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Non-Singular Second Order Terminal Sliding Mode Incorporating Time Delay Estimation for Uncertain Exoskeleton Robot

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ABSTRACT
Advanced robotic technology has become an important component in various medical specializations, including rehabilitation treatment such as physiotherapy. Robot aided rehabilitation is a new practical approach created to provide intensive therapy that typically required an important effort by the therapist in conventional rehabilitation. Robot aided rehabilitation is used to assist patients such as stroke victims while saving the therapist's time. This treatment also aims to help the patient in recovering from their lacking functional capability, obtaining new skills, and increasing their quality of life. In addition to the complex design of this kind of robots, the collaboration with humans who suffer from an uncontrollable upper limb makes the robot subject to many uncertain dynamics which can influence the performance of the robot. This paper presents a tracking control by proposing a new Non-Singular Terminal Second-Order Sliding Mode Control incorporating Time Delay Estimation implemented to an exoskeleton robot with dynamic uncertainties and unknown bounded disturbances. The success of the second-order sliding mode is due to its attractive features of accuracy, attenuation of chattering and fast convergence. However, its dilemma is that the unknown dynamics of the exoskeleton robot and external disturbances generated by its different wearers can be magnified by the second derivative of the switching surface, which drives to the instability of the exoskeleton system. Applying Time Delay Estimation will approximate the uncertain dynamics while overcoming the main restriction of the second-order sliding mode. The stability analysis is formulated and established based on the Lyapunov function. Experimental results with two healthy subjects validate the effectiveness of the suggested control.

Keywords: Rehabilitation Robot, Time Delay Estimation, Second-Order Sliding Mode Control, passive assistive motion.

1. Introduction

Recently rehabilitation robots have drawn significant attention from the scientific community since exoskeleton robots are able to provide similar types of rehabilitation therapy as provided by the physiotherapists, i.e. the conventional therapeutic approach [1]. The significance of the rehabilitation robots lies in their ability to provide intensive physical therapy for a long period of time [1]. The feedback data of the exoskeleton allows the physiotherapist to accurately evaluate the patient's performance [1, 2]. An important perspective is that the design of this kind of robots must be in accordance with the human anatomy. In order to provide a modern rehabilitation treatment/therapy for the patients who suffer from the dysfunction of the upper limb, we have developed an exoskeleton robot named ETS-MARSE (École de Technologie Supérieure - Motion Assistive Robotic-exoskeleton for Superior Extremity) that is compatible with the human arm configuration and is able to provide different types of rehabilitation therapy ranging from passive to active assisted arm movement therapy [3-5].

Making the exoskeleton system perform the smooth motion corresponding to the recommended therapeutic arm movements is one of the challenging tasks of these kinds of rehabilitation robots. However, the dynamics of these kinds of robots is hardly obtained accurately due to their complex design, and non-smooth nonlinear characteristics of the actuators such as backlash, hysteresis, dead zone, and saturation [6-8]. Furthermore, the collaboration between the exoskeleton and human makes the exoskeleton subject to many external disturbances. These later are caused by different conditions or musculoskeletal system variances of the wearer of the exoskeleton robot. Without doubt, these constraints degrade the performance of the exoskeleton system. It is consequently imperative for us to design a robust adaptive controller that approximates the dynamic model of the robot and minimizes the non-smooth nonlinear constraints effects meanwhile maintaining the stability of the exoskeleton robot.

Sliding Mode control is one of the robust approaches designed to control a perturbed system that is widely applied on robotic systems thanks to its attractive characteristics of robustness to the dynamics nonlinear uncertainties and external disturbances [9]. A key feature used to achieve this robustness is to limit the chattering effects with fast convergence of the system's trajectories to the equilibrium [9, 10]. For this, various conventional approaches tried to decrease the chattering and increase the convergence speed of the error by exchanging the discontinuous function by a continuous function, e.g., a saturation function, in order to provide a continuous control [9, 10]. Terminal sliding mode control (TSMC) is proposed in [11] to provide an asymptotic convergence with finite time by introducing the fraction order on the switching surface. This allows the trajectories of the system to converge to the equilibrium faster. The fast convergence feature of TSMC can deteriorate controller

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performance. Many solutions have been developed to the fast TSMC [12] and non-singular TSMC [13] to improve the accuracy performance of TSMC. Second Order Sliding Mode Controller (SOSMC) [14-16] is one of the effective strategies applied to the robotics system to reduce chattering dilemmas and provide a better performance accuracy. Additionally, several control strategies have been developed to enhance the performance of SOSMC such as twisting control and Super-Twisting control algorithms [17-19]. The principal concept of SOSMC is to permit a sliding surface and its consecutive derivative to reach the equilibrium in finite time convergence. In addition, the design of the control makes the discontinuous control always work under an integral function, which can attenuate the undesirable chattering. Nevertheless, the second-time derivative of the switching surface might engender instability of the system, a risk that the non-smooth nonlinear uncertainties function and external disturbances magnify. Recently, the Second Order Terminal Sliding Mode Control (SOTSMC) was proposed to provide an excellent control performance to deal with the chattering problem and to provide a finite time convergence [14-16]. Therefore, according to the best of our knowledge, no non-singular SOTSMC has been proposed before to solve the mentioned problems.

Motivated to deal with the above mentioned problem and based on our previous works [2, 20], we designed a new Non-Singular Second-Order Terminal Sliding mode control combined with time delay estimation [2, 21] to maneuver the exoskeleton robot. First, the control action aims to design the switching surface to ensure a fast (finite time) transient convergence both at a distance from and at a close area of the equilibrium. Secondly, to provide a good approximation of the dynamics of the uncertainties and/or non-smooth nonlinear function that can be amplified with the second derivative of the switching surface. Therefore, the features SOSMC will be improved by producing the high precision, eliminating the chattering dilemma and providing a finite-time convergence to equilibrium. The stability analysis of the exoskeleton system is formulated and proved based on the Lyapunov candidate function. The contribution of this paper can be summarized in two points:

i. Design of a Non-Singular Second-Order Terminal Sliding mode control surface so that fast (finite time) transient convergence both at a distance from and at a close reach of the equilibrium can be achieved.
ii. Design a control approach incorporating Non-Singular Second-Order Terminal Sliding mode control with a time delay estimation in order to provide a good approximation of dynamic model of the exoskeleton robot and external bounded disturbances by delay one step the inputs and the states of the system.

The remainder of the paper is organized as follows: The dynamics of the robot is presented in the next section; the control scheme is described in section 3. Experimental results and some comparisons are given in section 4 and the conclusion is presented in section 5.

2. Characterization of robot aided rehabilitation

2.1 Exoskeleton Robot Development

As shown in Fig. 1, the developed exoskeleton robot ETS-MARSE is a redundant robot. It has 7-degrees of freedom (DOFs). It was developed to provide therapeutic movements to the impaired upper limb. The exoskeleton was ergonomically designed based on the anatomy and the joint articulation of the human upper limb while considering the safety and the comfort of the patients wearing this robot. The shoulder motion support part consists of three joints, the elbow motion support part comprises one joint and the wrist motion support part consists of three joints. The ETS-MARSE can provide every variety of upper limb motions. Key characteristics of the ETS-MARSE and comparison with similar existing exoskeleton robots are summarized in [3-5].

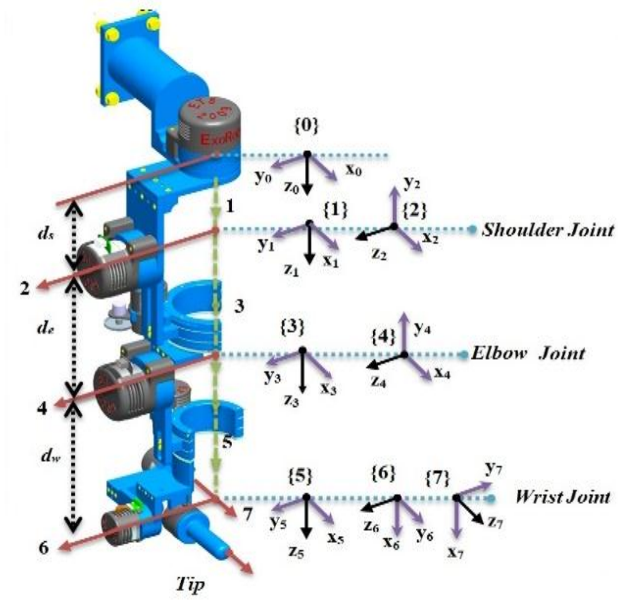

Fig. 1: Reference frames of ETS-MARSE [3-5].

The modified Denavit-Hartenberg (DH) [22] parameters of the developed ETS-MARSE (corresponding to the links-frames attachment as shown in Fig.1) are given in Table 1. These parameters are used to obtain the homogeneous transformation matrices [22].

TABLE 1 Modified Denavit-Hartenberg Parameters

Joint (i)	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	d_s	θ_1
2	$-\pi/2$	0	0	θ_2
3	$\pi/2$	0	d_e	θ_3
4	$-\pi/2$	0	0	θ_4
5	$\pi/2$	0	d_w	θ_5
6	$-\pi/2$	0	0	$\theta_6 - \pi/2$
7	$-\pi/2$	0	0	θ_7

2.2 Dynamics of ETS-MARSE Robot

The dynamics of ETS-MARSE is expressed by the well-known rigid body's dynamic equation as follows [22]:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + f_{dis} = \tau \quad (1)$$

where θ, $\dot{\theta}$, and $\ddot{\theta} \in \mathbb{R}^7$ are respectively the joints position, velocity, and acceleration vectors, $M(\theta) \in \mathbb{R}^{7\times 7}$, $C(\theta,\dot{\theta})\dot{\theta} \in \mathbb{R}^7$, and $G(\theta) \in \mathbb{R}^7$ are respectively the symmetric positive-definite inertia matrix, the Coriolis and centrifugal vector, and the gravitational vector due to the exoskeleton and the human arm. $\tau \in \mathbb{R}^7$ is the torque vector, $f_{dis} \in \mathbb{R}^7$ is the external disturbances vector caused by the human. Without loss of generality, the dynamic model (1) can be rewritten as follows:

$$\begin{cases} M(\theta) = M_0(\theta) + \Delta M(\theta) \\ C(\theta,\dot{\theta}) = C_0(\theta,\dot{\theta}) + \Delta C(\theta,\dot{\theta}) \\ G(\theta) = G_0(\theta) + \Delta G(\theta) \end{cases} \quad (2)$$

where $M_0(\theta)$, $C_0(\theta,\dot{\theta})$, and $G_0(\theta)$ are respectively the known inertia matrix, the Coriolis/centrifugal matrix, and the gravity vector. $\Delta M(\theta)$, $\Delta C(\theta,\dot{\theta})$, and $\Delta G(\theta)$ are the uncertain parts. Let us introduce a new variable such that: $\eta_1 = \theta$ and $\eta_2 = \dot{\theta}$; hence, the dynamic model expressed in Eq. 1 can be rewritten as follows:

$$\begin{aligned} \dot{\eta}_1 &= \eta_2 \\ \dot{\eta}_2 &= U(t) + f(t) + H(t) \end{aligned} \quad (3)$$

where, $U(t) = U(\eta_1)$; $H(t) = H(\eta_1,\eta_2,\dot{\eta}_2)$ and $f(t) = f(\eta_1,\eta_2)$. This notation is used to facilitate the handling of the control methodology with: $U(t) = M_0^{-1}(\theta)\tau(t)$; $H(t) = M_0^{-1}(\theta)(-f_{dis} - \Delta M(\theta)\ddot{\theta} - \Delta C(\theta,\dot{\theta})\dot{\theta} - \Delta G(\theta))$, and $f(t) = M_0^{-1}(\theta)(-C_0(\theta,\dot{\theta})\dot{\theta} - G_0(\theta))$.

Property 1: [22] The known part of inertia matrix $M_0(\theta)$ is symmetric and positive definite for all $\theta \in \mathbb{R}^n$.

Assumption 1: The function $H(t)$ and its time derivative $\frac{d}{dt}[H(t)]$ are globally Lipschitz functions.

Assumption 2: The desired trajectory is bounded.

Assumption 3: The external disturbance f_{dis} is supposed to be continuous, has finite energy, and satisfies $\|f_{dis}\| \le \varepsilon$, with an unknown positive disturbance boundary ω.

3. Control Design

The first step in the control development is to define the surface S in terms of position error. Then, select the Non-Singular Second Order Terminal Sliding surface to ensure fast convergence without a chattering problem. The proposed approach combines a Non-Singular Second Order Terminal Sliding Mode Control (N-SSOTSMC) and Time Delay Estimation TDE, applied on a second-order dynamic model of the exoskeleton robot given by Eq. 3.

The sliding set of n-th linked to the surface or equivalent surface is determined by:

$$S = \dot{S} = \cdots = S^{n-1} = 0 \quad (4)$$

Equation (4) shows an n-dimensional condition of the parameter system. In this case, it is sufficient to differentiate the sliding surface once to obtain the desired control input. We can choose the switching function such that:

$$S = \dot{e} + \Lambda e \quad (5)$$

where $e = \eta_1 - \eta_1^d \in R^7$ and $\dot{e} = \eta_2 - \eta_2^d \in R^7$ are the position and velocity errors respectively, and $\eta_1^d, \eta_2^d \in R^7$ are the desired position and desired velocity respectively, $\Lambda = \mathrm{diag}(\Lambda_{ii})$ for $i = 1, \dots, 7$ is a diagonal positive matrix. Taking the first derivative of selected surface S we obtain:

$$\begin{aligned} \dot{S} &= \ddot{e} + \Lambda\dot{e} \\ &= \dot{\eta}_2 - \dot{\eta}_2^d + \Lambda\dot{e} \\ &= U(t) + f(t) + H(t) - \dot{\eta}_2^d + \Lambda\dot{e} \end{aligned} \quad (6)$$

In this paper, we are looking forward to reduce the chattering problem using second-order sliding mode to transform the discontinuous control to continuous signal using integral action. So, the second derivative of surface S can be expressed as :

$$\begin{aligned} \ddot{S} &= \dddot{e} + \Lambda\ddot{e} \\ &= \ddot{\eta}_2 - \ddot{\eta}_2^d + \Lambda\ddot{e} \\ &= \frac{d}{dt}[U(t)] + \frac{d}{dt}[f(t)] + \frac{d}{dt}[H(t)] - \\ &\quad \ddot{\eta}_2^d + \Lambda\ddot{e} \end{aligned} \quad (7)$$

The first and second derivatives of S drive us to create a new sub-system. Let us before that define two new variables as $\mu_1 = S$, and $\mu_2 = \dot{S}$, therefore, the new state-space equation is given such that:

$$\begin{aligned} \dot{\mu}_1 &= \dot{S} \\ \dot{\mu}_2 &= \frac{d}{dt}[U(t)] + \frac{d}{dt}[f(t)] + \frac{d}{dt}[H(t)] - \\ &\quad \ddot{\eta}_2^d + \Lambda\ddot{e} \end{aligned} \quad (8)$$

As we remark in Eq.8, the time derivative of the control input $\frac{d}{dt}[U(t)]$ is the input to manage the second-order sliding mode system (8). Usually, in all types of sliding mode design, the reaching law contains a discontinuous term. In our case, to perfectly control the exoskeleton system (3), we must integrate once $\frac{d}{dt}[U(t)]$ to get the control input $U(t)$ with the desired torque $\tau = M_0(\theta)\,U(t)$. The integration permits to transform the discontinuous control action to a continuous one, which helps attenuating the undesirable chattering problem.

To complete the proposed controller procedure, let us introduce the Non-Singular Second Order Terminal

Sliding surface for the state-space equation given by (8) such that:

$$\rho = \mu_1 + \varphi\lfloor\mu_2\rceil^{\beta} \tag{9}$$

where $\varphi = \mathrm{diag}[\varphi_{ii}]$ for $i = 1, \dots, 7$ is a diagonal positive definite matrix, and $\lfloor\mu_2\rceil^{\beta} = [\mu_{21}{}^{\beta}, \dots, \mu_{27}{}^{\beta}]^T$ and $1 < \beta < 2$ [13]. Since the Non-Singular Second Order Terminal Sliding surface is designed, the application of the proposed controller with TDE can be easily employed. Taking the time derivative of the Eq.(9) and using Eq.8 , we find:

$$\begin{aligned}\dot{\rho} &= \dot{\mu}_1 + \beta\varphi\mu_2{}^{\beta-1} \\ &= \mu_2 + \beta\varphi\mu_2{}^{\beta-1}\Big[\frac{d}{dt}[U(t)] + \frac{d}{dt}[f(t)] \\ &\qquad + \frac{d}{dt}[H(t)] - \ddot{\eta}_2^d + \Lambda\ddot{e}\Big]\end{aligned} \tag{10}$$

where $\mu_2{}^{\beta-1} = \mathrm{diag}(\mu_{21}{}^{\beta-1}, \dots, \mu_{27}{}^{\beta-1})$. The fast convergence is ensured by choosing the reaching law as follows:

$$\dot{\rho} = -\beta\varphi\mu_2{}^{\beta-1}K\mathrm{sign}(\rho) \tag{11}$$

where $K = \mathrm{diag}[k_{ii}]$ with $k_{ii} > 0$ for $i = 1, \dots, 7$ is a switching positive gain, and function $\mathrm{sign}(\rho) = [\mathrm{sign}(\rho_1), \dots, \mathrm{sign}(\rho_7)]^T$ is determined such that:

$$\mathrm{sign}(\rho_i) = \begin{cases} 1 & \text{for } \rho_i > 0 \\ 0 & \text{for } \rho_i = 0 \\ -1 & \text{for } \rho_i < 0 \end{cases} \tag{12}$$

where $i = 1, \dots, 7$. From Eq. 10 and equation (11), we can conclude the time derivative of the control input such that:

$$\begin{aligned}&\tfrac{d}{dt}[U(t)] = -\tfrac{d}{dt}[f(t)] - \tfrac{d}{dt}[H(t)] + \ddot{\eta}_2^d - \\ &\Lambda\ddot{e} - \tfrac{1}{\beta}\varphi^{-1}\lfloor\mu_2\rceil^{2-\beta} - K\mathrm{sign}(\rho)\end{aligned} \tag{13}$$

Since $H(t)$ and $\frac{d}{dt}[H(t)]$ are uncertain that may influence the control purpose. In such case, the control law (13) is not feasible. To overcome this dilemma, TDE approach is used to estimate the uncertainties of the nonlinear exoskeleton's dynamics. So, if **Assumption 3** is verified, $\frac{d}{dt}[H(t)]$ can be estimated such that:

$$\begin{aligned}&\tfrac{d}{dt}[\hat{H}(t)] \approx \tfrac{d}{dt}[H(t - t_d)] = \ddot{\eta}_2(t - t_d) - \\ &\tfrac{d}{dt}[f(t - t_d)] - \tfrac{d}{dt}[U(t - t_d)]\end{aligned} \tag{14}$$

where t_d is a very small time-delay constant. Practically, the smallest constant that can be used in real time is the sampling-time period. Let us now define the time delay error such that:

$$\begin{aligned}&\varepsilon_i = \tfrac{d}{dt}[H_i(t)] - \tfrac{d}{dt}[\hat{H}_i(t)] = \tfrac{d}{dt}[H_i(t)] - \\ &\tfrac{d}{dt}[H_i(t - t_d)] \le \delta_i|t - (t - t_d)| \le \delta_i t_d\end{aligned} \tag{15}$$

where δ_i for $i = 1, \dots, 7$ is a positive constant known as Lipschitz constant that satisfies the Lipschitz condition in **Assumption 3**.

Theorem 1: Consider the exoskeleton robot system (3), the proposed control law that can handles the exoskeleton system and ensures the stability of the Non-Singular Second Order Terminal Sliding mode with TDE is given by:

$$\begin{aligned}&\tfrac{d}{dt}[U(t)] = -\tfrac{d}{dt}[f(t)] - \tfrac{d}{dt}[\hat{H}(t)] + \ddot{\eta}_2^d - \\ &\Lambda\ddot{e} - \tfrac{1}{\beta}\varphi^{-1}\lfloor\mu_2\rceil^{2-\beta} - K\mathrm{sign}(\rho)\end{aligned} \tag{16}$$

where $\int\frac{d}{dt}[U(t)]$ gives $U(t)$; if the following condition is verified:

$$k_{ii} > \delta_i t_d;\ \text{for } i = 1, \dots, 7 \tag{17}$$

Proof:
The proposed Lyapunov function candidate that ensures the stability of the robot is:

$$V = \frac{1}{2}\rho^T\rho \tag{18}$$

The time derivative of equation (18) is given by:

$$\begin{aligned}\dot{V} &= \rho^T\dot{\rho} \\ &= \rho^T\Big(\mu_2 + \beta\varphi\lfloor\mu_2\rceil^{\beta-1}\Big[\tfrac{d}{dt}[U(t)] + \\ &\quad \tfrac{d}{dt}[f(t)] + \tfrac{d}{dt}[H(t)] - \ddot{\eta}_2^d + \Lambda\ddot{e}\Big]\Big)\end{aligned} \tag{19}$$

Substituting control law $\frac{d}{dt}[U(t)]$ from Eq.16 into Eq.19 using Eq.15. Then, Eq. 19 becomes such that:

$$\begin{aligned}\dot{V} &= \rho^T\beta\varphi\lfloor\mu_2\rceil^{\beta-1}\Big(\Big[\tfrac{d}{dt}[H(t)] - \\ &\quad \tfrac{d}{dt}[\hat{H}(t)]\Big] - K\mathrm{sign}(\rho)\Big) \\ &\le \\ &\textstyle\sum_{i=1}^{7}\beta\varphi_{ii}\mu_{2i}{}^{\beta-1}|\rho_i|\big(|\varepsilon_i| - \\ &\quad k_{ii}\mathrm{sign}(\rho_i)\big) \\ &\le \\ &\textstyle\sum_{i=1}^{7}\beta\varphi_{ii}\mu_{2i}{}^{\beta-1}|\rho_i|\big(\delta_i t_d - \\ &\quad k_{ii}\mathrm{sign}(\rho_i)\big)\end{aligned} \tag{20}$$

where from Eq. 15 it is clear that the time delay error ε_i is always positive. Since $1 < \beta < 2$, therefore, for $\mu_{2i} \neq 0$ the expression $\lfloor\mu_{2i}\rceil^{\beta-1} > 0$ is always true [13]. Hence, to ensure the negativeness of $\dot{V}$, the following condition must be fulfilled:

$$k_{ii} > \delta_i t_d;\ \text{for } i = 1, \ldots, 7 \tag{21}$$

Hence, $\dot{V}$ is negative definite, thus, the selected surface ρ_i and its derivative is converging to zero as $t \longrightarrow \infty$. Therefore the system is stable.

4. Experiments and Comparative study

4.1 Experiment set-up

The robot system consists of three processing units, the first is a PC where the top-level commands are sent to the robot using LabVIEW interface, i.e. the control scheme selection, joint or Cartesian space trajectory, etc. This PC also receives the data after the exoskeleton robot task is executed to analyze its performance. The other two processing units are part of a National Instruments PXI platform. Firstly, a NI-PXI 8081 controller card with an Intel Core-Duo processor; in this card, the main operating system of the robot and the top-level control scheme are executed. In our case, the non-singular second-order terminal sliding mode based controller as well as the estimation based on time delay approach, at a sampling time of 500μs. Finally, at input/output level, a NI PXI-7813R remote input/output card with a FPGA (field programmable gate array) executes the low-level control; i.e. a PI current control loop (sampling time of 50 μs) to maintain the current of the motors required by the main controller. Also, in this FPGA, the position feedback via Hall-sensors (joint position) and basic input/output tasks are executed. The joints of the ETS-MARSE are powered by Brushless DC motors (Maxon EC-45 and Maxon EC-90) combined with harmonic drives (gear ratio 120:1 for motor-1 and motor-2, and gear ratio 100:1 for motors 3–7). The diagram of the experiment architecture is shown in Fig. 2. The parameters of the proposed control are illustrated in Table 2.

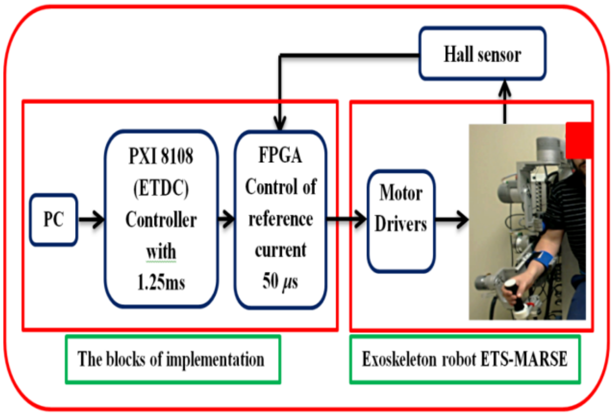

Fig. 2. Experiments platform (Note that the subject's figure is published with the written informed consent of the depicted individual.)

TABLE 2 Controller parameters

Gains	Value ($i = 1:7$)
φ_i	15.7
Λ_i	42.2
k_{ii}	15
β_{ii}	1.5

4.2 Experiment Results

In this test, the proposed exercise consisted of the two joints (elbow joint: flexion/extension and shoulder joint internal/external rotation). This exercise was performed with subject-1 (age: 30 years; height: 177 cm; weight: 75 kg). In this case, the trajectory was repeated two times for each movement with velocity varying less than 50 Deg/sec). The result of the task conducted with subject-1 is illustrated in Fig. 3. We can observe from Fig.3 that for both joints (elbow and shoulder), the desired trajectory, represented by the red line, practically overlaps the measured trajectory, represented by the solid blue line. It is clear from the plots in this figure (Fig.3) that the proposed controller provides a good performance. Where the controller has the ability to keep the stability of the exoskeleton system along the designed physical therapy movement with a position error (3rd row of Fig. 3) less than 2^o for shoulder joint and less than 0.05^o for elbow joint. The second row presents the desired velocity compared with the real velocity. It is clear from the smoothness of the velocity profile that the therapeutic motion was very good. The last row of Fig. 3 shows the control input which is clearly smooth and without any chattering effect.

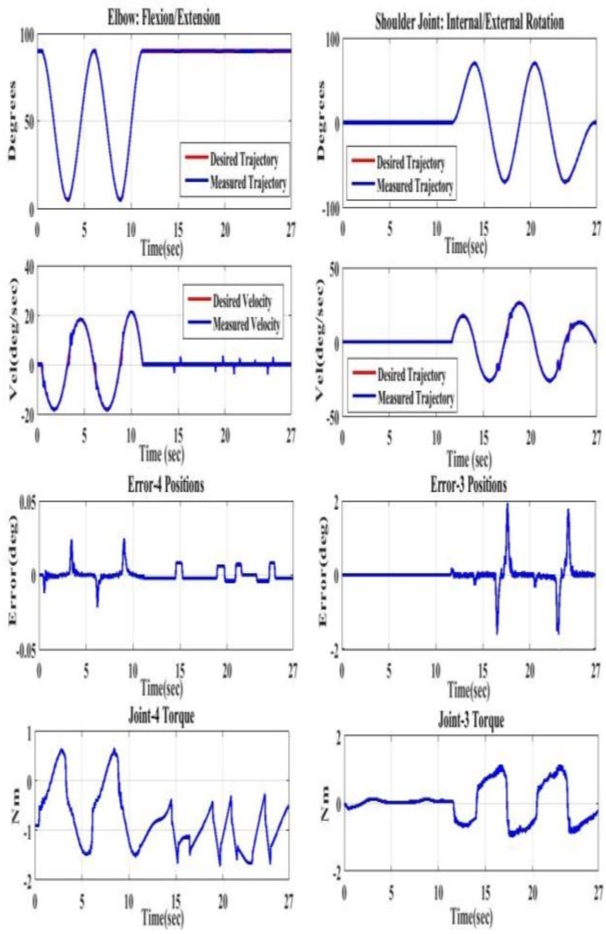

Fig. 3. Tracking trajectory of ETS-MARSE with subject-1 (constant acceleration).

4.3 Comparative study

The designed controller is compared with conventional second-order sliding mode controller SOSMC [14] with the same gains to show the feasibility and advantage of the designed controller. The comparison is made in terms of tracking position error, and torque input by computing the Root-Mean Square (RMS).

It is clear from Table 3 that the proposed controller achieves an excellent performance with a small value of overall RMS error and RMS torque, even when the dynamic model of the exoskeleton is not completely known, and in presence of external disturbances. Hence, these results demonstrate the efficiency and suitability of our proposed controller scheme.

Table. 3 Controller evaluation

Subjects	**Root Mean Square (RMS)**			
	Proposed Controller		**Conventional SOSMC controller**	
	$\|\|\mathbf{e}\|\|_{\text{error}}$ **(deg)**	$\|\|\boldsymbol{\tau}\|\|_{\text{Torque}}$ **(Nm)**	$\|\|\mathbf{e}\|\|_{\text{error}}$ **(deg)**	$\|\|\boldsymbol{\tau}\|\|_{\text{Torque}}$ **(Nm)**
Subject-1	1.3695	2.1125	2.5894	3.2147
	2.0379	3.1537	3.7840	4.8579

5. Conclusion

In this paper, we studied the control design employed to passive rehabilitation protocol of an exoskeleton robot named ETS-MARSE by introducing a new Non-Singular Terminal Second-Order Sliding Mode Control combined with time delay estimation. An experimental physiotherapy session with a healthy subject was created to examine the effectiveness and feasibility of the suggested control, which is established. As we see through experimental results that the proposed control has proved its capability to maneuver the exoskeleton to achieve the designed physical therapy with differences exoskeleton's wearers even the dynamics model of the robot is not completely known. Clearly that the controller deals very well with the uncertainties of robot's dynamics and external disturbances by given a good tracking of the trajectory without any chattering phenomenon. In the light of these excellent results obtained with healthy subject, we looking forward to implementing the proposed control with real unhealthy subjects as stroke victims in future work which permit to evaluate the controller with true case of disturbances such spasticity/dystonia, and muscle weakness in neurological patients, etc.

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