Robust Adaptive Fuzzy Control of Nonlinear Systems

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Abstract-In this paper, an adaptive Fuzzy Fast Terminal Synergetic Controller (FFSC) for a certain class of SISO unknown nonlinear dynamic systems is proposed, that uses the concept of terminal attractor design, adaptive fuzzy synergetic control scheme, and Lyapunov synthesis approach. In contrast to the existing adaptive fuzzy synergetic control design, where the fuzzy systems are used to approximate the unknown system functions while the synergetic control guarantees robustness and achieves the asymptotic stability of the closed-loop system, in our technique both the continuous synergetic control law and the fuzzy approximator are derived to ensure finite-time convergence. Lyapunov conditions for finite-time stability and accuracy proofs in mathematics are presented to prove that the proposed adaptive scheme can achieve finite-time stable tracking of reference input and guarantee of the bonded system signals. Simulation results illustrate the design procedures and demonstrate the performance of the proposed controller.

Keywords-nonlinear dynamic systems; synergetic control; robust control; fast time convergence; adaptive fuzzy systems

I. INTRODUCTION

Over the last few years, the development of nonlinear control techniques has been an active research topic and significant methods have been established, such as adaptive control [1], feedback control [2, 3], backstepping control [4], and Sliding Mode Control (SMC) [1, 5-8]. SMC is often adopted due to its inherent advantages of fast dynamic response, guaranteed stability, robustness against matching external disturbances, and internal parameter variations [5-7], but it suffers from the drawback of chattering phenomena which limit the SMC from being widely applied. Therefore, another concept recently introduced, similar to the SMC in the design, robustness, performance, and without discontinuous control law is the Synergetic Control (SC) theory [9-11]. The SC law, not causing chattering as in the SMC approach, depends on a designer chosen macro-variable function imposing the desired dynamics to the system. In this process, system control design needs no model linearization but rather relies on the complete nonlinear system. Its robustness and its ease in implementation have put forth this fairly new control approach. The SC has been successfully applied to nonlinear systems [12, 13], in the design of power system stabilizers [14, 15], and in many other electronic devices [10, 11]. In most of these applications, the SC law was designed based on the analytical description of the system dynamics, which is not available or is difficult to formulate. Fuzzy systems [16, 17] have been presented to overcome the abovementioned problems in which the universal approximation theorem is used to prove that fuzzy systems can approximate any unknown dynamic system. The adaptive fuzzy SC concept has been proposed to address the control issue of unknown nonlinear dynamics systems [18-20]. The SC guarantees robustness and stability of the closed-loop system while the fuzzy systems are used in an adaptive scheme to approximate the nonlinear system functions. However, in this application, the SC law was designed based on asymptotic stability analysis and the system trajectories evolve to a specified attractor reaching the equilibrium in an infinite time.

To address the issues of globally asymptotic stabilization, a Terminal SC (TSC) scheme based on the concept of terminal attractor [4, 21-26] has recently been developed [22]. The scheme exhibits superior properties such as fast finite-time convergence to the origin, less steady-state errors, and high-precision performance in addition to disturbance attenuation. These features, however, have been achieved including requirement of prior knowledge about the dynamics of the process to be controlled. In this paper, a fast finite time algorithm combined with adaptive fuzzy systems (FFSC) is proposed to design a robust control system. This approach, inspired from adaptive fuzzy SC [18-20] aims to reinforce robustness and tracking. Different nonlinear systems are used in a simulation study to assess the performances and the

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effectiveness of the proposed FFSC approach. The obtained results are discussed and compared with the FSC.

II. FAST TERMINAL SC OF A NONLINEAR SYSTEM

Consider the nonlinear Single Input Single Output (SISO) system, described by:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = f(x,t) + g(x,t)u(t)) \\ y(t) = x_1(t) \end{cases} \quad (1)$$

where $x(t) = [x_1(t)\ x_2(t)]$ is a vector of measurable states and $f(x,t)$ and $g(x,t)$ are nonlinear continuous functions.

The control objective $u(t)$ is to force the system output $y(t)$ to track a given bounded desired reference trajectory in finite time and without chattering, i.e. the tracking error must converge to zero, under the constraint that all the signals must be bounded and the system be stable. The SC synthesis of the system (1) begins by defining a designer chosen macro-variable given as:

$$\psi = \lambda e + \dot{e} \quad (2)$$

where $e = y - y_m$ is the tracking error and $\dot{e} = x_2 - y_m$ its time derivative, y_m is the desired trajectory, and λ is a positive constant.

A. Terminal Synergetic Control

In this paper, we propose the following desired dynamic evolution of the macro-variable, aiming to reinforce robustness and better tracking in finite-time:

$$\dot{\psi} = -\frac{k}{T}\psi^{p/q} \quad (3)$$

where $k > 0$, $T > 0$ are positive constants and p and q are positive odd constants with $0 < p/q < 1$.

Taking the integral of both sides of (3) and evaluating the resulting equation in the closed interval $\psi(0)$ to $|\psi(t_f)|$ gives the following equation [23, 24, 26]:

$$t_f = \frac{T|\psi(0)|^{1-\frac{p}{q}}}{k\left(1-\frac{p}{q}\right)} \quad (4)$$

where t_f is finite, indicating a finite-time convergence as opposed to the asymptotic infinite-time convergence to the attractor $\psi = 0$. This approach inspired from sliding mode techniques [23, 24] will be used to formulate the terminal synergetic control law:

$$u = \frac{1}{g(x,t)}\left[\ \ddot{y}_m - f(x,t) - \lambda\dot{e} - \frac{k}{T}\psi^{p/q}\right] \quad (5)$$

Under the control law (5) with the macro variable (2), the trajectory of the closed-loop nonlinear system (1) can be driven onto the attractor $\psi = 0$ in finite-time given by (4) ensuring rapid tracking. However, the TSC controller is only suitable when the error trajectory is nigh from attractor $\psi = 0$. To further improve convergence, we propose the Fuzzy Fast Terminal Synergetic Controller given in the ensuing section.

B. Fast Terminal Synergetic Control

In this section, we will develop the Fast Terminal Synergetic Controller which will be robust to matched and mismatched uncertainties and the states system of (1) can converge to the equilibrium point in fast finite-time. Therefore, the proposed desired dynamic evolution of the macro-variable is given as:

$$T\dot{\psi} + k\psi^{p/q} + \beta\psi = 0 \quad (6)$$

The dynamic (6) avoids the above-mentioned problem. It consists on a terminal attractor $\dot{\psi} = -\psi^{p/q}(k/T)$ when the error trajectory is close to $\psi = 0$ and a fast convergence $\dot{\psi} = -\psi(\beta/T)$ when the error trajectory is far from $\psi = 0$. According to (6), we find the new convergence time determined by [23,24]:

$$t_f^* = \frac{T}{\beta\left(1-\frac{p}{q}\right)}\ln\frac{\beta\psi(0)^{1-p/q} + k}{k} \quad (7)$$

The fast synergetic control law u can then be obtained by (8):

$$u = \frac{1}{g(x)}\left[-f(x) + \ddot{y}_m - \lambda\dot{e} - \frac{k}{T}\psi^{p/q} - \frac{\beta}{T}\psi\right] \quad (8)$$

Under the control law (8) with macro-variable (2), the error trajectory of the closed-loop system (1) can be driven onto the manifold $\psi = 0$ in finite time (7) ensuring rapid tracking.

C. Stability and Robustness Analysis

The stability and robustness issue of the controller are addressed here by using the Lyapunov stability theory.

Lemma 1 [24,26]: Consider the nonlinear system described in (1). Suppose there is a continuously differentiable function $V(x)$ defined in a neighborhood $D \subset \Re^n$ of the origin, and there are real numbers $\rho, \sigma > 0$ and $0 < \gamma < 1$ such that $V(x) > 0$ on D. The extended Lyapunov function can be described as:

$$\dot{V}(x) + \rho\, V(x) + \sigma V^{\gamma}(x) \leq 0 \quad (9)$$

and the settling time can be given by:

$$t_f'(x_0) \leq \frac{1}{\rho(1-\gamma)} ln\frac{\rho|x_0|^{1-\gamma} + \sigma}{\sigma} \quad (10)$$

Proof**:** let's consider the Lyapunov function candidate $V=\frac{1}{2}\psi^2$. The time derivative of this function can be written as:

$$\dot{V}=\left[\lambda\dot{e}+f(x,t)+g(x,t)u-\ddot{y}_m\right]\psi \quad (11)$$

By substituting (8) into (11), we obtain:

$$\dot{V}\le -\frac{k}{T}\psi^{\left(\frac{p}{q}+1\right)}-\frac{\beta}{T}\psi^2 \quad (12)$$

Using $\psi=(2V)^{\frac{1}{2}}$, (12) can be rewritten as:

$$\dot{V}+\frac{2\beta}{T}V+\frac{2^{\left(\frac{p+q}{2q}\right)}k}{T}V^{\left(\frac{p+q}{2q}\right)}\le 0 \quad (13)$$

We define the constants: $\rho=\frac{2\beta}{T}$, $\sigma=\frac{2^{\left(\frac{p+q}{2q}\right)}k}{T}$ and $\gamma=(1+p/q)/2$, such that $0<(1+p/q)/2<1$. In (13), the stability of the closed-loop system is guaranteed and the error trajectory can be driven onto the manifold $\psi=0$ in the finite-time t_f' given in (10). These performances with the control law given by (8), are easily designed if the dynamics of the system are known. However, nonlinear system parameters are not well known and imprecise, so it is difficult to implement the control law (8). Therefore, an adaptive fuzzy finite time synergetic controller using a fuzzy logic system is proposed to circumvent these problems.

III. Fuzzy Fast Terminal Synergetic Control of a Nonlinear Unknown System

In a practical real case $f(x,t)$ and $g(x,t)$ are unknown and the external disturbance $d(t)\neq 0$, so obtaining the control law of (8) is difficult. In this case, our proposal is to replace $f(x,t)+d(t)$, and $g(x,t)$ with their approximates using fuzzy logic systems and design an online updating law to estimate the system parameters by using Lyapunov stability theory [25, 26]. Using singleton fuzzification, product inference, and center-average defuzzification, the output of the fuzzy system is obtained as:

$$y(x)=\frac{\sum_{l=1}^{M}y^l\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \quad (14)$$

where $\mu_{F_i}^l(x_i)$ is the membership function of the linguistic variable x_i and y^l is the point in R at which μ_{G^l} achieves its maximum value (assuming $\mu_{G^l}(y^l)=1$). Introducing the concept of fuzzy basis function vector $\xi(x)$, (14) can be rewritten as:

$$y(x)=\theta^T\xi(x) \quad (15)$$

where $\theta_l=\left[\theta_1...\theta_M\right]^T$ and $\xi(x)=\left[\xi^1(x)...\xi^M(x)\right]^T$ are the fuzzy basis functions defined as:

$$\xi_l(x)=\frac{\prod_{i=1}^{n}\mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \quad (16)$$

It should be noted that the approximation error issue has been addressed in detail in [16, 17], where the theorem is used to prove that the fuzzy systems can approximate any continuous real function on a compact set to any arbitrary accuracy while fuzzy rules are derived based on experts recommendations. Therefore, the new control law is rewritten as:

$$u=\frac{1}{\hat{g}(x/\theta_g)}\left[-\hat{f}(x/\theta_f)+\ddot{y}_m-\lambda\dot{e}-\frac{k}{T}\psi^{p/q}-\frac{\beta}{T}\psi\right] \quad (17)$$

Theorem [16, 17]: Consider the control problem of the nonlinear system (1). If the control (17) is used and the parameter vectors θ_f and θ_g adjusted by the adaptive law are:

$$\dot{\theta}_f=-r_f\psi\xi_f(x) \quad (18)$$

$$\dot{\theta}_g=-r_g\psi\xi_g(x)u \quad (19)$$

then the closed loop system signals will be bounded and the tracking error will converge to zero asymptotically.

Proof: The optimal parameters of fuzzy systems are defined as:

$$\hat{\theta}_f=\arg\min_{\theta_f\in Z_f}\left[\sup_{x\in R^n}\left|\hat{f}(x/\theta_f)-(f(x)+d(t))\right|\right] \quad (20)$$

$$\hat{\theta}_g=\arg\min_{\theta_g\in Z_g}\left[\sup_{x\in R^n}\left|\hat{g}(x/\theta_g)-g(x)\right|\right] \quad (21)$$

where Z_f and Z_g are constraint sets for θ_f and θ_g respectively.

The minimum approximation error is defined as:

$$w=\left[\left(f(x)+d(t)-\hat{f}(x,\theta_f)\right)+\left(g(x)-\hat{g}(x,\theta_g)\right)u\right] \quad (22)$$

Then, we have:

$$\dot{\psi}=\lambda\dot{e}+\theta_f^T\xi_f(x)+\theta_g^T\xi_g(x)u-\ddot{y}_m \quad (23)$$

$$\begin{aligned}\dot{\psi}=&\lambda\dot{e}+\hat{\theta}_f^T\xi_f(x)+\hat{\theta}_g^T\xi_g(x)u+\tilde{\theta}_f^T\xi_f(x)\\&+\tilde{\theta}_g^T\xi_g(x)u+w-\ddot{y}_m\end{aligned} \quad (24)$$

Let:

$$\begin{cases} \tilde{\theta}_f = \theta_f - \hat{\theta}_f \\ \tilde{\theta}_g = \theta_g - \hat{\theta}_g \end{cases} \quad (25)$$

and let's consider the Lyapunov function candidate:

$$V = \frac{1}{2}\psi^2 + \frac{1}{2r_f}\tilde{\theta}_f^T\tilde{\theta}_f + \frac{1}{2r_g}\tilde{\theta}_g^T\tilde{\theta}_g \quad (26)$$

where r_f and r_g are positive constants that will be used as learning rates in the adaptation procedure. The time derivative of V is obtained as:

$$\dot{V} = \psi\dot{\psi} + \frac{1}{r_f}\tilde{\theta}_f^T\dot{\tilde{\theta}}_f + \frac{1}{r_g}\tilde{\theta}_g^T\dot{\tilde{\theta}}_g \quad (27)$$

$$\begin{aligned} \dot{V} &= \psi\left[\lambda\dot{e} + \hat{\theta}_f^T\xi_f(x) + \hat{\theta}_g^T\xi_g(x)u + w - \ddot{y}_m\right] \\ &+ \tilde{\theta}_f^T\left(\psi\xi_f(x) + \frac{1}{r_f}\dot{\tilde{\theta}}_f\right) + \tilde{\theta}_g^T\left(\psi\xi_g(x)u + \frac{1}{r_g}\dot{\tilde{\theta}}_g\right) \end{aligned} \quad (28)$$

Substituting the derivatives of θ_f and θ_g into (25), leads to:

$$\begin{aligned} \dot{V} &= \psi\left[-\frac{k}{T}\psi^{p/q} - \frac{\beta}{T}\psi + w\right] \\ &\le -\frac{k}{T}|\psi|^{(p/q+1)} - \frac{\beta}{T}|\psi|^2 + |\psi|w \end{aligned} \quad (29)$$

Based on the universal approximation theorem, the term $|\psi|w$ is very small, such that $\dot{V} \le 0$. As a result, all closed-loop system signals are bounded.

IV. SIMULATION RESULTS

In order to investigate the proposed controller, simulations of the following examples were considered.

A. Example1: First Order Nonlinear System

To illustrate the effectiveness of the proposed control algorithm, we design the FFSC controller for high-precision tracking of a nonlinear dynamic system given by (30), whose simulation results are compared with the FSC control scheme.

$$\dot{x}(t) = f(x) + u(t) + d(t) \quad (30)$$

where the nonlinear function $f(x) = \frac{1-e^{-x(t)}}{1+e^{-x(t)}}$ is assumed to be unknown. The fuzzy set is defined over the discourse interval [-3, +3]. The membership functions are chosen as:

$$\mu_{NB}(x) = \left(1+\exp\left(5(x+2)\right)\right)^{-1},\ \mu_{NM}(x) = \exp\left(-(x+1.5)^2\right),$$

$$\mu_{NS}(x) = \exp\left(-(x+0.5)^2\right),\ \mu_{PS}(x) = \exp\left(-(x-0.5)^2\right),$$

$$\mu_{PM}(x) = \exp\left(-(x-1.5)^2\right),\ \mu_{PB}(x) = \left(1+\exp\left(5(x-2)\right)\right)^{-1}$$

The simulation results with two different initial conditions are shown in Figures 1-3. In both cases, the system outputs have good tracking, in the other hand the new controller has a faster convergence rate than FSC. The disturbance $d(t) = 0.3\ randn(1.1)$ has been taken into consideration in the simulation at $0.15\text{s} \le t \le 1\text{s}$. As shown in Figure 1, the control signals for both approaches are continuous and smooth despite the external perturbations, while the convergence of the signal of the proposed control to the equilibrium is faster. It can be seen from Figure 1 that the macro-variable signal using FFSC reaches zero in a fast finite-time.

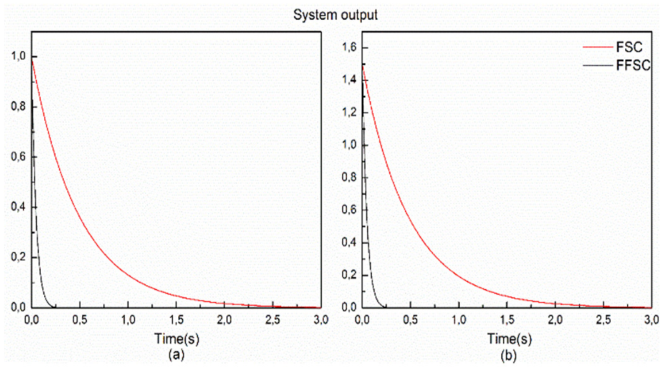

Fig. 1. The output trajectories with initial condition: (a) $x(0) = 1$, (b) $x(0) = 1.5$.

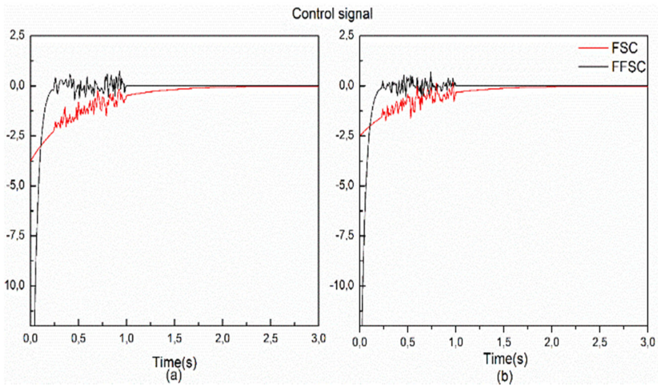

Fig. 2. Control signals with initial condition: (a) $x(0) = 1$, (b) $x(0) = 1.5$.

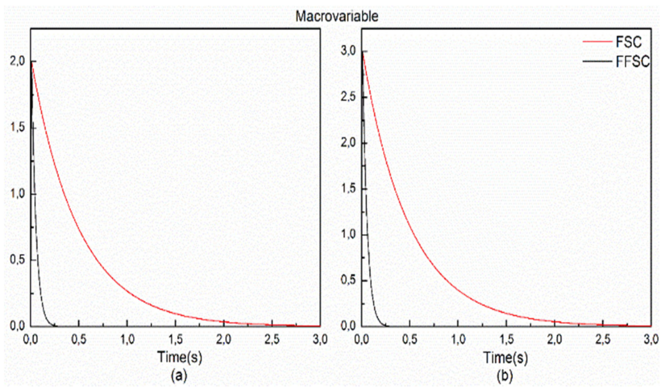

Fig. 3. Macro-variable evolution signals with initial condition: (a) $x(0) = 1$, (b) $x(0) = 1.5$.

B. Example2: Duffing Forced-Oscillation System

The proposed approach will be furthermore used to control the Duffing forced-oscillation system given by (31).

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -0.1x_2 - x_1^3 + 12\cos(t) + u(t) + d(t) \end{cases} \quad (31)$$

The control objective is to force the perturbed system to track a desired trajectory $y_m = \sin(t)$ and remove totally the effect of external disturbances. The disturbance is chosen as $d(t) = 1 + 5\sin(t)$. The membership functions for system states x_i, $i = 1,2$ are chosen as in Example 1 and the 36 fuzzy rules are used to approximate the nonlinear function of the system $f(x)$. The controller parameters are chosen as: $k = 0.1$, $\beta = 1.5$, $\lambda = 8$, $T = 0.2$, $q = 5$, $p = 3$. The simulation results are shown in Figures 4-6. Figure 4 describes the tracking performance of the proposed controllers, e.g. FFSC and FSC. The control signals and the macro-variables of two different schemes are depicted in Figures 5 and 6 respectively. Through the comparison, we can see that the proposed method can achieve better tracking performance than the FSC.

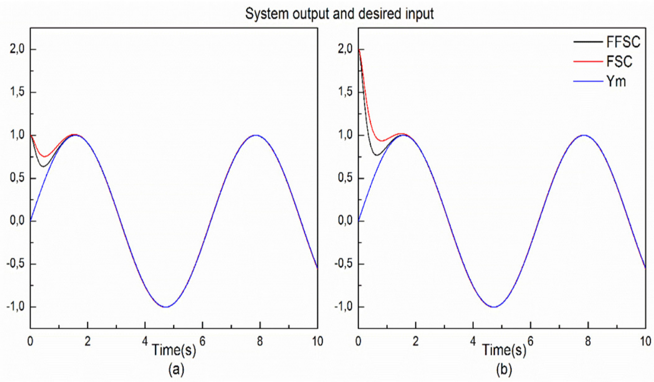

Fig. 4. The output trajectories with initial condition: (a) $x(0) = [1,0]^T$ and (b) $x(0) = [2,0]^T$.

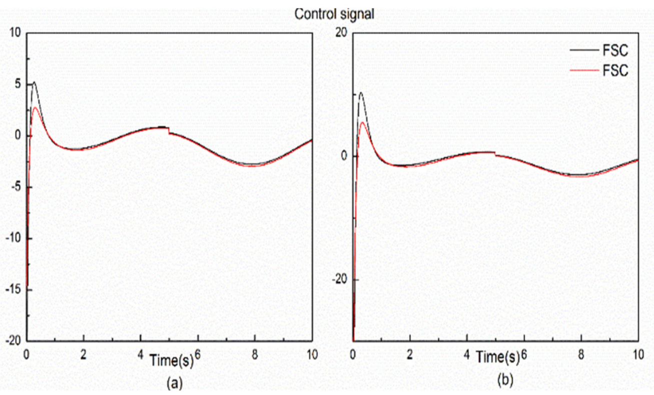

Fig. 5. Control signals with initial condition: (a) $x(0) = [1,0]^T$ and (b) $x(0) = [2,0]^T$.

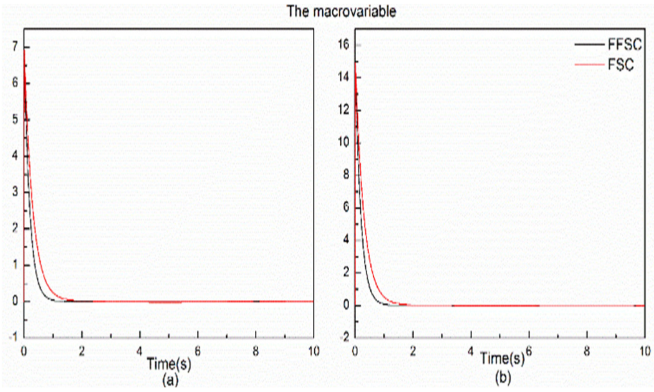

Fig. 6. Macro-variable evolution signals with initial condition: (a) $x(0) = [1,0]^T$ and (b) $x(0) = [2,0]^T$.

C. Example3: Inverted Pendulum System

In this example, the simulation has been carried out for an inverted pendulum system described by (32):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)u + d(t) \\ y(t) = x_1 \end{cases} \quad (32)$$

The state-space variables are the position x_1 and the velocity x_2. $u(t)$ and $y(t)$ are respectively the input and the output of the system. $f(x)$ and $g(x)$ are nonlinear continuous functions, such that:

$$f(x) = \frac{g\sin(x_1) - \dfrac{(m)l\,x_2^2\cos(x_1)\sin(x_1)}{(m_c + m)}}{l\left(\dfrac{4}{3} - \dfrac{(m)\cos^2(x_1)}{(m_c + m)}\right)} \quad (33)$$

$$g(x) = \frac{\dfrac{\cos(x_1)}{(m_c + m)}}{l\left(\dfrac{4}{3} - \dfrac{(m)\cos^2(x_1)}{(m_c + m)}\right)} \quad (34)$$

where $m_c = 1\text{kg}$, $m = 0.1\text{kg}$, $l = 0.5\text{m}$, and $g = 9.8\text{m/s}^2$. In order to approximate the functions $f(x)$ and $g(x)$, we consider the following membership functions:

$$\mu_{F_i^1}(x_i) = \exp\left[-\left((x_i + \pi/6)/\pi/24\right)^2\right] \quad (35)$$

$$\mu_{F_i^2}(x_i) = \exp\left[-\left((x_i + \pi/12)/\pi/24\right)^2\right] \quad (36)$$

$$\mu_{F_i^3}(x_i) = \exp\left[-\left(x_i/\pi/24\right)^2\right] \quad (37)$$

$$\mu_{F_i^4}(x_i) = \exp\left[-\left((x_i - \pi/12)/\pi/24\right)^2\right] \quad (38)$$

$$\mu_{F_i^5}(x_i) = \exp\left[-\left(\left(x_i - \pi/6\right)/\pi/24\right)^2\right] \quad (39)$$

The reference signal is given by:

$$y_m = \frac{\pi}{10}\left(\sin(t) + 0.3\sin(3t)\right) \quad (40)$$

and the controller parameters are chosen as: $k = 2.25$, $\beta = 5.5$, $\lambda = 2$, $T = 0.8$, $q = 13$, $p = 13$.

In the numerical simulation, we chose the disturbances and uncertainties as: $d(t) = 0.3randn(1.1)$ and $\Delta m_c = \pm 0.1\text{kg}$, $\Delta m = \pm 0.01\text{kg}$, at $t = 5\text{s}$. The reference tracking capability of the proposed FFSC controller is investigated and the results are compared with those given by the FSC controller for the same initial conditions.

The system responses are given in Figures 7-9. From these curves, the superior performance of faster and high-precision tracking of the proposed FFSC is clearly visible. Unlike the conventional FSC control, the FFSC holds its robustness and stability in the presence of uncertainties and external disturbances, and can drive system states to a desired trajectory signal in a fast finite-time.

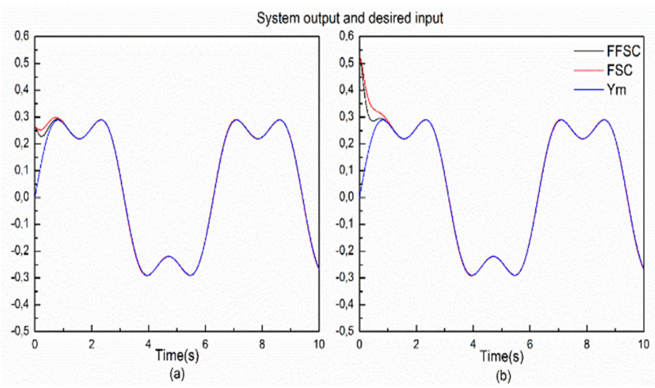

Fig. 7. The output trajectories with initial condition: (a) $x(0) = [\pi/12, 0]$ and (b) $x(0) = [\pi/6, 0]$.

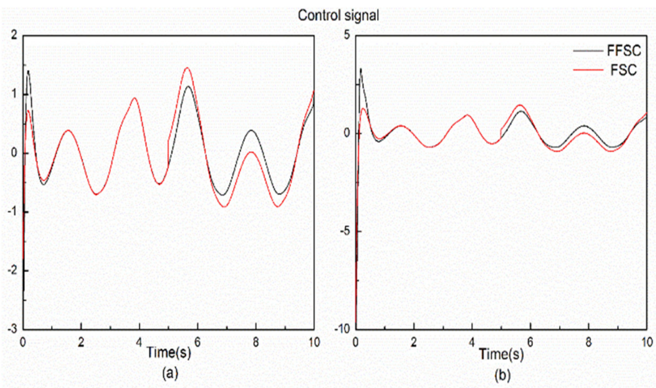

Fig. 8. Control signals with initial condition: (a) $x(0) = [\pi/12, 0]$ and (b) $x(0) = [\pi/6, 0]$.

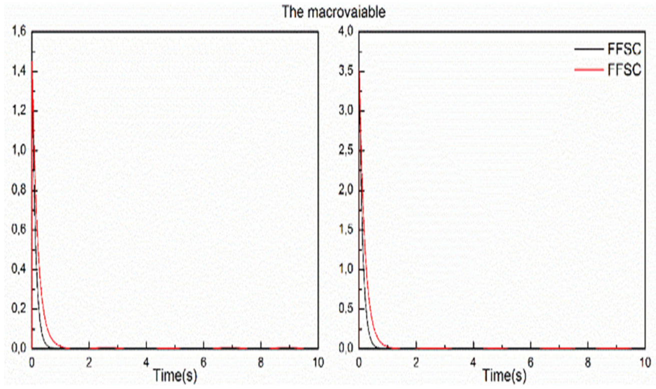

Fig. 9. Macro-variable evolution signals: (a) with initial condition $x(0) = [\pi/12, 0]$ and (b) with initial condition $x(0) = [\pi/6, 0]$.

V. Conclusion

A robust fuzzy fast finite-time synergetic control for the trajectory tracking of a class of nonlinear unknown systems has been proposed in this paper. The proposed FFSC can be used to design not only the continuous control law with fast and finite-time convergence to the equilibrium, but also the approximation of unknown dynamics of a nonlinear system with the use of fuzzy systems. Based on the Lyapunov stability theorem, it is rigorously proved that the stability of the closed-loop system, in the presence of external disturbances, is ensured and the tracking performance is achieved in finite-time.

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