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Model Free Terminal Sliding Mode with Gravity Compensation: Application to an Exoskeleton-Upper Limb System

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Abstract**—**This paper deals with a robust model free terminal sliding mode with gravity compensation approach used to control an exoskeleton-upper limb system. The considered system is a 2-DoF robot in interaction with an upper limb used for rehabilitation. The aim of this paper is to control the flexion/extension movement of the shoulder and the elbow joints in presence of matched disturbances. In the first part, we present the exoskeleton-upper limb system modeling. Then, we controlled the considered system by the model free terminal sliding mode with gravity compensation. A stability study is realized. To prove the controller performance, a robustness analysis was needed. Simulation results are provided to confirm the robustness of the gravity compensation combined with to the Model free terminal sliding mode in presence of uncertainties.

Keywords**—**Exoskeleton-upper limb system, gravity compensation, model free terminal sliding mode, robustness analysis, Monte Carlo, H∞ methods.

I. Introduction

ABILITY to move upper limbs is very necessary to ensure the basic activities of human everyday life. The upper limb is characterized by its mobility and its ability to handle and grasp objects [1]. The inability to operate the upper limb, due to an accident, makes human life more complex. So, it is necessary to find a solution to help these people and improve their comforts.

Robotics naturally emerged in the field of upper/lower limb rehabilitation in the 1960s [4], [5], as an evolution of existing mechanical devices and in response to the need to improve the quality of treatments.

Rehabilitation robots are systems in physical interaction with humans used to encourage the subject's participation in the movement, even when assisted. They act as an amplifier that augment, reinforce or restore human performances. This interaction must then be fine enough to meet the requirements of human motor control and allow the establishment of controls dedicated to rehabilitation.

In literature, upper limb exoskeletons are utilized in different fields of applications. In the medical field, exoskeletons are used to perform basic activities of daily life for hemiplegics or for rehabilitation [6]. For military application, they are employed to increase the physical endurance of soldiers and to help them to lift heavy loads. Also, exoskeletons are used for assistance to dependent persons. A motorized exoskeleton can allow monitoring and robotic assistance of sports training (achieving the perfect gesture with adequate strength, speed and precision) [7].

With the use of exoskeletons distributed along the limb, it becomes possible to control not only the movements of the hand but one can also control the articular movements of the subject's arm [21]. This method makes it possible to approach the problem of neuromotor rehabilitation differently. Joint rehabilitation also allows better recovery in people with hemiparetics.

The objective of controlling an exoskeleton is to follow the movements of a healthy user. To achieve this goal, it is necessary to apply appropriate, performing and robust controllers. The dynamic of the exoskeleton-upper limb system is characterized by its complexity, so researchers developed many control laws like the sliding mode [10], the mixed force and position controller [11], universal approximations of fuzzy logic or neural networks approaches [12], adaptive control [24], etc.

Uncertainties and disturbances can influence the performance and the effectiveness of the applied controllers when tracking the desired trajectories. So, we are interested in the robustness study of the exoskeleton-upper limb system. The robustness test is important in order to identify the operating factors that are not necessarily studied during the development phase of the method, but which could have an influence on the results, and consequently to anticipate the problems that may occur at the moment of control application.

The contribution of this paper is to develop a robust Model Free Terminal Sliding mode algorithm with gravity compensation to control a 2-DoF exoskeleton-upper limb system. As a robustness study in presence of matched uncertainties, Monte Carlo and H∞ methods were used.

The paper is organized as follows: The modelling of the exoskeleton-upper limb system is presented in Section II. Section III deals with the control and the stability study. The robustness analysis of the considered system using Monte Carlo and H∞ methods is given in Section IV. In Section V, simulation and results are given. Finally, Section VI is kept for the conclusion and future work.

II. The Exoskeleton-Upper Limb System Modeling

To control the flexion/extension movement of the shoulder and the elbow joints of the exoskeleton-upper limb system, we start by modeling the considered system.

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The system is an exoskeleton in interaction with a human upper limb [13], [14] presented by Fig. 1.

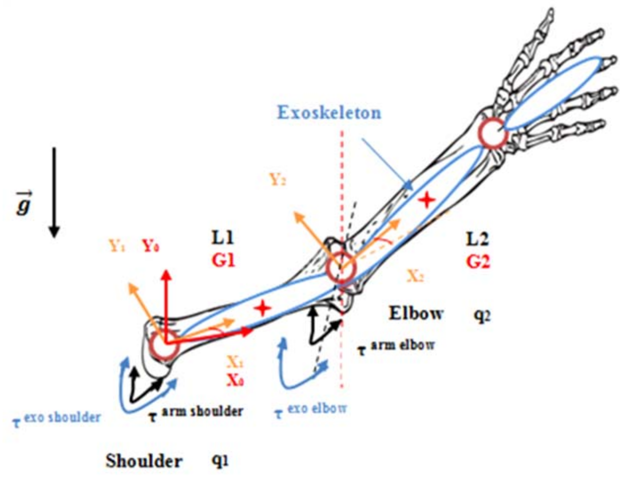

Fig. 1 General configuration of a 2 DoF exoskeleton-upper limb system

The kinematic model of the considered system is given by Fig. 2.

Referring to Euler Lagrange equation, the dynamic model of the system having two degrees of freedom (DoF) in the presence of friction is given by:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + f_v\,\dot{q} + k_i \mathrm{sign}(\dot{q}_i) = \tau^{exo} + \tau^{arm} + \tau^{ext} \quad (1)$$

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q}) = \tau^{exo} + \tau^{arm} + \tau^{ext} \quad (2)$$

with $q \in \mathbb{R}^2$ present the joint positions vector; $\dot{q} \in \mathbb{R}^2$ is the joint velocities vector; $\ddot{q} \in \mathbb{R}^2$ is the joint accelerations vector; $M(q) \in \mathbb{R}^{2x2}$ is the inertia matrix; $C(q,\dot{q}) \in \mathbb{R}^{2x2}$ is the Coriolis matrix; $G(q) \in \mathbb{R}^2$ is the gravitational vector; $F(q,\dot{q}) \in \mathbb{R}^2$ is the force generated by friction; $\tau^{exo} \in \mathbb{R}^2$ is the control vector applied by exoskeleton; $\tau^{arm} \in \mathbb{R}^2$ is the torque applied by the human; $\tau^{ext} \in \mathbb{R}^2$ is the external torque; $F(q,\dot{q}) = f_v\,\dot{q} + k_i\,\mathrm{sign}(\dot{q}_i)$; $k_i\,\mathrm{sign}(\dot{q}_i)$ is the resistive torque due to dry friction; $f_v\,\dot{q}$ corresponds to the resistive torque due to the viscous friction of the human exoskeleton-arm system;

$$M(q) = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix};\ C(q,\dot{q}) = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix};\ G(q) = \begin{pmatrix} G_1 \\ G_2 \end{pmatrix}$$

where $\alpha = q_1 + q_2$; $l_1 = O_1G_1$; $l_2 = O_2G_2$; m_i are the exoskeleton joint mass; m_{ii} are the arm joint mass; l_{ii} are the arm joint length; I_{ii} are the arm joint inertia; $M_{11} = m_1 l_1^2 + m_{11} l_{11}^2 + I_1 + I_{11} + (m_2 + m_{22})L_2^2$; $M_{12} = 2 L_2 (m_2 l_2 + m_{22} l_{22}) \cos(\alpha - q_1)$; $M_{21} = 2 L_2 (m_2 l_2 + m_{22} l_{22}) \cos(\alpha - q_1)$; $M_{22} = I_2 + I_{22} + m_{22} l_{22}^2 + m_2 l_2^2$; $C_{11} = 0$; $C_{12} = -\dot{\alpha}(m_2 l_2 + m_{22} l_{22}) L_2 \sin(\alpha - q_1)$; $C_{21} = 0$; $C_{22} = \dot{q}_1 (m_2 l_2 + m_{22} l_{22}) L_2 \sin(\alpha - q_1)$; $G_1 = [m_1 l_1 + m_{11} l_{11} + (m_2 + m_{22}) L_2]\, g \cos q_1$; $G_2 = [m_2 l_2 + m_{22} l_{22}]\, g \cos \alpha$.

We developed then a control law used in order to get good desired trajectories tracking by the exoskeleton-upper limb system.

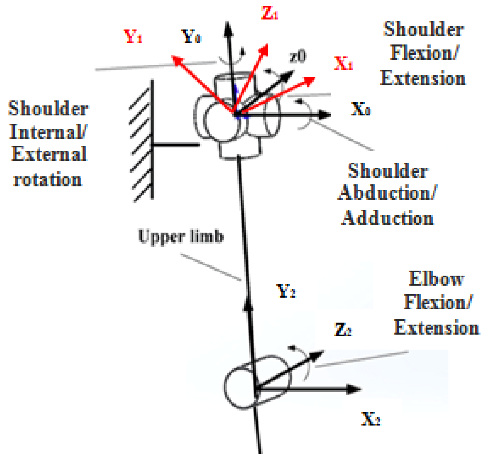

Fig. 2 Kinematic model of 2 DoF exoskeleton-upper limb system

The operating principle of the exoskeleton-upper limb system is described in Fig. 3. In the next sections, we suppose that $\tau^{ext} = 0$ and we consider $U = \tau^{exo} - \tau^{arm}$.

III. The Exoskeleton-Upper Limb System Control

In this section, we developed a control law in order to track the desired trajectories. So, a Model Free Terminal Sliding Mode with gravity compensation was proposed.

A. Gravity Compensation

Gravity compensation applied to robotics could avoid some problems. It acts as a corrector that only compensates for all of the forces that create the overshoot and the asymmetric transient behavior of the system. Also, the control with gravity compensation is able to reach the control objective in position globally for n DOF robots.

The use of gravity compensation is beneficial for robotic system which can be operated with relatively small actuators generating less torque [25].

In the literature, we find the use of two design approaches to obtain gravity compensation. The first approach is to use counterweights to compensate for the weight of the links. The counterweights can be mounted directly on the manipulator [26], [27], [8], [9].

The main advantage of this approach is the maintenance of the center of mass of the fixed mechanism for any given orientation of the gravity acceleration vector. This is particularly interesting when the manipulators have to operate with their base mounted in an arbitrary orientation.

The second approach is based on the storage of potential energy in elastic components such as springs. The advantage of this method is to add a smaller mass and inertia to the system. On the other hand, the resulting mechanism tends to be more complex: it can lead to mechanical interference and have a limited range of motion [27].

B. Model Free Terminal Sliding Mode Control with Gravity Compensation (MFTSMCGC)

The proposed control law consists in combining the Model Free (MF) with the Terminal Sliding Mode (TSM) using gravity compensation. The system control block diagram is shown in Fig. 4.

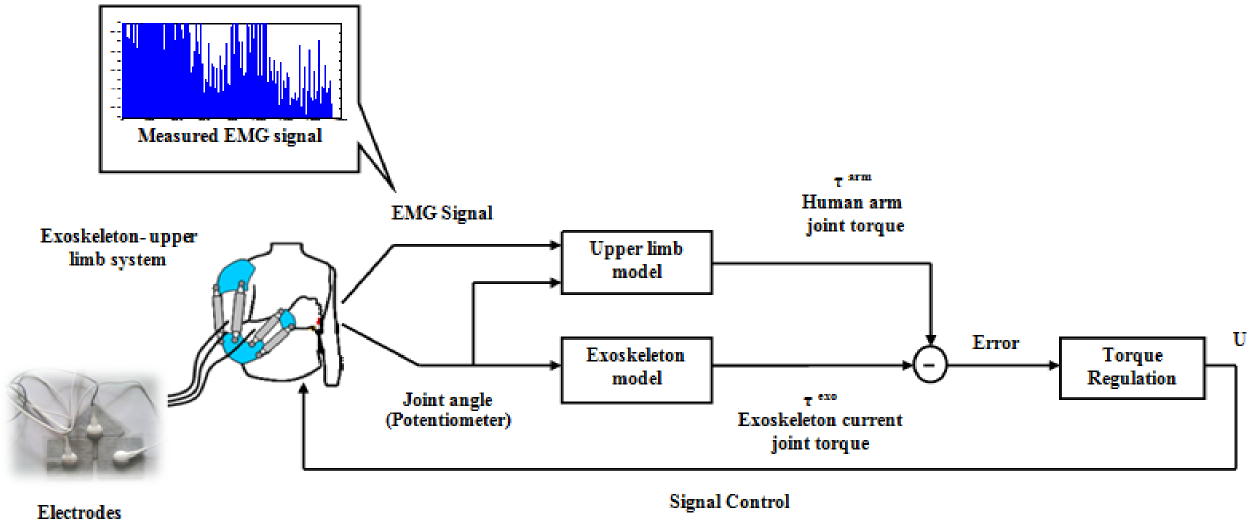

Fig. 3 The operating principle of the exoskeleton-upper limb system

The TSM has been developed by adding the non-linear fractional power element to the sliding surface to offer certain superior properties, such as the convergence in finite time of the state variables, faster and better tracking precision [28]-[30].

The MF control consists of a PID controller supplemented by compensation conditions provided by the online estimation of the system dynamics [19]-[21].

The MF controller is presented by [22], [23]:

$$\ddot{q} = F(t) + \alpha\, u_{MF}(t) \tag{3}$$

where q presents the output. F is an unknown nonlinear term including unmodeled dynamics and uncertainties. α is the input gain. u_{MF} is the corresponding input signal.

By closing the loop via the intelligent proportional-derivative controller (iPD), we get:

$$u_{MF} = -\frac{\hat{F} - \ddot{q}_d + u_c}{\alpha} \tag{4}$$

with u_c presents the feedback controller to track the desired output signal. q_d is a desired output trajectory. u_c is defined as the classic PD controller with:

$$u_c = K_D\, \dot{e} + K_p\, e \tag{5}$$

and:

$$e = q - q_d \tag{6}$$

with $e = q - q_d$ is the error of trajectory tracking. K_d and K_i are the PD's gains matrices. $\dot{q}_d$ presented the desired velocity. We get:

$$u_{MF} = -\frac{\hat{F} - \ddot{q}_d + K_D\, \dot{e} + K_p e}{\alpha} \tag{7}$$

From (3) and (4), we get:

$$\ddot{e} + u_c = F - \hat{F} \tag{8}$$

The estimation method is given as:

$$F(t) = \hat{F}(t) = F(t - \varepsilon) = \ddot{q}(t - \varepsilon) - \alpha\, u_{MF}(t - \varepsilon) \tag{9}$$

where ε is a small time delay.

According to the previous equations, we get:

$$\ddot{e} + K_D\, \dot{e} + K_p\, e = e_{est} \tag{10}$$

with: $e_{est} = F - \hat{F}$.

To remove the estimation error, the TSMC is combined with the MF control [12], and this gives the following MFTSMC:

$$U = u_{MF} + u_{TSM}$$

where u_{TSM} presents the TSM control law. u_{MF} presents the MF control law. We get:

$$U = -\frac{\hat{F} - \ddot{q}_d + K_D\, \dot{e} + K_p e}{\alpha} + u_{TSM} \tag{11}$$

We get:

$$\ddot{e} + K_D\, \dot{e} + K_p\, e = e_{est} + \alpha\, u_{TSM} \tag{12}$$

We considered the following system:

$$\begin{cases} x_1 = e \\ x_2 = \dot{e} \end{cases} \Longrightarrow \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -K_D\, \dot{e} - K_p\, e + e_{est} + \alpha\, u_{TSM} \end{cases}$$

To ensure a fast follow-up of the desired trajectory, the surface in sliding mode is defined as [18]:

$$S_t = x_1 + \frac{1}{\beta} x_2^{\,r/s} \qquad (13)$$

with: $\beta > 0$; r and s are positive odd integers satisfying the condition r > s.

We calculate $\dot{S}_t$:

$$\dot{S}_t = \dot{x}_1 + \frac{1}{\beta}\frac{r}{s} x_2^{\,(r/s)-1}\dot{x}_2 \qquad (14)$$

We get:

$$\dot{S}_t = \dot{x}_1 + \frac{1}{\beta}\frac{r}{s} x_2^{\,(r/s)-1}\left(-K_D\,\dot{e} - K_p\,e + e_{est} + \alpha\,u_{TSM}\right) \qquad (15)$$

We have:

$$u_{TSM} = u_{eq} + u_n$$

with: $u_n = -\frac{K}{\alpha}\,\mathrm{sign}(S_t)$

The function of the second term, called correction control, is to force the system's trajectories to achieve the sliding surface. u_{eq} is obtained when the condition $\dot{S}_t = 0$ is satisfied. So:

$$u_{eq} = -\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{K_D}{\alpha}\,\dot{e} + \frac{K_p}{\alpha}\,e \qquad (16)$$

We get:

$$u_{TSM} = -\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{K_D}{\alpha}\,\dot{e} + \frac{K_p}{\alpha}\,e - \frac{K}{\alpha}\,\mathrm{sign}(S_t) \qquad (17)$$

We obtain so:

$$U = -\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) \qquad (18)$$

Using gravity compensation [16], the control law is written in the following form:

$$U = -\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) + G(q_d) \qquad (19)$$

The system control block diagram is shown in Fig. 4.

To prove the stability of the considered system, we use the following Lyapunov function:

$$V = \frac{1}{2}\,\dot{q}^T M(q)\,\dot{q} + \frac{1}{2} S_t^2 \qquad (20)$$

$$\dot{V} = \dot{q}^T M(q)\,\ddot{q} + \frac{1}{2}\,\dot{q}^T \dot{M}(q)\,\dot{q} + S_t\dot{S}_t \qquad (21)$$

$$\dot{V} = \dot{q}^T M(q)\,\ddot{q} + \frac{1}{2}\,\dot{q}^T \dot{M}(q)\,\dot{q} + S_t\dot{S}_t \qquad (22)$$

Replacing $\dot{S}_t$ by its expression, we get:

$$\dot{V} = \dot{q}^T\left[-\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t) - C(q,\dot{q})\,\dot{q}\right] + \frac{1}{2}\,\dot{q}^T \dot{M}(q)\,\dot{q} + S_t\left[\frac{1}{\beta}\frac{r}{s} x_2^{\,(r/s)-1}\left(e_{est} - K\,\mathrm{sign}(S_t)\right)\right] \qquad (23)$$

$$\dot{V} = \dot{q}^T\left[-\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} - \frac{\hat{F}-\ddot{q}_d}{\alpha} - \frac{K}{\alpha}\,\mathrm{sign}(S_t)\right] + \frac{1}{2}\,\dot{q}^T\left[\dot{M}(q) - 2C(q,\dot{q})\right]\dot{q} + S_t\left[\frac{1}{\beta}\frac{r}{s} x_2^{\,(r/s)-1}\left(e_{est} - K\,\mathrm{sign}(S_t)\right)\right] \qquad (24)$$

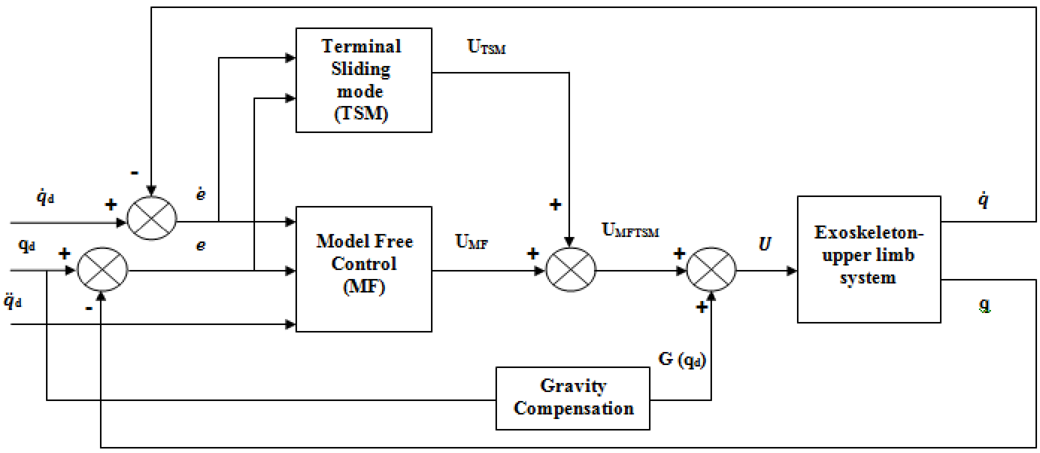

Fig. 4 The MF TSM with gravity compensation block diagram

As the inertia matrix and the Coriolis matrix are asymmetric, that is to say that they satisfy the following relation [31], [2]:

$$\dot{q}^T\left[\dot{M}(q) - 2\,C(q,\dot{q})\right]\dot{q} = 0$$

We can eliminate the term $\frac{1}{2}\,\dot{q}^T\left[\dot{M}(q) - 2\,C(q,\dot{q})\right]\dot{q}$. So we get:

$$\dot{V} = -\dot{q}^T\left[\frac{\beta s}{\alpha r}\,\dot{e}^{\,2-r/s} + \frac{\hat{F}-\ddot{q}_d}{\alpha} + \frac{K}{\alpha}\,\mathrm{sign}(S_t)\right] + \frac{1}{\beta}\frac{r}{s} x_2^{\,(r/s)-1}$$

$$(S_t\, e_{est} - S_t\, K\, \mathrm{sign}(S_t)) \quad (25)$$

$$\dot{V} < -\,|\dot{q}|^T \frac{\beta s}{\alpha r}\, \dot{e}^{\,2-r/s} \frac{K}{\alpha}\, |\dot{q}|^T - \frac{1}{\beta}\frac{r}{s}\, K\, x_2^{\,(r/s)-1}\, |S|_t \quad (26)$$

As:

- r and s are positive odd integers;
- $1 < r/s < 2$, then $x_2^{(r/s)-1} > 0$ for tt $x_2 \neq 0$ and $\dot{e}^{\,2-r/s} > 0$;
- K, β and α are positive.

So, for $x_2 \neq 0$, we have $\dot{V} < 0$.

IV. Robustness Analysis

The robustness of a system is defined as the stability of its performance in presence of disturbances. The robustness test is important in order to identify the operational factors which are not necessarily studied during the development phase of the method, but which could have an influence on the results, and therefore anticipate the problems that may arise at the time of the application of the method.

In this part, we will study the robustness of the considered system in presence of matched disturbances using Monte Carlo and H∞ methods.

A. Monte Carlo

This method is applied in different fields like finance, telecommunication, physical engineering, biology, social sciences [33], [32]. It is a powerful and very general mathematical tool which has earned it a wide range of applications. It is used to study the effects of parameters on stability properties.

The Monte Carlo method uses exhaustive and repeated simulations, where a specific value for each independent parameter of a model is drawn randomly from a given range of values, and then the output is computed. It constitutes a powerful and very general mathematical tool which has earned a wide range of applications [3].

The Monte Carlo method is done according to the following steps:

- Identifying and characterizing the uncertain parameters in the model.
- Sampling and randomly generation tests according to the identified probabilistic laws.
- The propagation of the uncertainty defined by the dataset resulting from step 2 will be done.
- The identification of the output set.
- A statistical analysis of the set results corresponding to the data set.
- Analyzing the convergence of the distribution of the model output.

B. H∞ Methods

H∞ methods are developed in order to synthesize algorithms to reach stabilization with assured performance and robustness.

H∞ techniques have the advantage over conventional control techniques in that they are easily applicable to problems involving multivariate systems with cross-coupling between channels.

This technique can be used to minimize the closed loop impact of a disturbance: depending on the formulation of the problem, the impact will be measured in terms of either stabilization or performance.

In this part, we applied a uniform random distribution to the system which will have the following form in presence of matched uncertainties [15], [17]:

$$\ddot{q} = (f(q, \dot{q}, t) + g(q)\,(u(t) + \delta_1) \quad (27)$$

where δ_1 presents matched uncertainties.

V. Simulation and Results

Simulation results are provided to prove the efficiency of gravity compensation applied to the proposed controller law.

The desired trajectories are given by:

- q_{1d}= sin (2*pi*t);
- q_{2d}= sin (2*pi*t);

The initial conditions of the real trajectories are:

- q (0) = [0; 0] ;
- $\dot{q}$ (0) = [0; 0];

Fig. 5 presents the measured and the desired trajectories of the released tests as well as the tracking trajectories errors in position and velocity. From this figure, we can clearly see the good position as well as velocity tracking of the desired trajectories in presence of matched uncertainties using the MF TSM controller with gravity compensation.

By calculating the Root-Mean-Square (RMS), the mean (Mean) and the standard deviation (Std), a robustness study is done in order to prove the controller performance when tracking the desired trajectories.

The RMS is calculated using the following expression:

$$q_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} |q\,n|^2} \quad (28)$$

The Std can be expressed by:

$$\Sigma_q = \sqrt{E[q - E[q])^2]} = \sqrt{E[q^2] - E[q]^2} \quad (29)$$

and the sample mean is defined as:

$$\bar{q} = \frac{1}{m}\sum_{i=1}^{m} q_i \quad (30)$$

TABLE I
The Results Summary of the Robustness Study: The RMS, The Error Average Value and the Standard Deviation Calculation for Each Joint q_1 and q_2 Using the MF TSM Control with Gravity Compensation When Tracking the Desired Trajectories in Positions in Presence of Matched Uncertainties

		RMS [rad] 10^{-3}	Mean [rad] 10^{-3}	Std [rad] 10^{-3}
Monte Carlo	**q_1**	0.88	0.64	0.74
	q_2	0.92	0.86	0.82
H∞ method	**q_1**	1.05	0.89	1.01
	q_2	1.11	0.97	1.07

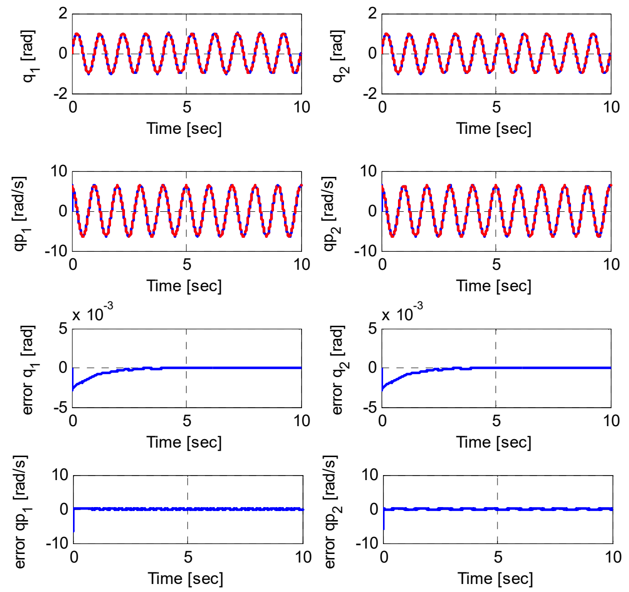

Fig. 5 Simulation results of q_1 and q_2 joints using the MF TSM with gravity compensation Control

Table I presents RMS, the error average value and the standard deviation calculation for each joint q_1 and q_2 using the MF TSM control gravity compensation when tracking the desired trajectories in positions in presence of matched uncertainties. It illustrates the robustness analysis using Monte Carlo and H∞ methods. Both of these methods approve the efficiency of the proposed controller in terms of performance and robustness.

VI. Conclusion

In this paper, the control, the stability study and the robustness analysis of an exoskeleton-upper limb system, used for rehabilitation, in presence of matched uncertainties, were presented. First, the modeling of the considered system was done. Then, a MF TSM algorithm with gravity compensation is developed. A robustness study using Monte Carlo and H∞ methods was done to analyze the performance of the exoskeleton-upper limb system in presence of matched uncertainties. Simulation results are provided to prove the performance and the robustness of the gravity compensation applied to the MF TSM when tracking the desired trajectories. As a future work, experimental results will be done when the exoskeleton is worn by the human upper limb.

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