [M_1, M_2]$ with a constant standard deviation σ. To facilitate the manipulation of these sets, each of them will be represented by its superior membership functions $\overline{u}_{\tilde{F}_i^l} = (x_i)$ and lower

  $\underline{u}_{\tilde{F}_i^l} = (x_i)$

  where $K = 1, ..., mi, \sigma = \pi / 24, M_1 = [-0.3491, 0, 0.3491]$ and $M_2 = [-0.4491, 0, 0.2491]$.
- The bases of the rules are constructed in the same way as for type-1 fuzzy systems, except that the antecedents are fuzzy sets type-2, and the consequent sets as the centres of fuzzy sets type-1 in the interval [–3, 3] for the function $f(x)$ and in the interval [1, 1, 3] are initially chosen for the function $g(x)$, later these centres will be adjusted using adaptation laws.

- The fuzzy functions of the left base are calculated $\xi_{f_l}^i$, $\xi_{g_l}^i$ and right $\xi_{f_r}^i$, $\xi_{g_r}^i$, in order to calculate $\hat{f}(x,\theta_f)$ and $\hat{g}(x,\theta_g)$.

5.2.1 Simulation results

The simulation results of fuzzy type-2 adaptive control are obtained for both cases, namely with and without disturbance for initial conditions $x(0) = [-\pi/60, 0]^T$. The perturbation used is constant of amplitude $d = 2$ at the instant $t = 14$ s.

Without disturbance:

Figures 10–13 show that the output of our system $y(t)$ performs a good tracking of the reference signal $y_m(t)$ for the two initial conditions.

Figure 10 Answer in system position

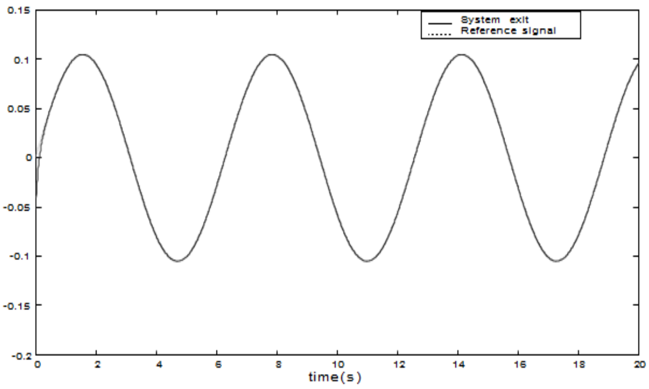


Figure 11 Speed response of the system

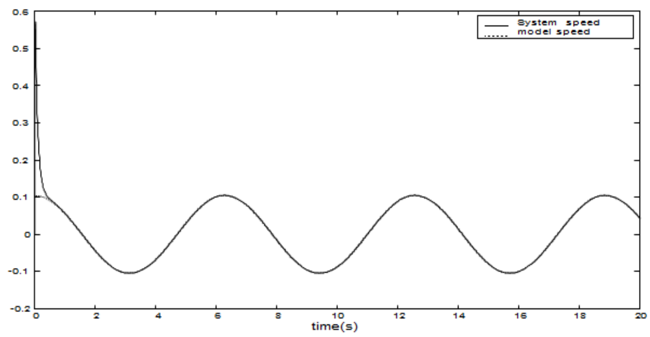


Figure 12 Control signal

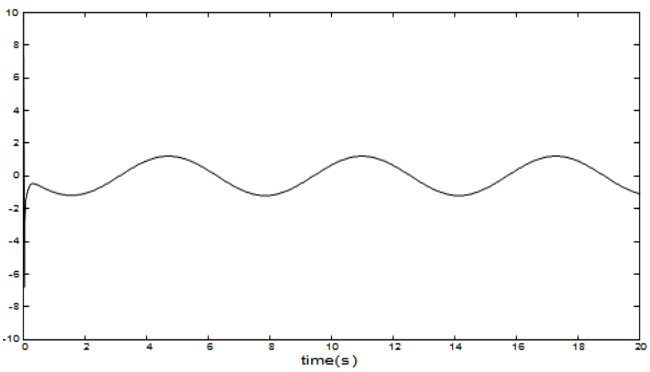
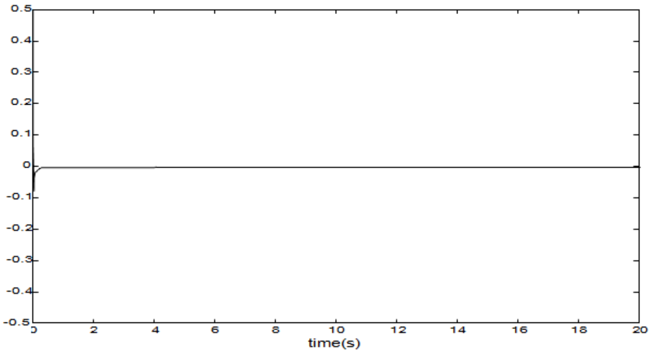


Figure 13 Evolution of the macro-variable



The control signal has switching in the regime transient in the case where the initial condition is far from the reference signal $x(0) = [-\pi/60, 0]^T$ These switches are due to the activation of the supervisory command u_s, this command is not enabled (null) in the case of $x(0) = [-\pi/60, 0]^T$.

With disturbance:

Figure 14 System response in position

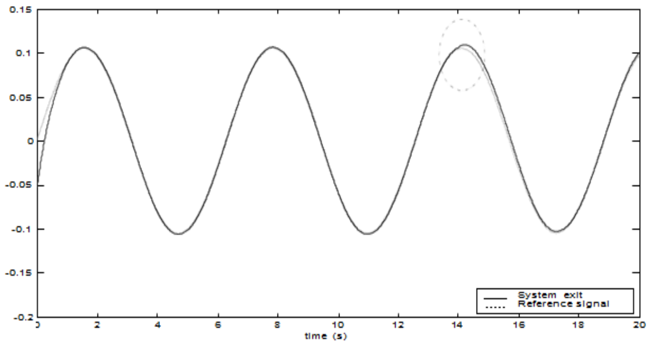
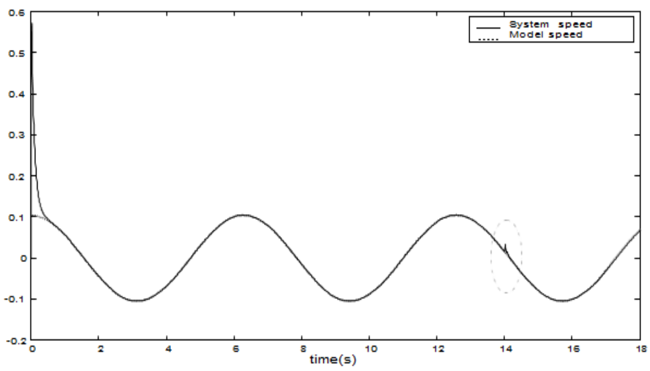


Figure 15 System speed response



Figures 14 and 15 shows that despite the presence of external disturbances, the output of the system keeps a good tracking of the reference signal.

On the other hand, Figures 4, 8, 12 and 16 show that the control signal in the case of type-2 has a smoother shape and has less significant stress variation compared to that of type-1, especially for the initial condition $x(0) = [-\pi/60, 0]^T$.

Figure 16 Control signal

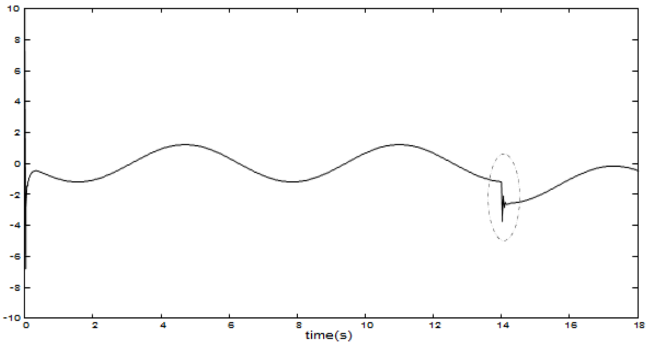
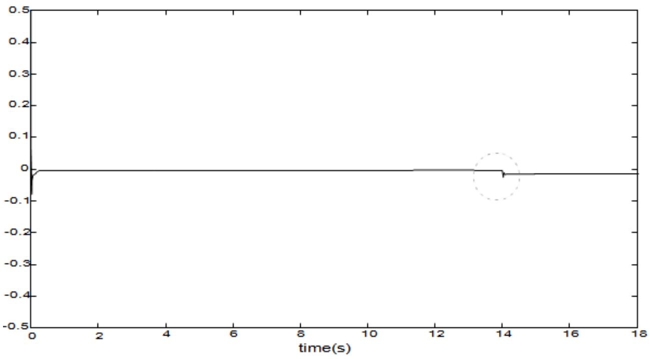


Figure 17 Evolution of the macro-variable



6 Conclusions and future work

It is clear from the simulation results concerning the control signals and those concerning the error signals that the synergetic approach has certain advantages with a much shorter response time. The main advantages of synergetic control are that it is well-suited for digital implementation, it gives constant switching frequency operation, and it gives better control of the off-manifold dynamics. The hard implementation of these approaches as well as the optimisation of the parameters specific to synergetic control constitutes our main perspective. The stability and robustness of the closed-loop system is ensured by the Lyapunov synthesis in the sense that all the signals are bounded while the controller parameters are adjusted in line via the adaptation laws developed. Finally, the proposed methods have been applied to the control of a number of nonlinear systems, the simulation results under the Matlab environment prove that the adaptive synergistic controller is fuzzy and robust enough to provide acceptable despite disturbances.

Another technique based on the application of the adaptive fuzzy synergetic terminal control for nonlinear systems will be studied in future work.

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