Adaptive Finite-Time Control of Master-Slave Manipulators with Time-Varying Delay

Asma Ounissi and Neila Mezghani Ben Romdhane

December 25, 2020

Adaptive finite-time control of master-slave manipulators with time-varying delay

Asma Ounissi
Laboratory of sciences and technique of automatic control and computing (Lab-STA)
Nationnal school of engineering of sfax
Sfax, Tunisia
Asmaounissi1995@gmail.com

Neila Mezghani Ben Romdhane
Laboratory of sciences and technique of automatic control and computing (Lab-STA)
Nationnal school of engineering of sfax
Sfax, Tunisia
neilamezghani@yahoo.fr

***Abstract*— The work presented in this paper focuses on the finite-time control of the master-slave manipulators with time-varying delay. First, a nonsingular fast terminal sliding mode control (NFTSMC) is used for this system based on the knowledge of the upper bound of the uncertainties and disturbances. Despite of the presence of the uncertainties, disturbances, load variation and time-varying delay, the controller is robust and present a finite-time convergence. Second, an adaptive nonsingular fast terminal sliding mode control (ANFTSMC) is applied to master-slave manipulators to avoid the knowledge of the upper bound of the uncertainties and disturbances. This controller presents good performance compared to the first one. The two controllers are evaluated in simulation.**

Keywords—master-slave robot, non-singular fast terminal sliding mode control, adaptive control, uncertainties and disturbances, time-varying delay, robust control.

I. Introduction

Remote operation consists of an operator, a master side, a communication channel and a slave side that acts on an environment [1]. This system (master-slave robot) is a non-linear system with variable parameters and subject to external perturbations [2].

It is then necessary to build a robust and efficient control system with respect to the presence of uncertainties, external perturbations and communication delays.

In [10], the control method is based on the modeling of the teleoperation system in the state space, considering all the possible interaction in this system. The proposed controller is robust to the uncertainties, disturbances and time delay in the communication channel. In [9], the developed controllers take the advantage of the NFTSM theory to ensure fast convergence rate, singularity avoidance, and robustness against uncertainties and external disturbances. In [17], adaptive control achieves system robustness in the presence of uncertainties, perturbations and delays. In [18] [19], a sliding mode control is proposed to achieve the trajectory tracking performance based on exponential approach law and considering the variable payloads and model uncertainties.

Much research have used NFTSMC and its adaptive version that are applied on the robotic manipulators. However, there are no works of this type for the master-slave manipulators. In this paper, The NFTSM technique has some superior properties such as fast finite time convergence, high robustness and complete singularity avoidance. Therefore, the NFTSMC is applied to the teleoperation system in presence of the uncertainties, disturbances, load variation and time-varying delay. The controller needs the knowledge of the upper bound of the uncertainties and disturbances. In practice, it is difficult to determine this bound. Then, an adaptive nonsingular fast terminal sliding mode control (ANFTSMC) is used to improve the performances of the NFTSMC and avoid the knowledge of the upper bound of the uncertainties and disturbances.

This work is organized as follows: In section 2, the system model is presented the non-singular fast terminal sliding mode control is described in section 3. In section 4, the adaptive version of the non-singular fast terminal sliding mode is exposed. Finally, some concluding remarks are exposed in section 5.

II. System Model

The dynamics of the master-slave teleoperation can be defined as follows [14] [15] [16]:

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = u_i + P_i(t) \tag{1}$$

where $i \in \{m,s\}$. $q_i, \dot{q}_i, \ddot{q}_i \in \mathrm{R}^n$ are the position, velocity and acceleration signals for master and slave manipulators respectively. $M_i(q_i) \in \mathrm{R}^{n\times n}$ is the inertia matrices. $C_i(q_i,\dot{q}_i) \in \mathrm{R}^{n\times n}$ is coriolis/centrifugal force matrices. $G_i(q_i) \in R^n$ is the gravitational force matrices. $P_i(t) \in \mathrm{R}^n$ is the external disturbance and modeling errors. n is the degree of freedom of manipulators. u_i is the control input torques of the teleoperations manipulators [6].

Assuming that the system described in (1) has known parts $M_{i0}(q_i), C_{i0}(q_i,\dot{q}_i)$ $G_{i0}(q_i)$ and unknown parts $\Delta M_i(q_i)$, $\Delta C_i(q_i,\dot{q}_i)$ and $\Delta G_i(q_i)$, then

$$M_i(q_i) = M_{i0}(q_i) + \Delta M_i(q_i) \tag{2}$$

$$C_i(q_i,\dot{q}_i) = C_{i0}(q_i,\dot{q}_i) + \Delta C_i(q_i,\dot{q}_i) \tag{3}$$

$$G_i(q_i) = G_{i0}(q_i) + \Delta G_i(q_i) \tag{4}$$

From (2)-(4), (1) can be described in the following equation;

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = u_i + F_i(q_i,\dot{q}_i,\ddot{q}_i)$$

Where

$$F_i(q_i,\dot{q}_i,\ddot{q}_i) = -\Delta M_i(q_i)\ddot{q}_i - \Delta C_i(q_i,\dot{q}_i)\dot{q}_i - \Delta G_i(q_i) + P_i(t)$$

Assuming that [33]

$$F_i(q_i,\dot{q}_i,\ddot{q}_i) = C_{i0} + C_{i1} \mid q_i \parallel + C_{i2} \parallel \dot{q}_i \parallel^2$$

The master-slave robot is a non-linear system with variable parameters, subject to external disturbances and communication delays at the slave. The problem is to design a robust and efficient control system with respect to the presence of uncertainties, external perturbations and communication delays.

III. Non-Singular Fast Terminal Sliding Mode Control

A. Control design

The robot can be described by the following error system:

$$\begin{cases} \dot{e}_{i1} = e_{i2} \\ \dot{e}_{i2} = \ddot{q}_{id} - M_{i0}^{-1}\left(q_i\right)(-C_{i0}(q_i,\dot{q}_i)\dot{q}_i \qquad i \in \{m,s\} \\ \quad - G_{i0}\left(q_i\right) + u_i + F_i(q_i,\dot{q}_i,\ddot{q}_i)) \end{cases} \quad (5)$$

Where $e_{i1} = q_{id} - q_i$ and $e_{i2} = \dot{q}_{id} - \dot{q}_i$

$q_{md} = q_d$ for the master

$q_{sd} = q_{md}(t-T)$ for the slave.

To apply the non-singular fast terminal sliding mode control to the master-slave manipulator, the first step is to choose the following sliding surface [4][5][8][7][9]:

$$s_i = e_{i1} + K_{i1}\left|e_{i1}\right|^{\beta_i} sign\left(e_{i1}\right) + K_{i2}\left|e_{i2}\right|^{\alpha_i} sign\left(e_{i2}\right) \quad (6)$$

The control is determined using the equivalent control method with putting $\dot{s} = 0$ [12],

Then

$$\dot{e}_{i1} + \beta_i K_{i1}\ diag\ (\left|e_{i1}\right|^{\beta_i - 1})\dot{e}_{i1} + \alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})\dot{e}_{i2} = 0$$

Using (5), proposing that $F_i(q_i,\dot{q}_i,\ddot{q}_i) = 0$, we obtain:

$$\dot{e}_{i1} + \beta_i K_{i1}\ diag\ (\left|e_{i1}\right|^{\beta_i - 1})\dot{e}_{i1} + \alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})$$
$$(\ddot{q}_{id} - M_{i0}^{-1}\left(q_i\right)(-C_{i0}(q_i,\dot{q}_i)\dot{q}_i - G_{i0}\left(q_i\right) + u_{ieq}) = 0$$

Then, the equivalent control is

$$u_{ieq} = \frac{M_{i0}}{\alpha_i K_{i2}} diag(\left|\dot{e}_{i1}\right|^{2-\alpha_i}) sign(\dot{e}_{i1})$$
$$(1 + \beta_i k_{i1} diag(\left|e_{i1}\right|^{\beta_i - 1})) + M_{i0}\left(q_i\right)\ddot{q}_{id} \quad (7)$$
$$+ C_{i0}\left(q_i,\dot{q}_i\right)\dot{q}_i + G_{i0}\left(q_i\right)$$

The control is the sum of equivalent control u_{ieq} and the discontinuous control u_{id}.

$$u_i = u_{ieq} + u_{id} \quad (8)$$

Where

$$u_{id}\ (t) = M_i\ (K_i * s_i + (C_{i0} + C_{i1} \parallel q_i \parallel$$
$$+ C_{i2} \parallel \dot{q}_i \parallel^2) sign\left(s_i\right)) \quad (9)$$

B. Stabilty Analysis

To verify the stability of the control, the following Lyapunov function is considered

$$\dot{V} = s_i^T \dot{s}_i \quad (10)$$

$$\dot{V} = s_i^T (\dot{e}_{i1} + \beta_i K_i\ diag\ (\left|e_{i1}\right|^{\beta_i - 1})\dot{e}_{i1}$$
$$+ \alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})\dot{e}_{i2}) \quad (11)$$

Remplacing the control (8) in the expression of the derivative lyapunov, we have:

$$\dot{V} = s_i^T (\dot{e}_{i1} + \beta_i K_{i1}\ diag\ (\left|e_{i1}\right|^{\beta_i - 1})\dot{e}_{i1} + \alpha_i K_{i2}$$
$$diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})\ (\ddot{q}_{id} - M_{i0}^{-1}(q_i)(\quad (12)$$
$$-C_{i0}(q_i,\dot{q}_i)\dot{q}_i - G_{i0}(q_i) + u_i + F_i(q_i,\dot{q}_i,\ddot{q}_i))))$$

Using equation (9), the derivative of V is

$$\dot{V} = -\ \alpha_i K_{i2}\ diag(\left|\dot{e}_{i1}\right|^{\alpha_i - 1})$$
$$(s_i^T\ M_{i0}^{-1} u_{id} - s_i^T\ F_i(q_i,\dot{q}_i,\ddot{q}_i)) \quad (13)$$

As a result

$$\dot{V} = -\alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})(s_i^T K s_i + s_i^T (C_{i0}$$
$$+ C_{i1} \parallel q_i \parallel + C_{i2} \parallel \dot{q}_i \parallel^2) sign\left(s_i\right) - s_i^T\ F_i(q_i,\dot{q}_i,\ddot{q}_i)) \quad (14)$$

$$\alpha_i K_{i2} diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})(-s_i^T K_i\ s_i - s_i^T (C_{i0} + C_{i1} \parallel q_i \parallel$$
$$+ C_{i2} \parallel \dot{q}_i \parallel^2) sign\left(s_i\right) + s_i^T\ F_i(q_i,\dot{q}_i,\ddot{q}_i))$$
$$\le \alpha_i K_{i2} diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})(-s_i^T K_i\ s_i + (-\ |\ s_i\ |\ (C_{i0} + C_{i1}$$
$$\parallel q_i \parallel + C_{i2} \parallel \dot{q}_i \parallel^2) sign\left(s_i\right) + |s_i\ | \parallel F_i(q_i,\dot{q}_i,\ddot{q}_i) \parallel |))$$
$$\le -\ \alpha_i K_{i2} diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1}) - s_i^T K_i\ s_i \quad \le 0$$

Then, the system is asymptotically stable.

IV. Adaptative Non-Singular Fast Terminal Sliding Mode Control

In practice, the upper bound of the system uncertainty is often unknown in advance and hence the components of the vector uncertainty $F_i(q_i,\dot{q}_i,\ddot{q}_i)$ are difficult to find. Then an adaptive tuning low is used to estimate C_{i0}, C_{i1} and C_{i2}. An adaptive non-singular fast terminal sliding mode control (ANFTSMC) has been studied to improve system output in the presence of parametric uncertainties, external disturbances and communication delay.

The same sliding surface (6) and equivalent control (7) are used.

The discontinuous control is [20]

$$u_{id}(t)=M_{i0}\ (K_i * s_i + (a_i+\hat{C}_{i0} + \hat{C}_{i1}\ \| q_i \| + \hat{C}_{i2}\ \| \dot{q} \|^2) sign(s_i)) \tag{16}$$

Where a_i is a positive constant.

To study the stability of this control, we consider the following Lyapunov function:

$$V = V_1 + V_2 \tag{17}$$

$$V_1 = \frac{1}{2} s_i^{\ 2} \tag{18}$$

$$V_2 = \alpha K_2 \sum_{i=0}^{2} \frac{1}{2\gamma_i} \tilde{C}_{ij}^{\ 2} \tag{19}$$

Where γ_i are positive constants.

$$\tilde{C}_{ij} = \hat{C}_{ij} - C_{ij} \tag{20}$$

Where $\hat{C}_i$ is the estimated value of C_i and $\tilde{C}_i$ is the estimation error.

The derivative of (18) is

$$\begin{aligned}\dot{V}_1 &= s_i^{\ T} \dot{s}_i = s_i^{\ T} (\dot{e}_{i1} + \beta_i K_{i1}\ diag\ (\left|e_{i1}\right|^{\beta_i - 1}) \\ &\quad \dot{e}_{i1} + \alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1}) \dot{e}_{i2}) \\ &= s_i^{\ T} (\dot{e}_{i1} + \beta_i K_{i1}\ diag\ (\left|e_{i1}\right|^{\beta_i - 1}) \dot{e}_{i1} \\ &\quad + \alpha_i K_{i2}\ diag\ (\left|\dot{e}_{i1}\right|^{\alpha_i - 1})\ (\ddot{q}_{id} - M_{i0}^{-1}(q_i) \\ &\quad (-C_{i0}(q_i,\dot{q}_i)\dot{q}_i - G_{i0}(q_i) + u_i + F_i(q_i,\dot{q}_i,\ddot{q}_i))))\end{aligned}$$

For the system to be stable, it is necessary that $\dot{V}_1 < 0$ then the discontinuous control be as the following:

$$u_{id}(t) = M_{i0}\ (K_i s_i + (a_i + \hat{C}_{i0} + \hat{C}_{i0}\ \| q_i \| + \hat{C}_{i2}\ \| \dot{q}_i \|^2) sign(s_i)) \tag{21}$$

$$\dot{V}_1 = \alpha_i K_{i2}\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right) [-s_i^{\ T} K_i s_i - s_i^{\ T} (a_i + \hat{C}_{i0} + \hat{C}_{i1}\ \| q_i \| + \hat{C}_{i2}\ \| \dot{q}_i \|) sign(s_i) + s_i^{\ T} F_i(q_i,\dot{q}_i,\ddot{q}_i)] \tag{22}$$

The derivative of (19) is

$$\dot{V}_2 = \alpha_i K_{i2} \sum_{i=0}^{2} \frac{1}{\gamma_i} = (\hat{C}_{ij} - C_{ij}) \dot{\hat{C}}_{ij} \tag{23}$$

Finally, the equations (22) and the control (7) (8) (16) in the equation (21) we obtain

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \tag{24}$$

$$\begin{aligned}\dot{V} &= \alpha_i K_{i2}\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right)(-s_i^{\ T} K_i s_i - s_i^{\ T} (a_i + \hat{C}_{i0} \\ &\quad + \hat{C}_{i1}\ \| q_i \| + \hat{C}_{i2}\ \| \dot{q}_i \|) sign(s_i)) + s_i^{\ T} F_i(q_i,\dot{q}_i,\ddot{q}_i)) \\ &\quad + \alpha_i K_{i2} \sum_{j=0}^{2} \frac{1}{\gamma_{ij}} (\hat{C}_{ij} - C_{ij}) \dot{\hat{C}}_{ij}\end{aligned} \tag{25}$$

So that to have $\dot{V} < 0$ you need [11] [13] [20]

$$\begin{aligned}\dot{\hat{C}}_{i0} &= \gamma_{i0} s_i^T\ diag\left(\left|\dot{e}_i\right|^{\alpha_i - 1}\right) sign(s_i) \\ \dot{\hat{C}}_{i1} &= \gamma_{i1} s_i^T\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right) sign(s_i) \| q_i \| \\ \dot{\hat{C}}_{i2} &= \gamma_{i2} s_i^T\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right) sign(s_i) \| q_i \|^2\end{aligned} \tag{26}$$

$$\begin{aligned}\dot{V} &= \alpha_i K_{i2}\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right)(-s_i^{\ T} K_i s_i - s_i^{\ T} (a_i + C_{i0} \\ &\quad + C_{i1}\ \| q_i \| + C_{i2}\ \| q_i \|^2) sign(s_i)) + s_i^{\ T} F_i(q_i,\dot{q}_i,\ddot{q}_i))\end{aligned}$$

Replace (25) in (24), we obtain [20]

$$\begin{aligned}\dot{V} &= \alpha_i K_{i2}\ diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right)(-s_i^{\ T} K_i s_i - s_i^{\ T} (a_i + \hat{C}_{i0} \\ &\quad + \hat{C}_{i1}\ \| q_i \| + \hat{C}_{i2}\ \| q_i \|^2) sign(s_i)) + s_i^{\ T} F_i(q_i,\dot{q}_i,\ddot{q}_i)) \\ &\quad + \alpha_i K_{i2}((\hat{C}_{i0} - C_{i0}) s_i^T diag\ |\ \dot{e}_{i1}\ |^{\alpha_i - 1}\ sign(s_i) \\ &\quad + (\hat{C}_{i1} - C_{i1}) s_i^T diag\ |\ \dot{e}_{i1}\ |^{\alpha_i - 1}\ sign(s_i) \| q_i \| \\ &\quad + (\hat{C}_{i2} - C_{i2}) s_i^T diag\ |\ \dot{e}_{i1}\ |^{\alpha_i - 1}\ sign(s_i) \| q_i \|^2)\end{aligned}$$

After simplification, we get

$$\begin{aligned}\dot{V} &= -\alpha_i K_{i2} s_i^T diag\left(\left|\dot{e}_{i1}\right|^{\alpha_i - 1}\right)(s_i^{\ T} K_i s_i - s_i^{\ T} (a_i + C_{i0} \\ &\quad + C_{i1}\ \| q_i \| + C_{i2}\ \| q_i \|^2) sign(s_i)) + s_i^{\ T} F_i(q_i,\dot{q}_i,\ddot{q}_i))\end{aligned} \tag{27}$$

$$\dot{V} \le 0 \forall\ \ |\ \dot{e}_i\ | \ne 0$$

V. Simulation Result

In order to evaluate the effectiveness of the proposed controller, it has been applied on two degree-of-freedom teleoperations systems. The dynamic description of the master-slave manipulator is given as in the following [6].

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = u_i + P_i(t)$$

$$M_i(q_i) = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

$$C_i\left(q_i,\dot{q}_i\right)=\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}$$

$$G_i\left(q_i\right)=\begin{pmatrix} G_1 \\ G_2 \end{pmatrix}$$

With

$$M_{11}=m_{i2}l_{i2}^2+l_{i2}^2\left(m_{i1}+m_{i2}\right)+2l_{i1}l_{i2}m_{i2}cos\left(q_{i2}\right)$$
$$M_{12}=M_{12}=m_{i2}l_{i2}^2+l_{i1}l_{i2}m_{i2}cos\left(q_{i2}\right)$$
$$M_{22}=m_{i2}l_{i2}^2$$

$$C_{11}=-2l_{i1}l_{i2}m_{i2}\sin\left(q_{i2}\right)\dot{q}_{i2}$$
$$C_{12}=-l_{i1}l_{i2}m_{i2}\sin\left(q_{i2}\right)\dot{q}_{i2}$$
$$C_{21}=l_{i1}l_{i2}m_{i2}\sin\left(q_2\right)\dot{q}_{i1}$$
$$C_{22}=0$$

$$G_1=g_il_{i2}m_{i2}\cos\left(q_{i2}+q_{i1}\right)+l_{i1}\left(m_{i1}+m_{i2}\right)\cos\left(q_{i1}\right)$$

$$G_2=g_il_{i2}m_{i2}cos\left(q_{i2}+q_{i1}\right)$$

The parameters of the system are $m_{m2}=m_{s2}=0.5Kg\pm10\%$, $m_{m1}=m_{s1}=4Kg\pm10\%$, $l_{m1}=l_{s1}=l_{m2}=l_{s2}=0.5m$ and $g_i=9.81NKg^{-1}$, initials state are $\begin{bmatrix} q_{m1} \\ q_{m2} \end{bmatrix}=\begin{bmatrix} 0.6 \\ 0.1 \end{bmatrix}$ and $\begin{bmatrix} q_{s1} \\ q_{s2} \end{bmatrix}=\begin{bmatrix} -4 \\ -5 \end{bmatrix}$, the desired joints are $\begin{bmatrix} q_{m1d} \\ q_{m2d} \end{bmatrix}=\begin{bmatrix} cos(t) \\ cos(t) \end{bmatrix}$ and $\begin{bmatrix} q_{s1d} \\ q_{s2d} \end{bmatrix}=\begin{bmatrix} q_{m1} \\ q_{m2} \end{bmatrix}$, $P_m=P_s=\sin(t)$ and the delay is: $T=1-0.5e^{-0.5t}$.

A. Non-Singular Fast Terminal Sliding Mode Control

The Simulink block of the non-singular fast terminal sliding mode control NFTSMC of the master-slave manipulator with time varying delay and sudden load variation is considered.

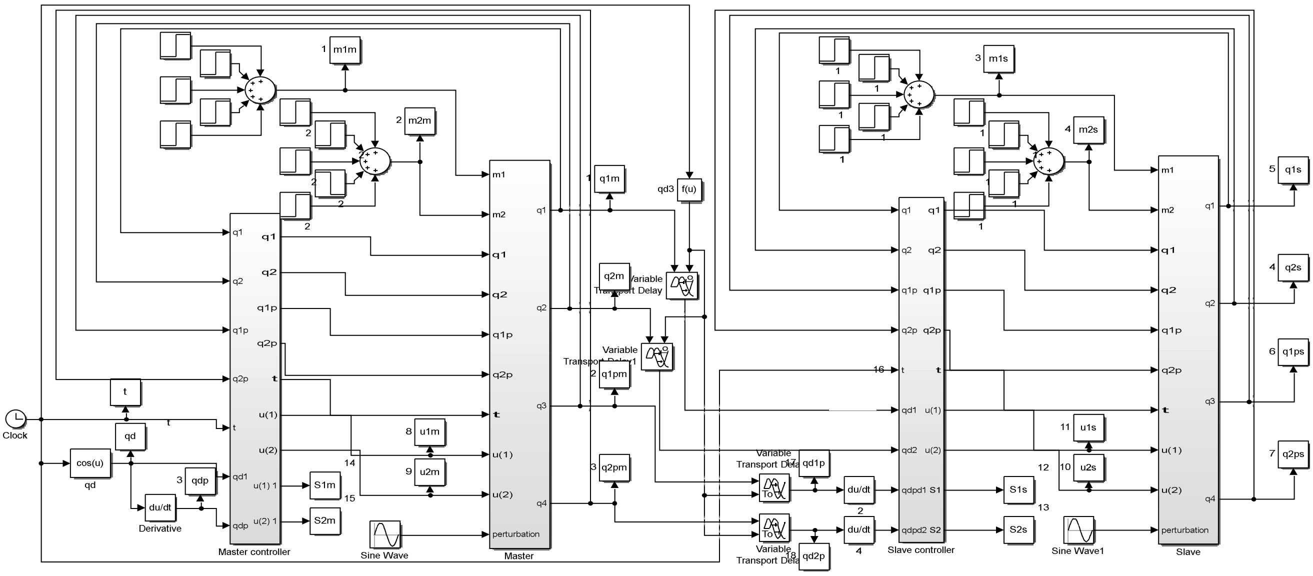

Fig. 1. Simulink block of the NFTSMC of the master-slave manipulator with time varying delay and sudden load variation

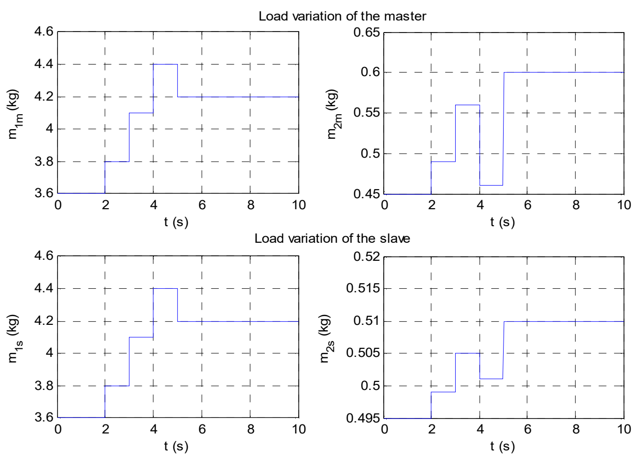

Fig. 2. Mass uncertainties

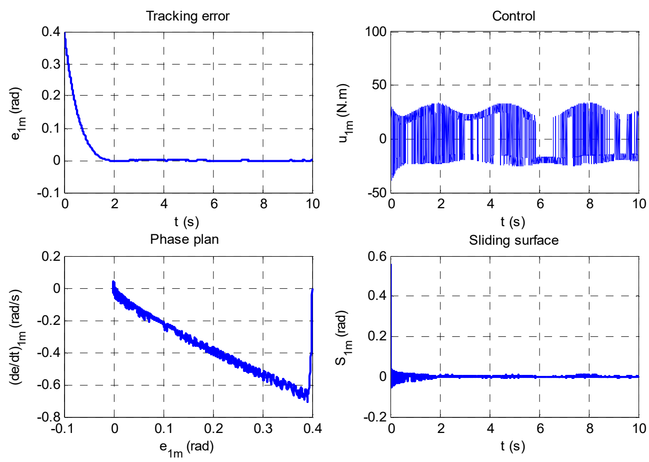

Fig. 3. Tracking of the first joint of the master by the NFTSMC

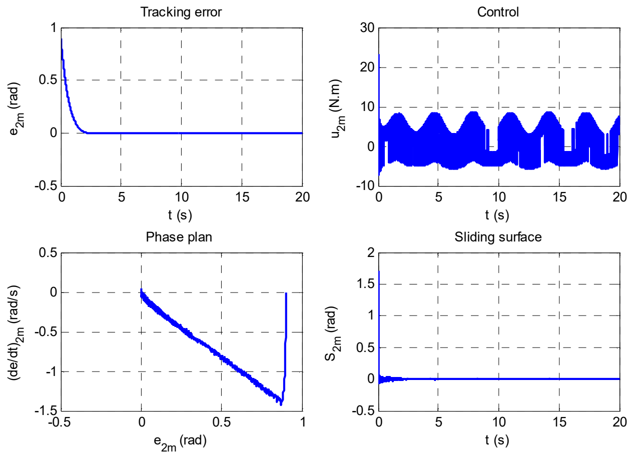

Fig. 4. Tracking of the second joint of the master by the NFTSMC

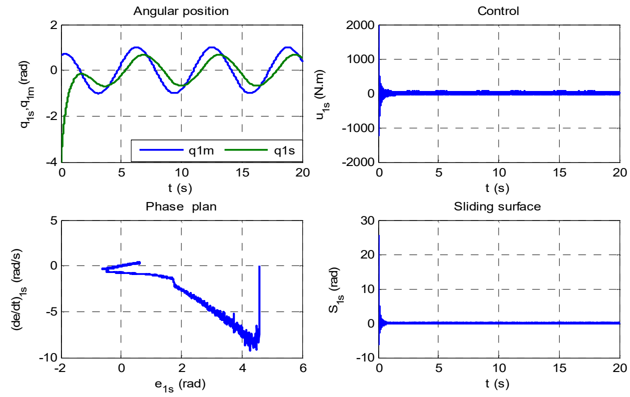

Fig. 5. Tracking of the first joint of the slave by the NFTSMC

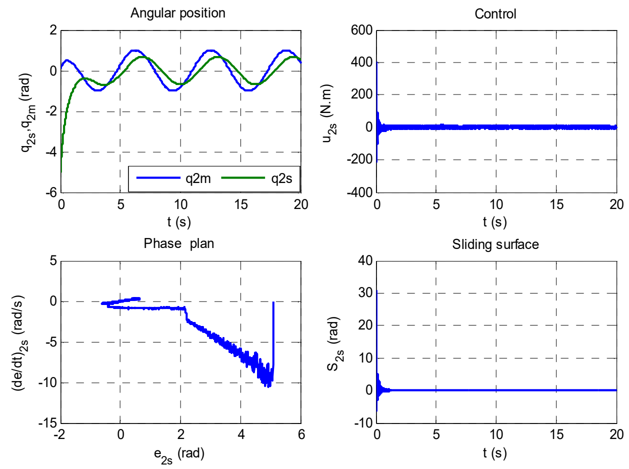

Fig. 6. Tracking of the second joint of the slave by the NFTSMC

For $\alpha_m = \alpha_s = 1.5, \beta_m = \beta_s = 2, K_{m1} = K_{s1} = 1, K_{m2} = K_{s2} = 1, C_{m0} = C_{s0} = 9.5, C_{m1} = C_{s1} = 2.2, C_{m2} = C_{s2} = 2.8$, a variable delay, equal to $T = 1 - 0.5e^{-0.5t}$ is added, and the robot carries a load equal to $100\,g$ at time $t = 5s$. The simulation results Figs 3-6 show that the error tends towards zero and the sliding surface remains around zero. The trajectory in the phase plan slides in the vicinity of the sliding surface until it reaches the origin. The angular position figures present that the slave follows the master but with a shift due to the variable delay, then this method gives unsatisfactory results for the presence of varying delays. In the control figures, a high frequency switching is noted, that is the problem of chattering.

In spite of the presence of disturbances, uncertainties and variable delays, the system always remains stable so that it converges rapidly towards a sliding surface.

B. Adaptive Non-Singular Fast Terminal Sliding Mode Control

The same Simulink block of NFTSMC of the master-slave manipulator with the time varying delay and sudden load variation is considered.

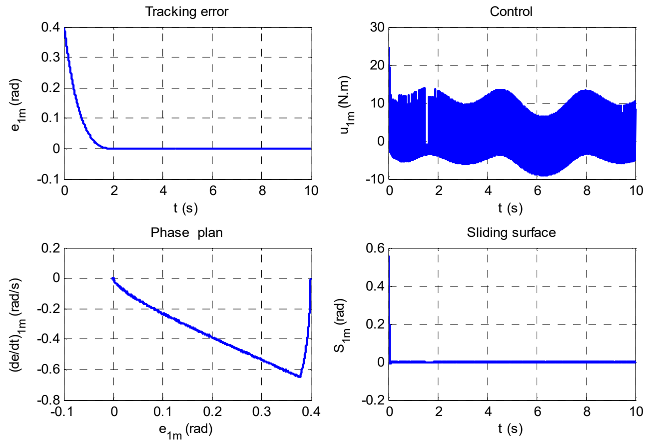

Fig. 7.Tracking of the first joint of the master by the ANFTSMC

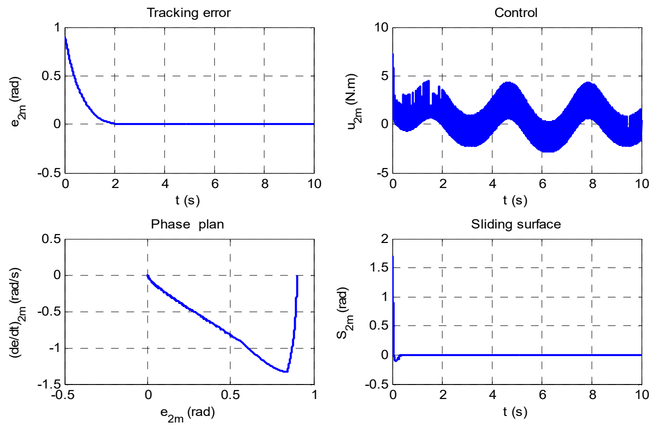

Fig. 8. Tracking of the second joint of the master by the ANFTSMC

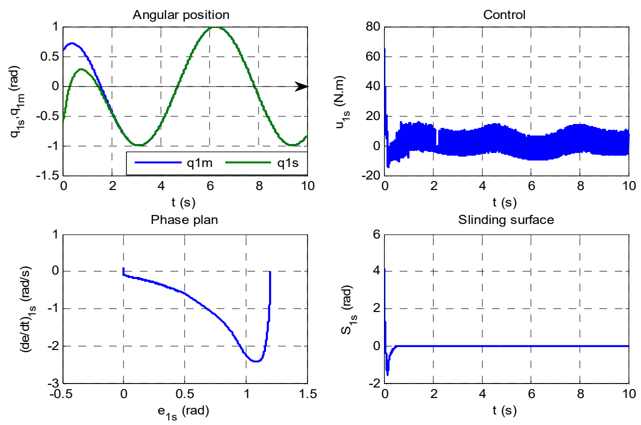

Fig. 9. Tracking of the first joint of the slave by the ANFTSMC

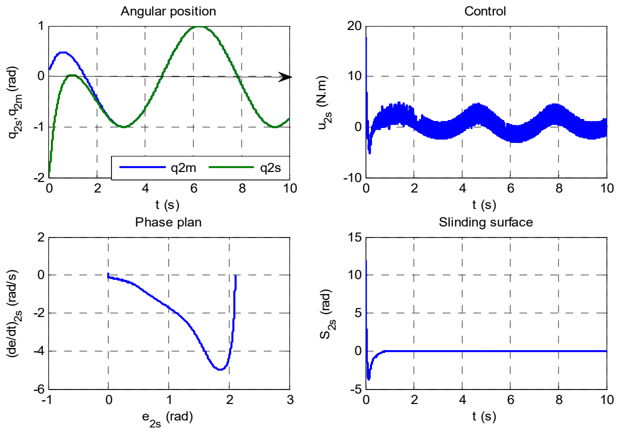

Fig. 10. Tracking of the second joint of the slave by the ANFTSMC

For the same values of the system parameters, a variable delay equal to $T=1-0.5e^{-0.5t}$, and that the robot carries a load equal to 100 g at the instant t=5s .

The Figs 7-10 of the angular position illustrate that the slave follows the master with a very reduced response time despite the presence of delay (the presence of delay does not affect the output). The rate of the tracking error shows the convergence of the system towards zero in the order of one second.

It can be seen that the sliding surface remains around zero, and the trajectory in the phase plan slides in the vicinity of the sliding surface until it reaches the origin.

This control eliminates the influence of the varying time delay on the slave.

VI. Conlusion

In this paper, two controllers are guaranteeing a finite-time convergence and robustness to the uncertainties, disturbances, load variation and time-varying delay for the master-slave manipulators are used. The non-singular fast terminal sliding mode control is used in the case of the knowledge of the upper bound of the uncertainties and disturbances. In order to improve this controller, an adaptive nonsingular fast terminal sliding mode control is tested to the master-slave manipulator by avoiding the knowledge of the upper bound of the uncertainties and disturbances. Simulation results showed its better performance. In our future work, we will concentrate with the adaptive second-order control on bilateral teleoperations.

References

[1] M. Mohamed, “Commande à distance d'un bras manipulateur en présence d'un retard de temps constant,” Master, Faculty of Engineering Sciences, Batna, Algeria, 2012.

[2] B. Zhang, “Sur la commande à retour d’effort à travers des réseaux non dédiés : stabilisation et performance sous retards asymétriques et variable,” Thesis, Centrale Lille School, France, 2012.

[3] Deghboudj Imen, “Commande des systemes non lineaires par mode glissant d’ordre superieur, ” Master, Faculty of Technology Sciences, Algeria, 2013.

[4] B. Walid, “Commande par modes glissants du suivi detrajectoires pour un robot mobile,” Master, Faculty of Technology, Batna, Algeria, 2015.

[5] M. Benyamina. H. fadila, “Contrôle latérale d’un véhicule Avec la technique hybride mode Glissant/backstepping,” Master, Tahar Moulay of Saida, Algeria, 2016.

[6] M. Zou, Y. Pan, S. Forbrigger and U. Ahmad, “Adaptive robust control for bilateral teleoperated robotic manipulators with arbitrary time delays,” 2nd Internationnal Conference On Robotics and Artificial Intelligence (ICRAI), vol 9, pp. 105-111, 2016.

[7] F. Chen, R. Hou, B. Jiang and G.Tao, “Study on fast terminal sliding mode control for a helicopter via quantum information technique and nonlinear fault observer,” International Journal of Innovative Computing Information and Control, vol. 9, no. 8, pp. 3437-3447, 2013.

[8] W. Khalil, E. Dombre, “Modeling, Identification & Control of Robots,” Hermes Penton Science, London, 2004.

[9] M. Boukattaya, N. Mezghani, T. Damak, “Adaptive nonsingular fast terminal sliding-mode control for the tracking problem of uncertain dynamical systems,” ISA Transactions, vol. 77, pp. 1-19, 2018.

[10] J. M. Azorin, O. Reinoso, R. Aracil and M. Ferre, “Control of teleoperators with communication time delay through state convergence,” Journal of Robotic Systems, vol. 21, no. 4, pp. 167–182, 2004.

[11] M. Labbadi and M. Cherkaoui, “Robust adaptive nonsingular fast terminal sliding-mode tracking control for an uncertain quadrotor UAV subjected to disturbances,” ISA Transactions, vol. 99, pp. 290-304, 2020.

[12] M.-D. Tranand H.-J. Kang, “Non-singular Terminal Sliding Mode Control of Uncertain Second-Order Nonlinear Systems,” Mathematical Problems in Engineering, pp. 1–8, 2015.

[13] L. Wan, G. ChenM. Sheng Y. Zhang and Z. Zhang, “Adaptive chattering-free terminal sliding-mode control for full-order nonlinear system with unknown disturbances and model uncertainties,” International Journal of Advanced Robotic Systems, vol. 17, no. 3, pp. 1-11, 2020.

[14] S. Chen, W. Liu and H. Huang, “Nonsingular Fast Terminal Sliding Mode Tracking Control for a Class of Uncertain Nonlinear Systems,” Journal of Control Science and Engineering, vol. 12, pp. 1–17, 2019.

[15] L. Yang and J. Yang, “Nonsingular fast terminal sliding-mode control for nonlinear dynamical systems,” International Journal of Robust and Nonlinear Control, vol. 21, no. 16, pp. 1865–1879, 2010.

[16] Z. Zhou, G. Tang, H. Huang, L. Han and R. Xu, “Adaptive nonsingular fast terminal sliding mode control for underwater manipulator robotics with asymmetric saturation actuators,” Control Theory and Technology, vol. 18, pp. 81-91, 2020.

[17] Y. Xia, S. S. Ge, G. P. Liu, P. Shi and D. Rees, “Robust adaptive sliding mode control for uncertain time-delay systems,” International Journal of Adaptive Control and Signal Processing, vol. 23, no. 9, pp. 863–881, 2009.

[18] G. Xu, Z. Xiao, Y. Guo and X. Xiang, “Trajectory tracking for underwater manipulator using sliding mode control,” IEEE International Conference on Robotics and Biomimetics (ROBIO), Sanya, pp. 2127 – 2132, 2007.

[19] D. S. Kwon, J. H. Ryu, P. M. Lee and S-W. Hong, “Design of a teleoperation controller for an underwater manipulator,” IEEE International Conference on Robotics and Automation, San Francisco, CA, USA, vol. 4, pp. 3114 – 3119, 2000.

[20] A. Ounissi, “Commande de manipulateurs maitre esclave, ” Master, Higher Institute of Industrial Systems (ISSIG) , Gabes, 2019.