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Control of a robotic exoskeleton for children lower limb rehabilitation

Rafael Pérez , Iván Salgado and Isaac Chairez

Abstract—**This manuscript describes the instrumentation and control of an exoskeleton prototype to improve the rehabilitation of children between 5 and 8 years old. The prototype has the characteristic of being programmable with different rehabilitation tasks traduced in several rehabilitation pathways defined by medical specialists. The control strategy was to achieve the desired movements associated to medical therapies, which are obtained by a discrete-time proportional derivative controller. The instrumentation includes the use of an 32-bits ARM processor that performed all the desired trajectories as well as the decentralized control strategies proposed for the exoskeleton. Experimental results show the behavior of the robotic exoskeleton fulfilling the expected movements for the proposed tracking signal reference.**

Index Terms—**Exoskeleton robot; Embedded controller; Lower limb rehabilitation; Lower limb children injuries; Proportional-Derivative controller.**

I. Introduction

IN recent years, the development of clinical assistance technologies has acquired great importance for the relevant solutions offered by the emerged devices in the treatment of diverse illnesses. The field of orthopedics and rehabilitation plays an important role in the recovering of patient's health. Nowadays, medical robots are commonly used, not just in orthotics and rehabilitation, but in a lot of different clinical areas [1].

In February 2017, World Health Organization (WHO) hosted Rehabilitation 2030, where rehabilitation experts highlighted the urgency of addressing the profound needs for rehabilitation around the world. According to the results presented in this meeting, excluding acute and remitting conditions, 74% of Years Lived with Disability (YLDs) in the world are the result of health conditions for which rehabilitation could be beneficial, that actually represents an important amount of disability cases all over the world. YLDs represent a measurement of the burden of diseases, and they are calculated by multiplying the prevalence of a disorder by the short or long-term loss of health associated with that disability. Furthermore, Rehabilitation 2030, reported that the need for rehabilitation continues to grow worldwide, especially in low and middle-income countries, as a result, a comprehensive strategy is required to strengthen rehabilitation and address global needs. Prosthetic and orthotics are areas of specialized rehabilitation services, which concern services for people with physical impairments, including older populations, to maintain or improve their correct functioning and independence, facilitate participation, and enhance overall well-being. While prostheses are devices meant to replace wholly or partially a limb segment, orthoses are meant to modify the structural and functional characteristics of neuromuscular and skeletal systems [2].

According to the World Report on Disability, there are more than 1000 million people with disability worldwide, about 15% of global population. Of this number, around 93 million children is estimated to live with moderate or severe disability. The majority of this population would highly benefit from prosthetics and orthotics services, if they were available in their country. Additionally, not every person has access to prosthetic or orthotic devices, in fact, only 5-15% of the population in need has access to them. This problem is more accute in low and middle-income countries [3].

Several researches have been made to test the behavior of lower limb's exoskeletons with different characteristics. The approach of the work depends on the objectives of each research group; therefore, results vary as well. MINDWALKER exoskeleton's goal was to create a mind-controlled orthosis to help paraplegics walk. However, the balance control is partially addressed [4]. Other researches apply control schemes, which show a neat response when simulated, but vary when implemented [5] [6]. Some works present the development and testing of robotic orthosis that need a treadmill to operate, and a harness to set the patient. An example of this kind of orthosis is Lokomat, a robotic device that provides support for physiological gait training [7]. Studies have been made in order to test it [8]. Nevertheless, it is not a dynamic system, making it difficult to use when correct infrastructure is not available. The prototype presented in this paper is intended to have a certain autonomy degree, by excluding the need of a treadmill or a harness attached to some fixed structure. It is also intended to be a low-cost exoskeleton without the need of attaching the patient to some static structure, while achieving optimal system's response in reference tracking.

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Figure 1: Mechanical exoesqueleton prototype

II. Description of prototype and instrumentation

The exoskeleton used in this work was previously built by students from Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas (UPIITA) [9]. It consists of mechanical devices, including gears and spindles, electronic devices, such as electronic H bridges (to accomplish the correct performance of the electrical power stage) and opto-isolators (to guarantee electrical safety of the system), among other elements like aluminum bars and actuators. The exoskeleton also has a static structure to hold the whole system to prevent it from falling. It has an approximate weight of 8 kilos. Figure 1 shows the complete prototype employed in this manuscript and its dimensions.

In order to have a suitable system to the requirements of this work, slight improvements and modifications were made to the donated exoskeleton, including the adaptation of the power sources according to the characteristics of the electronic and electrical devices used in the exoskeleton, as well as the substitution of some elements like gears. In addition, mechanical structures were designed in order to implement sensors in the system.

Six sensors for angular position measurements were integrated into the mechanical system, these are described as lineal precision potentiometers, which have 300 degrees of angular movement. These potentiometers, used as rotational sensors, are absolute, meaning that they have a fixed value range and that they offer a variation in an electrical signal depending just on the angular position of each joint. The previous characteristics make this kind of elements ideal to measure angular position in each of the joints of the exoskeleton. Its lineal behavior allows measurement of position by previous calibration, which results in a lineal equation that depends on voltage to get a specific angle. Angular movement in every joint of lower limbs is never described by more than 300 degrees. Therefore, the range of these potentiometers makes them suitable for the exoskeleton proposed in this paper. To accomplish the implementation of the control algorithm, a microcontroller with 120 MHz 32-bit ARM Cortex M4F CPU and On-board, in-circuit debug interface (ICDI) is used. This kind of microprocessors are capable of solving advanced mathematical problems without the use of personal computers, which makes them suitable for systems like the one proposed in this paper, however, the development of discrete-time schemes is necessary to apply control algorithms in microcontrollers. Notice that this kind of technology allows an independent execution of gait cycle for the exoskeleton device. The purpose of this work is to achieve a suitable control in an exoskeleton prototype, not including tests in patients. Further work is required to attach it to lower limbs. Tracking responses can be programmed according to the therapy's needs. In this paper, the normal gait tracking signal was analyzed.

III. Control Strategy

Control strategy was designed by implementing a class of decentralized Proportional Derivative (PD) controller aided by a Super-Twisting algorithm (STA) as differentiator. This strategy simplified the execution of the controller for the exoskeleton and limited the negative effect of noises in the position measurements.

A. Mathematical description of the exoskeleton system

Notice that the complete mathematical description of the six degrees of freedom mechanical exoskeleton can be described by the following set of second order differential equations [10], [11]:

$$\begin{aligned} \dot{x}_{1,i}(t) &= x_{2,i}(t) \\ \dot{x}_{2,i}(t) &= f\left(x_{1,i}, x_{2,i}, t\right) + g(x_{1,i}(t))u(t) + \eta\left(x_{1,i}, x_{2,i}, t\right) \\ y(t) &= x_{1,i}(t) \end{aligned} \tag{1}$$

where $x_{1,i} \in \mathbb{R}$ corresponds to the position of the i-articulation of the exoskeleton (with $i = 1:6$), $x_{2,i} \in \mathbb{R}$ corresponds to the velocity of the i-articulation. $y = \begin{bmatrix} y_1 & \dots & y_6 \end{bmatrix}^\top$ is the available output of the system and each element of y is equal to the measurement of the position in each articulation of the device. The function $\eta \in \mathbb{R}$ describes parametric uncertainties in the mathematical model as well as internal perturbations or interactions by each articulation over the others (1). The reference trajectories suggested by medical specialists are defined by the following set of objective second order systems with $x^*_{1,i} = r_i$ and r_i being the desired trajectory of the i-articulation [12].

B. Sliding mode PD controller

In general, a PD controller for a SISO (single-input single-output) was designed using the following structure [13]

$$u_i(t) = -k_{1,i}e(t) - k_{2,i}\dot{e}(t) \tag{2}$$

where $k_{1,i}$ and $k_{2,i}$ are the controller gains that must be adjusted off-line and $e \in \mathbb{R}$ is the output error of each articulation given by

$$e(t) := y_i(t) - y_i^*(t) \tag{3}$$

However, the measure of $\dot{e}(t)$ was not considered to be an available output. Therefore, in classical literature, one can find two important solutions: to construct an observer or to use a first order filter to approximate the error derivative [14]. The first one required the system structure (However, in this manuscript the complete mathematical description is unavailable). In the second case, if the output information was contaminated with noise, the derivative approximation was usually deficient. One additional option was obtained considering a class of robust differentiator that can provide a suitable and accurate approximation of the error derivative. The STA has demonstrated to be one of the best robust differentiator.

C. *Super-twisting algorithm*

For the scalar case, the STA is composed by two differential inclusions. In counterpart of some others second order sliding modes algorithms, the STA can be used with systems having relative degree one with respect to the chosen output [15]. The STA has been used as a controller [16], a state estimator [17] and as a robust exact differentiator (RED) [18]. The STA application as a RED is described as follows. If $w_1(t) = r(t)$ where $r(t) \in \mathbb{R}$ is the signal to be differentiated, $w_2(t) = \dot{r}(t)$ represents its derivative and under the assumption of $|\ddot{r}(t)| \leq r^+$, the following auxiliary equation is gotten $\dot{w}_1(t) = w_2(t)$ and $\dot{w}_2(t) = \ddot{r}(t)$. These differential equations are the state representation of the signal $r(t)$. The STA algorithm to obtain the derivative of $r(t)$ looks like

$$\begin{gathered}\dot{s}_1(t) = s_2(t) - \lambda_1 |s_1(t) - w_1(t)|^{1/2} \operatorname{sign}(s_1(t) - w_1(t)) \\ \dot{s}_2(t) = -\lambda_2 \operatorname{sign}(s_1(t) - w_1(t)) \\ \\ d(t) = \dot{s}_1(t)\end{gathered} \tag{4}$$

where $\lambda_1, \lambda_2 > 0$ are the STA gains. Here $d(t)$ is the output of the differentiator [18]. In this equation,

$$\operatorname{sign}(z) := \begin{cases} 1 & if \quad z > 0 \\ [-1, 1] & if \quad z = 0 \\ -1 & if \quad z < 0 \end{cases}$$

Therefore, the STA was applied six times to obtain the derivative of the tracking error in each articulation. The control signal becomes into:

$$u_i(t) = -k_{1,i} e(t) - k_{2,i} d_i(t) \tag{5}$$

In last equation d_i is the output of the differentiator.

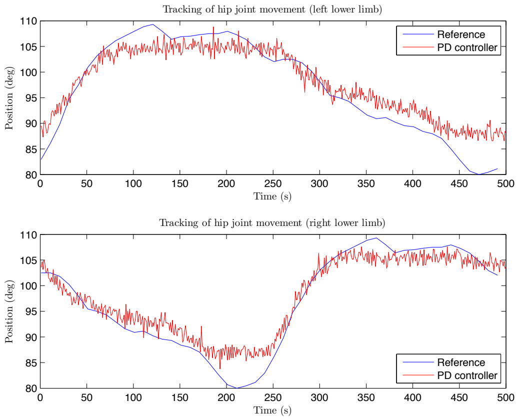

Figure 2: Angular movement tracking of hip joints

IV. Results

According to previous gait biomechanics researches [19] [20], the trajectories for each joint was proposed. Furthermore, the tracking response for the hip, knee and ankle joints is accurate (See figures 2, 3 and 4). Despite that, it is clear that the system is affected by noise in the output. This noise signal is due to electrical noise in the sensors (potentiometers). This phenomenon happens in each joint of the exoskeleton. The major impact of noise affects the estimation of time derivative for the tracking error. However the STA improves the set of PD controllers working in decentralized form. A better response can be appreciated in ankle joints' movement than in hip and knee joints. This characteristic could be a consequence of the capability of the electromechanical systems implemented to the controller. The execution of the control that justify the tracking of the reference trajectory proposed to attain the suggested therapy is the first step toward the possibility of solving the design of a robotic device for children rehabilitation. Figure 5 shows the control signal $u(t)$ described by the PWM signal needed to achieve the right angular joint movement throughout time in the hip joints. Similar results were obtained for ankle joints. The significant reduction of energy in the application of the control executed in the exoskeleton is a consequence of the accurate estimation of velocity offered by the decentralized STA design according the results in [13].

V. Conclusions

The application of a robust PD controller in a decentralized structure supported the regulation for a prototype of an exoskeleton that was designed to offer a reliable assistance for children with lower limb movement restrictions. Second Order Sliding Modes algorithms, like the STA, show great responses in systems when used as differentiators, in contrast with more classical derivative methods. Furthermore, when implemented as part of the execution of a PD controller, the close-loop

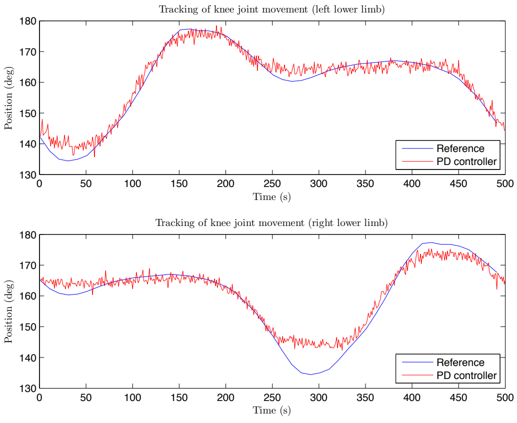

Figure 3: Angular movement tracking of knee joints

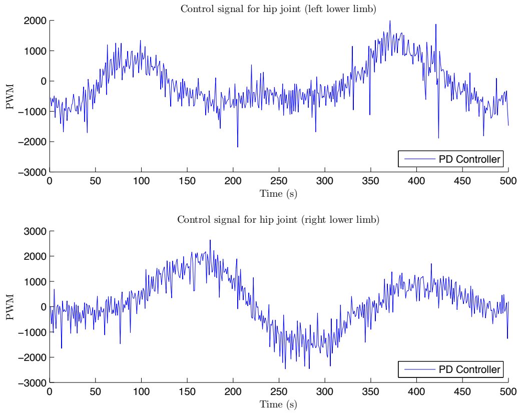

Figure 5: Control signal $u(t)$ for hip joints

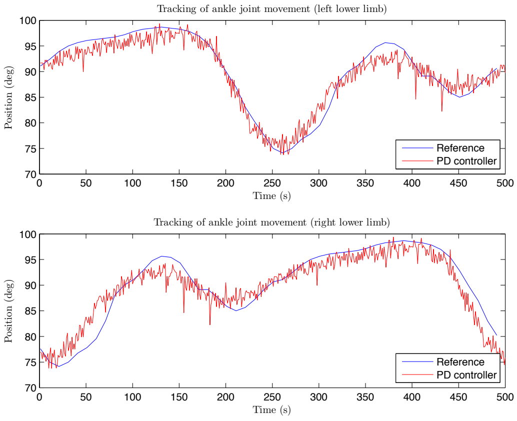

Figure 4: Angular movement tracking of ankle joints

system performance becomes accurate which is a major and necessary characteristic in the time evolution of robotic exoskeleton. However, external parameters must be taken into consideration, such as physical limitations or the capability characteristics of elements used in the implementation of the system, as well as external noise signals. In this paper, these situations were analyzed while applied to a prototype of a robotic exoskeleton meant for children lower limb rehabilitation. The solution attained in this study is the major first step toward the correct execution of the sequence of movements needed to complete the set of therapies.

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