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# Adaptive integral terminal sliding mode control for upper-limb rehabilitation exoskeleton

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ABSTRACT

A robust adaptive integral terminal sliding mode control strategy is proposed in this paper to deal with unknown but bounded dynamic uncertainties of a nonlinear system. This method is applied for the control of upper limb exoskeleton in order to achieve passive rehabilitation movements. Indeed, exoskeletons are in direct interaction with the human limb and even if it is possible to identify the nominal dynamics of the exoskeleton, the subject's limb dynamics remain typically unknown and defer from a person to another. The proposed approach uses only the exoskeleton nominal model while the system upper bounds are adjusted adaptively. No prior knowledge of the exact dynamic model and upper bounds of uncertainties is required. Finite time stability and convergence are proven using Lyapunov theory. Experiments were performed with healthy subjects to evaluate the performance and the efficiency of the proposed controller in tracking trajectories that correspond to passive arm movements.

## 1. Introduction

In the recent years, the interest in exoskeleton has increased in many application fields. Especially, medical applications paid increasing attention to exoskeletons to obtain more efficient rehabilitation therapies (Burgar, Lum, Shor, & Van der Loos, 2000; Krebs, Volpe, Aisen, & Hogan, 2000; Marini et al., 2017; Masiero & Armani, 2011; Veerbeek, Langbroek-Amersfoort, van Wegen, Meskers, & Kwakkel, 2017; Xu, Chu, & Rogers, 2014), and to provide suitable health care to disabled patients and elderly people not only in hospitals but also in their own homes. The problem is that, such robotic systems are very complex and hard to model owing to their direct interaction with the user's limb. Even if the dynamics of the exoskeleton is known, that of the human limb is typically unknown and greatly variable form a person to another. Therefore, the use of exoskeleton in interaction with a human subject, depends on the quality of the associated controller, in order to obtain satisfactory performances.

Several control strategies for exoskeletons have been proposed in the literature, for example: Adaptive control (Pehlivan, Losey, & O'Malley, 2016; Wei, Balasubramanian, Xu, & He, 2008), EMG-based control (Kiguchi, Rahman, Sasaki, & Teramoto, 2008; Loconsole, Dettori, Frisoli, Avizzano, & Bergamasco, 2014), Admittance control (Culmer et al., 2010), Fuzzy and backstepping control (Chen, Li, & Chen, 2017; Li, Su, Li, & Su, 2015), Impedance control and reinforcement learning (Li et al., 2017) and Coordination control (Li, Kang, Xiao, & Song, 2017). A recent review on control strategies for upper limb exoskeletons can be found in Proietti, Crocher, Roby-Brami, and Jarrassé (2016).

Among the existing robust control schemes, this work focuses on Sliding Mode Control (SMC) which is a powerful approach to control robotic systems with uncertain dynamics and bounded disturbances (Park, Choi, & Kong, 2007; Yuri, Christopher, Leonid, & Arie, 2014; Zhihong, Paplinski, & Wu, 1994). This nonlinear control strategy works by dragging the non-linear path to a predetermined hyperplane so-called sliding surface, then the system stays confined to the sliding surface while sliding along to the origin (Slotine, Li, et al., 1991). In general, conventional SMC uses linear sliding surface which can only achieve asymptotic stability of the system during the sliding mode phase (Perruquetti & Barbot, 2002). Thereafter, more advanced techniques such as Terminal SMC (TSMC) were proposed (Feng, Zhou, Zheng, & Han, 2016; Zhihong & Yu, 1997) which can guarantee finite time convergence of the tracking error to zero. The Fast Terminal Sliding Mode (FTSM) surface has been introduced to further reduce the finite-settling-time (Madani, Daachi, & Djouani, 2017; Yu & Zhihong, 2002). However, TSMC and FTSM suffer from singularity problems due to the use of fractional power in sliding surface design. Therefore, a Nonsingular TSMC (NTSMC) have been proposed in Feng, Yu, and Man (2002), Komurcugil (2013) and Madani, Daachi, and Djouani (2016), to overcome the singularity problem. In Peng, Jianjun, Lina, and Zhiqiang

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(2015) an Integral TSMC (ITSMC) is proposed to eliminate singularities and lead to less chattering effect compared to the conventional SMC (Morshed & Fekih, 2015).

This paper proposes an Adaptive ITSMC (AITSMC) for upper limb exoskeletons in order to perform passive rehabilitation. First, the dynamic modeling of the considered exoskeleton is introduced as well as properties and assumptions. Then, an integral terminal sliding mode surface is used to guarantee tracking errors converge to zero in finite time when the sliding surface is reached. The proposed ITSMC is thus designed to guarantee the reaching of the sliding mode, as well as the good tracking performance in finite time. With this control scheme, the singularity problem is removed without adding any constraints. Furthermore, the lack of knowledge of the system uncertainties bounds leads to set them to very high values which may result in intense control torques. To address this problem an adaptive approach is proposed to adaptively tune the uncertainties bounds while guaranteeing finite time convergence. Finally, to validate the proposed control scheme, experiments were carried out with a healthy subject using a 3 Degrees of Freedom (DoF) upper limb exoskeleton called ULEL[1] to perform trajectories that correspond to passive arm movements.

The rest of the paper is set as follows. Section 2 expresses the dynamic modeling and model properties and assumptions. In Section 3 controller design is presented. Section 4 introduces an adaptation method to tune the controller gains. Section 5 shows the implementation of the proposed approach for the upper limb exoskeleton ULEL and experimental results in performing passive movements with healthy subjects. Conclusion is presented in Section 6.

## 2. Dynamic modeling

The dynamic behavior of robotic systems can be expressed by the well known rigid body's dynamic equation in Khalil and Dombre (2004) as

$$M(q)\ddot{q} + H(q,\dot{q}) = \tau(t), \tag{1}$$

with

$$H(q,\dot{q}) = C(q,\dot{q})\dot{q} + G(q) + D(\dot{q}), \tag{2}$$

where $q \in \mathbb{R}^n$, $\dot{q} \in \mathbb{R}^n$ and $\ddot{q} \in \mathbb{R}^n$ are respectively the joint positions, velocities and accelerations; $M(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix; $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the Coriolis/centrifugal matrix; $G(q) \in \mathbb{R}^n$ is the gravity vector; $D(\dot{q}) \in \mathbb{R}^n$ is the dissipation term; $\tau(t) \in \mathbb{R}^n$ is the applied torque vector.

In the case of human-exoskeleton system, the dynamic model (1) can be used with some known parts and unknown parts. The terms $M(q)$, $H(q,\dot{q})$ and $\tau(t)$ can be written in the form

$$\begin{cases} \tau(t) &= \tau_N(t) + \tau_\Delta(t) \\ M(q) &= M_N(q) + M_\Delta(q) \\ H(q,\dot{q}) &= H_N(q,\dot{q}) + H_\Delta(q,\dot{q}) \end{cases}, \tag{3}$$

where $\tau_N(t)$, $M_N(q)$ and $H_N(q,\dot{q})$ are known nominal parts and $\tau_\Delta(t)$, $M_\Delta(q)$ and $H_\Delta(q,\dot{q})$ are unknown parts. The term $\tau_N(t)$ represents the actuated torque generated by the exoskeleton's motors and $\tau_\Delta(t)$ includes the torques applied by the human arm on the exoskeleton and external disturbances.

Using (3), the dynamic equation (1) can be written in the following form :

$$M_N(q)\ddot{q} + H_N(q,\dot{q}) = \tau_N(t) + \Delta(t), \tag{4}$$

where $\Delta(t)$ is the system uncertainties defined as

$$\Delta(t) = \tau_\Delta(t) - M_\Delta(q)\ddot{q} - H_\Delta(q,\dot{q}), \tag{5}$$

which is related to the position, velocity and acceleration signals.

[1] *Upper Limb Exoskeleton of LISSI.*

**Remark 1.** Only the position and velocity are measurable in our application setup using an exoskeleton. Therefore, the use of acceleration term in (5) is the key problem for controller designing. This issue will be addressed in the following of the paper.

### *2.1. Model properties and assumptions*

In the case of robotic systems with only pivot joints (revolute joints), the following properties are obviously verified for any $q \in \mathbb{R}^n$.

**Property 1.** *The inertia terms $M(q)$ and $M_N(q)$ are symmetric positive definite matrices. Moreover, these matrices are bounded* (Ghorbel, Srinivasan, & Spong, 1998)

$$\begin{cases} \underline{m} I \le M(q) \le \bar{m} I \\ \underline{m}_N I \le M_N(q) \le \bar{m}_N I \end{cases}, \tag{6}$$

*where $\underline{m}$, $\bar{m}$, $\underline{m}_N$ and $\bar{m}_N$ are positive constants such that $0 < \underline{m} < \bar{m}$ and $0 < \underline{m}_N < \bar{m}_N$. Therefore, it is straightforward that $M^{-1}(q)$ and $M_N^{-1}(q)$ are also positives and bounded as*

$$\begin{cases} \bar{m}^{-1} I \le M^{-1}(q) \le \underline{m}^{-1} I \\ \bar{m}_N^{-1} I \le M_N^{-1}(q) \le \underline{m}_N^{-1} I \end{cases}. \tag{7}$$

**Property 2.** *Using the euclidean norm, it can be written that* (Mulero Martínez, 2007)

$$\|C(q,\dot{q})\| \le \bar{c}\|\dot{q}\|, \tag{8}$$

*where $\bar{c}$ is a non-negative constant.*

As the exoskeleton interacts with the human arm, it is considered that the term $\Delta(t)$ is unknown. Only the following assumptions are adopted.

**Assumption 1.** The gravity vector $G(q)$ is bounded such as $\|G(q)\| \le \bar{g}_1 + \bar{g}_2\|q\|$, where $\bar{g}_1$ and $\bar{g}_2$ are non-negative constants.

**Assumption 2.** The dissipation vector $D(\dot{q})$ is bounded such as $\|D(\dot{q})\| \le \bar{d}_1 + \bar{d}_2\|\dot{q}\|$, where $\bar{d}_1$ and $\bar{d}_2$ are non-negative constants.

**Assumption 3.** The torque vector $\tau_\Delta(t)$ is bounded such as $\|\tau_\Delta(t)\| \le \bar{\tau}_\Delta$, where $\bar{\tau}_\Delta$ is a non-negative constant.

Considering Property 2, and Assumptions 1–3, then $H(q,\dot{q})$ in (2) can be upper-bounded as follows:

$$\|H(q,\dot{q})\| \le \bar{g}_1 + \bar{d}_1 + \bar{g}_2\|q\| + \bar{d}_2\|\dot{q}\| + \bar{c}\|\dot{q}\|^2. \tag{9}$$

Assume that $H_N(q,\dot{q})$ and $H_\Delta(q,\dot{q})$ are upper-bounded as follows:

$$\begin{cases} \|H_N(q,\dot{q})\| < \bar{h}_{N1} + \bar{h}_{N2}\|q\| + \bar{h}_{N3}\|\dot{q}\| + \bar{h}_{N4}\|\dot{q}\|^2 \\ \|H_\Delta(q,\dot{q})\| < \bar{h}_{\Delta1} + \bar{h}_{\Delta2}\|q\| + \bar{h}_{\Delta3}\|\dot{q}\| + \bar{h}_{\Delta4}\|\dot{q}\|^2 \end{cases}, \tag{10}$$

where $\bar{h}_{N1}, \ldots, \bar{h}_{N4}$ and $\bar{h}_{\Delta1}, \ldots, \bar{h}_{\Delta4}$ are non-negative constants.

Using (4), the acceleration $\ddot{q}$ can be written as

$$\ddot{q} = M_N^{-1}(q)\left[\tau_N(t) + \Delta(t) - H_N(q,\dot{q})\right], \tag{11}$$

then the dynamic model (1) can be written as

$$\ddot{q} = f(q,\dot{q}) + \varphi(q)u(t) + \xi(t), \tag{12}$$

where $u(t) = \tau_N(t)$ represents the control input torque, and the functions $f(q,\dot{q})$, $\varphi(q)$ and $\xi(t)$ are given by

$$\begin{cases} f(q,\dot{q}) &= -M_N^{-1}(q)H_N(q,\dot{q}) \\ \varphi(q) &= M_N^{-1}(q) \\ \xi(t) &= M_N^{-1}(q)\Delta(t) \end{cases}. \tag{13}$$

In what follows, to simplify the writing of the equations, the notational dependency will be omitted on $u$, $f$, $\varphi$, $\xi$, $\Delta$, $M_N$, $M_\Delta$, $H_N$, $H_\Delta$, $\tau_N$ and $\tau_\Delta$.