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Non-singular terminal sliding mode controller: Application to an actuated exoskeleton

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ABSTRACT

This paper presents a robust controller of an active orthosis used for rehabilitation purposes. The system is composed of the orthosis worn by the shank and has a complex dynamical model. No prior knowledge is considered on the dynamical model and the flexion/extension movements considered are of sinusoidal form and are generally defined by the doctor. The used non-singular terminal sliding mode technique permits to have a finite time convergence. The experimental results have been conducted online on an appropriate dummy and then on three healthy subjects. A comparison of performances obtained by the proposed approach with those obtained by a conventional controller has also been realized. Several situations have been considered to test the robustness and it has been concluded with the effectiveness of the developed controller.

1. Introduction

Currently, exoskeletons/orthoses represent a considerable part of robotics research. These wearable robots are used in various fields such as rehabilitation, assistance and can sometimes replace completely the upper or lower limbs of human. In addition, exoskeletons can also be used to improve comfort and help on various daily tasks (gardening, carry heavy loads, climb stairs, walk longer, etc.). Some of main problems considered for this type of robot are related to control, identification of dynamic parameters or behavior and to observe some physical phenomena that can improve exoskeletons performance. Now, the challenge is to improve the cognitive abilities of exoskeletons to enable them to learn, adapt and make decisions based on their own mistakes in the same way than humans. In literature, it can be found several exoskeletons/orthoses developed and used for various applications. The University of Agriculture and Technology of Tokyo has designed an exoskeleton to help the wearer to perform agricultural work considered difficult and tough [7]. Another kind of exoskeleton namely “Hercules” has been made to improve the performance of soldiers.[1] The University of Berkeley has recently developed a lower limb exoskeleton called BLEEX that allows the holder to carry heavy loads [12]. Furthermore, Refs. [4,9] constitute a good state of the art on the exoskeletons and their applications.

To allow the exoskeleton to meet the needs of the wearer, it is necessary to apply an appropriate control law. The complexity of the system dynamics consisting of the exoskeleton and its wearer associated with external perturbations make the traditional controllers inefficient. This complexity has led researchers to propose a variety of appropriate controllers. Some control schemes are based on the preliminary step of identifying the dynamic parameters of the set consisting of the exoskeleton and its wearer. Other approaches are adaptive and are dedicated to generic exoskeletons designed to be worn by humans of different morphologies. An example of such controllers is based on neural networks [10,25]. The universal approximation of neural networks [5,21] is one of their advantages. However, neural approaches require generally offline learning step in order to avoid undesirable behavior of the exoskeleton during the initialization step. In [1], the authors use a dynamical model of the upper limb exoskeleton to amplify the human power. In that human-robot cooperation, it is rarely possible to know the exact dynamical model and consequently the scope of this approach is reduced. Several works on nonlinear control of exoskeletons [8,11] can be also found.

Sliding mode controllers having the advantage of robustness against external disturbances and model uncertainties, have been widely applied to the robotic systems [19,22,23]. The classic sliding mode controllers use a linear sliding surface and the convergence of the system's states is asymptotic. Terminal Sliding Mode (TSM) technique based on a non-linear sliding surface is proposed to ensure, in finite time, the stability of the closed loop system [16,18,20]. The Fast Terminal Sliding Mode (FTSM) surface has been introduced [6,13,26] to further reduce the finite-settling-time. The Non-singular Terminal

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[1] http://www.army-technology.com/features/featurefrench-hercule-robotic-exoskeleton.

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Fig. 1. The dummy and human wearing an actuated knee joint orthosis (EICoSI).

Sliding Mode (NTSM) has been proposed [2,14,15] to overcome the classical singularity problem of the conventional TSM. Furthermore, a boundary layer augmented sliding mode controller is proposed in [3] for trajectory tracking of a robotic orthosis. Even if the obtained results are good, the stability of the system in closed loop is not ensured.

In this article, it is proposed to construct and experiment a NTSM controller for a powered knee orthosis. The goal of the proposed controller is to show the effectiveness of a sliding technique that ensures the convergence toward the sliding surface and avoiding any singularity problem. Surely it can be found other versions of this technique in the literature but as given in the article, it is unique with a particular way to compute the finite time convergence. In fact, a new optimization strategy at the vicinity of the singularity is proposed. This allows to compute the minimum reaching time to the sliding surface. Furthermore, this technique requires no prior knowledge on the dynamic model. Also, the advantage of this method over other methods is its robustness against parameter uncertainties and external disturbances. The system considered in this paper, consisting of the orthosis and knee of the wearer, has a complex dynamic that is difficult to mobilize by equations. For safety reasons, it is very important to control it by techniques including a very short transient tolerated by the standards set by the doctor. This is precisely what offers the NTSM technique that is used in this work. As this technique is almost never used in the field of control of exoskeletons, the presented work proposes a control taking into account the state of the carrier of the exoskeleton that can be active or completely passive (no muscular effort developed). So the proposed controller is firstly tested on an appropriate dummy and is only after eliminating all the risks that application can be made. Final validation is performed on a healthy subject.

The paper is organized as follows: in Section 2, the exoskeleton used for the experiments and formulate the considered problem are described. Section 3 deal with the analysis and controller proposed stability. The experimental results and their analysis are given in Section 4. Finally, Section 5 is dedicated for the conclusion and future work.

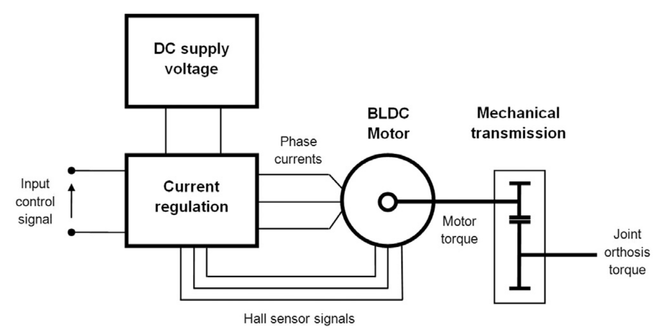

Fig. 2. Electrical architecture of the joint orthosis actuator.

2. Active orthosis system

The EICoSI (Exoskeleton Intelligently Communicating and Sensitive to Intention) is used to carry out the experimental validations of the proposed controller. EICoSI is an active knee-joint orthosis developed in LISSI Laboratory (Laboratoire Images, Signaux et Systèmes Intelligents) of University Paris-Est Créteil (UPEC), France. Two jointed segments compose the considered actuated orthosis, upper and lower. The mechanical part and the actuator are placed on the upper part of the orthosis. The torque generated by the orthosis realizes flexion/extension movements of the lower part, formed by the dummy shank and the lower part of the orthosis. Moreover, the knee joint is constrained by a range of motion between 0 and $\frac{2\pi}{3}$ for safety reason. In Fig. 1, a dummy and a human wearing the used actuated knee joint orthosis are presented.

2.1. Electrical part

The joint of the orthosis is actuated by a brushless DC motor (BLDC). A power supply and an adequate electrical system are used to provide the regulation for the current in the motor. A mechanical