Assisted Rehabilitation by Robotic Orthosis of Spinal Cord and Back Injuries

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Abstract— **This study addressed the design, construction and control of a prototype of active orthosis focused on assisting the rehabilitation of patients with spinal cord or/and back illnesses. The prototype was actuated with a collection of direct current motor commanded by distributed control strategy based on the so-called Twisting controller. This control action used a Super-Twisting algorithm as robust differentiator to supply the time derivative of the tracking error. A graphic user interface (GUI) was implemented to enforce the application of different therapies accordingly to the most common strategies used in clinical rehabilitation. The orthosis was implemented and the proposed controller forced the tracking of the reference trajectories supplied by the GUI. The orthosis was evaluated in simulation to adjust the controllers and differentiators gains. A real orthosis was constructed and controlled using the gains obtained at the simulation stage. The actual orthosis was evaluated to check the ability of the controller to track the reference trajectory despite the resistance of the patient that was simulated by different dummies devices.**

Keywords— **Active orthosis, spinal cord injuries, sliding mode control, Twisting controller, Super-Twisting algorithm.**

I. INTRODUCTION

Spinal Cord Injury (SCI) is a damage or trauma to the spinal cord that yields to loss of function, mobility and sensation below the level at which the spinal cord has been affected. This disorder is characterized according to the amount of functional or sensation loss and inability of an SCI individual to stand and walk. One possible and very traumatic consequence of SCI is the paralysis, whether partial or complete, may provoke complications in other parts of the body (respiratory disorder, gastrointestinal and cardiovascular disorders, skin and muscle-skeletal problems and psychological disorders). The better solution to this SCI is a very traumatic surgery, that demands long periods of rehabilitation. During this time, the patient suffers several episodes of pain [1].

On the other hand, back illnesses are classified into lumbar and thoracic back pain. Both type of sicknesses appear commonly in persons that have bad posture, remains seated for long periods, etc. Initial treatment of these illnesses require muscle relaxants or non-inflammatory medicaments. When the pharmacological treatment is not enough, muscular massages and physiotherapy are needed. If the illnesses became chronic, long term treatments included bed rest, vertebral traction, termotherapy, electrotherapy and wearing passive orthosis. This last option only provides a permanent posture control but it does not bring assisted therapy [2].

SCI and back illnesses are the major factor that motivates the back assisted therapy. Physiotherapy associated to back pain rehabilitation is an important part of helping patients get the most accelerated and complete recovery of their health. This work is regularly performed by specialized physiotherapists. However, this is very hard task and requires a lot of financial and human resources. One option to reduce the demand of resources is using active orthosis (AO) .

AO is a class of assisting robot which is designed to help patients to recover function without substituting structure. There are many examples of AO in real clinical situations and scientific literature. The majority of them were focused on assisting the movement of legs and arms. However, there are just a few of solutions regarding the active therapy for rehabilitating back pain caused by either, SCI and back illnesses [3].

AO design demands the solution of two relevant issues: 1) the controller proposed to regulate the movement of the device and 2) the reference trajectories used to force the accurate application of an automatic therapy. The first of the aforementioned stages must be solved with an automatic controller. Traditional control schemes based on classical PD controllers and Computed Torque control [4] have been successfully implemented in many AO. However, to obtain good performance in regulation and trajectory tracking applications, these controllers need the complete knowledge of the robot dynamics, which may be sensitive to problems in the presence of uncertainties, disturbance inputs, or non-modelled dynamics. Moreover, this schemes normally require high processing capacities in the control hardware [5]. The uncertainties introduced by the interaction between the orthosis and the patient must be tackled with a type of robust controller that can ensure the tracking of the reference trajectory.

In automatic control theory, exist several examples of robust control theories that can be used to solve the AO trajectory tracking problem. One of the most successfully the-

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ory of robust control is the so-called sliding modes (SM). SM and their variations have shown to be robust with respect to parametric uncertainties, presence of external perturbations and high degree of vagueness on the mathematical model of the system to be controlled or estimated (parameters or/and states). Twisting and Super-Twisting Algorithms (TA and STA) are two well known SM methods that have been used as controller and robust differentiator respectively. Recently, some results appeared where they both were used together to solve the problem of output based robust controller for second order system. This result presented the first version of Lyapunov functions that served to prove the stability of the closed-loop controller. This study used this result but in a distributed framework. Each articulation in the AO system was independently controlled based only on the reference trajectory provided by the physiotherapist. The robustness of the proposed controller was adequate to solve the tracking trajectory problem despite the global configuration of the AO back assisted therapy [6].

The aspect of designing reference trajectories in AO back assisted therapy plays a relevant role. A regular strategy for designing reference trajectories is based on the so-called Bezier curves. These curves must fulfil simple requirements including smoothness and zero derivatives in their extremal sections. The so-called Bezier polynomials have been the most popular way to get the reference trajectory curves. However they demand the estimation of many parameters for designing each polynomial.

In summary, this article deals with the problem of output base sliding mode control for a back therapy AO robotic system. The control problem was to solve the trajectory tracking task, based on the on-line reconstruction of the articulation velocity using a robust STA differentiator. The estimated states were used to design the closed-loop control based on the Twisting scheme. This combination of two different sliding mode methods was used at each articulation of the AO used in back assisted therapy.

II. ORTHOSIS DESIGN

The orthosis for active back assisted therapy emulated the concept of multi-legged robots. The idea was to design a fixed body with six independent manipulator with three degree-of-freedom attached to a central column. The whole robotic system can be fixed to the patient's back. The fixing process is proposed to be automatic using a pressure sensors in the distal part of each arm.

This design followed the regular mechanism used to track and move the back of injured patients. The dimensions and mechanical design were adjusted to standard anthropomorphic measures for Mexican people. The orthosis was constructed using a 3D printer. The material selected for building was the ABS polymer. Figure (1) depicts the mechanical design of the orthosis which has been built. The motors were located at the each arm of orthosis and they were instrumented with the corresponding sensors (electrical goniometer devices) and actuators (DC motors). All the electronic boards used to control and monitor the coordinates of the orthosis were placed in a central power device.

Fig. 1: Mechanical design of the active orthosis and the distribution of actuators and sensors

The position of each articulation was measured using a variable resistance placed over the motor guide (goniometer). These sensors were used to recover the articulation angle and feed into the robust differentiator based on STA as well as the output feedback controller. These variables were acquired by the corresponding microcontroller device. Each of these devices implemented its own output based controller. This strategy prevent the necessity of having a master device which must calculate all the controller together. This scheme was also an innovation presented in this study.

III. CONTROLLER DESIGN TO REGULATE THE ORTHOSIS POSITION

Using the Euler-Lagrange modelling process, the dynamic equations for the active hand orthosis can be derived. These equation can be represented as:

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

Here $M(q) \in \mathbb{R}^{6\times 6}$ is the inertia matrix and $b(q,\dot{q},t) : \mathbb{R}^{13} \rightarrow \mathbb{R}^{6}$ is a vector function containing the dynamical behaviour of the orthosis. Matrix $M(q)$ and vector $b(q,\dot{q},t)$ are defined in [7].

The model 1 belongs to a class of coupled second order nonlinear systems with uncertain structure. Based on the state variable theory, the active orthosis dynamic system can be represented as follows

$$\begin{aligned} \frac{d}{dt}x_a(t) &= x_b(t) \\ \frac{d}{dt}x_b(t) &= f(x(t)) + g(x_a(t))u(t) + \xi(x(t),t) \end{aligned} \tag{2}$$

where $x = [x_a^\top, x_b^\top]^\top,\ x \in \mathbb{R}^{12}$ is the state of the electromechanical system used to represent the state of the orthosis. Indeed, $x_a = q$ and $x_b = \frac{d}{dt}q$. The term $\xi(x,t)$ was included to consider the effect of perturbations/uncertainties wich can represent friction, backslash, patient resistance, etc. The system (2) has the initial condition given by $x(0) = x_0,\ \|x_0\| < \infty$. The bounded function $u \in \mathbb{R}^1 2$ is referred to as the control function. The nonlinear Lipschitz function $f : \mathbb{R}^{12} \rightarrow \mathbb{R}^6$ is composed by 6-uncertain nonlinear functions which describes the drift term of (2). The function g is fulfilling the following constraint

$$0 < g^- \leq \|g(\cdot)\| \leq g^+ \quad g^-, g^+ \in \mathbb{R}^+ \tag{3}$$

The uncertainties are included in the term $\xi(x,t)$ that can represent parameters variations, external perturbations, modelling errors, etc. The system (2) can be rewritten as follows

$$\begin{gathered} \dot{x}(t) = Ax(t) + G(x(t))u(t) + F(x(t)) \\ A = \begin{bmatrix} 0_{6\times 6} & I_{6\times 6} \\ 0_{6\times 6} & 0_{6\times 6} \end{bmatrix}, G(x) = \begin{bmatrix} 0_n \\ g(x) \end{bmatrix}, \\ F(x) := \begin{bmatrix} 0_1^\top & f(x) + \xi(x) \end{bmatrix}^\top \end{gathered}$$

The controller structure proposed in this study was a variation of output feedback form. In this case, this controller corresponds to a nonlinear discontinuous proportional derivative (PD) form usually known as Twisting [8]. Twisting control was selected to regulate the position of each actuator in robust way and forcing the finite time convergence to a reference trajectory. This controller has the form $u(t) = -k_1 S(e(t)) - k_2 S(d(t))$ where the vector function $S(v),\ v \in \mathbb{R}^n$ corresponds to .

$$\begin{gathered} S(v) = |sign(v_i)|_{i=1,..,n} \\ v = |v_i|_{i=1,..,n} \\ \text{sign}(z) := \begin{cases} 1 & if\ z > 0 \\ \in [-1,1] & if\ z = 0 \\ -1 & if\ z < 0 \end{cases} \end{gathered} \tag{4}$$

The matrix gains k_1 and k_2 are selected by a special rule proposed in [9].

The STA algorithm to obtain the derivative of $e(t)$ which is represented as d in the controller structure looks like

$$\begin{gathered} \tfrac{d}{dt}\bar{e}_1(t) = \bar{e}_2(t) - \lambda_1 |\tilde{e}_1(t)|^{1/2} \text{sign}(\tilde{e}_1(t)) \\ \tfrac{d}{dt}\bar{e}_2(t) = -\lambda_2 \text{sign}(\tilde{e}_1(t)) \\ \tilde{e}_1 := \bar{e}_1 - e;\ \ d(t) = \tfrac{d}{dt}\bar{e}_1(t) \end{gathered} \tag{5}$$

where $\lambda_1, \lambda_2 > 0$ are the STA gains. Here $d(t)$ is the output of the differentiator [10].

Because all the controllers were implemented in embedded micrcontrollers of 8 bits, the aforementioned controller and differentiator were implemented using an Euler discretization version. The convergence and properties of these discrete schemes have also been analysed in [11]. In particular, the controller did not suffer any modification but the STA was implemented as

$$\begin{gathered} \bar{e}_1((k+1)T) = \bar{e}_1((k)T) + T\bar{e}_2(kT) - \\ T\lambda_1 |\tilde{e}_1(kT)|^{1/2} \text{sign}(\tilde{e}_1(kT)) \\ \bar{e}_2((k+1)T) = \bar{e}_2((k)T) - T\lambda_2 \text{sign}(\tilde{e}_1(t)) \end{gathered} \tag{6}$$

where T is the sampling period which was adjusted to 0.01 seconds.

IV. Experimental results

The first part of results corresponded to the class of exercises developed by the active orthosis. These experiments were selected according to the most popular treatment methods used in actual physiotherapies. These sequences of movements were included in Figure 2 and they correspond to some exercises where all the different articulations were moved all together or independently. These movements were obtained after implementing the orthosis in Matlab. This orthosis was simulated to evaluate the performance of the distributed strategy of robust control based on the Twisting/Super-Twisting scheme.

Different reference trajectories were proposed to evaluate the ability of the orthosis to develop distinct therapies. These different trajectories were designed accordingly to the Bezier curves methodology. The specific function to design the curves was the sigmoid structure. Using these functions, the reference trajectories were supplied to the controller. Figure (2) demonstrates the corresponding movements which were produced by the controller in simulation.

The actual orthosis was built using the methodology already discussed. The orthosis was actuated with several DC

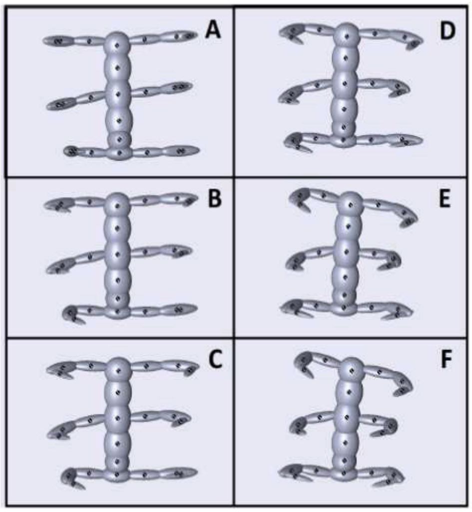

Fig. 2: Movements executed by the simulated orthosis using all the details already described. This simulation was implemented in Matlab using its SimMechanics Toolbox. The six different subfigures demonstrate different stages of the same therapy executed by the orthosis.

motors as can be observed in (3). This figure also shows the actual movements originate by the real device. A set of 23 independent controllers were placed in equal number of embedded systems. Each controller used its own differentiator implemented in discrete form as the one presented in figure 6. The embedded system was supplied with an optoelectronic device with isolating purposes.

The controller was evaluated with different dummies made of polyurethane. Three different densities of the same material were used as testing elements. Despite the type of dummy, the controller succeed to track some different reference trajectories as shows figure (3). Finally, the authors declare that they have no conflict of interest.

V. Conclusions

This paper describes the entire design of an active orthosis to assists the rehabilitation of spinal cord and/or back illnesses. This device was supplied with some electromechanical sensors which were used by an robust output based controller. This information produces a mixed structure based on robust observation and output based controller which served to adjust the movement of the active orthosis. A basic construction of the orthosis system was used to generate some actual evaluations that validated the theoretical results achieved in this study.

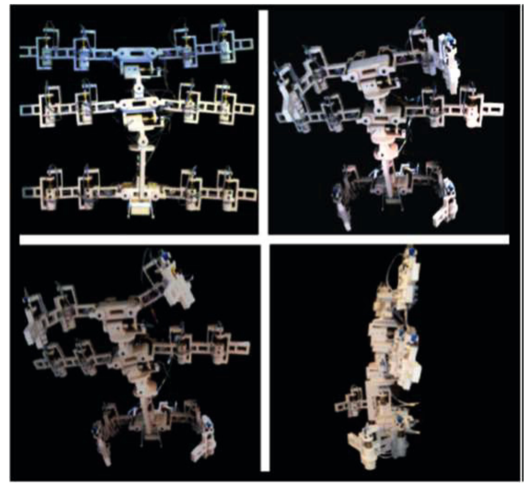

Fig. 3: Set of regular exercises used to generate the reference trajectories supplied to the active orthosis.

References

1. McGil S.. *Low Back Disorders: Evidenced-based Prevention and Rehabilitation*. Human Kinetics 2007.
2. Cuccurullo S.. *Physical Medicine and Rehabilitation Board Review*. Demos Medical Publishing 2004.
3. Luenberger L., Colombo G., Riener R., Dietz V.. Biofeedback in gait training with the robotic orthosis Lokomat in *IEMBS 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*;2:4888-4891 2004.
4. Codourey A.. Dynamic modelling and mass matrix evaluation of the DELTA parallel robot for axes decoupling control in *Proceedings of the 1996 IEEE-RSJ International Conference on Intelligent Robots and Systems (IROS)*:1211-1218 1996.
5. Jankowski K. P., Van-Brussel H.. An approach to discrete inverse dynamics control of flexible-joint robots *IEEE Transactions on Robotics and Automation.* 1992;8:651-658.
6. Moreno A., Osorio M.. Strict Lyapunov Funtions for the Super-Twisting Algorithm *IEEE Tran. Aut. Cont.*. 2012;57:1035-1040.
7. Hill J., Fahimi F.. Active disturbance rejection for bipedal walk of a humanoid using the motion of the arms in *ASME 2011 International Mechanical Engineering Congress and Exposition*:137-144 2011.
8. Polyakov A., Poznyak A.. Lyapunov function design for finite-time convergence analysis: "Twisting" controller for second order sliding mode realization *Automatica.* 2009;45:444-448.
9. Moreno J., Alvarez J., Rocha-Cozatl E., Diaz-Salgado J.. Super-Twisting observer-based output feedback control of a class of continuous exothermic chemical reactors in *Proceedings of the 9th International Symposium on Dynamics and Control of Process Systems (DYCOPS)*(Leuven, Belgium):727-732 2010.
10. Levant A.. Robust exact differentiation via sliding mode tecnique *Automatica.* 1998;34:379-384.
11. Levant A.. Finite Differences in Homogeneous Discontinuous Control *IEEE Transactions on Automatic Control.* 2007;52:1208-1217.