Intelligent Tuning of Augmented L_1 Adaptive Control for Cerebral Palsy Kids Rehabilitation

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Abstract – Walking ability can be lost due to several neurological diseases. In this paper, we are interested in the rehabilitation of pediatric patients. For this purpose, an extended L_1 adaptive control has been proposed to control 2 DOF lower limbs exoskeletons used to rehabilitate kids suffering from Cerebral Palsy (CP). Two methods based on PID controllers have been combined with L_1 adaptive control in order to ensure the limb movement along a predefined trajectory. Then, a comparison study has been established based on tracking errors. Moreover, to improve the robustness of these controllers against uncertainties, several tests with the variations of children masses and lengths have been carried out, with the presence of torque limits using fuzzy logic.
Keywords – Rehabilitation, Children, Exoskeletons, PID controllers, Augmented L_1 adaptive control, Fuzzy Logic.

1 Introduction

Nowadays Robotic systems have several interests in the area of neuro-motor rehabilitation [1], the most important is their ability to interact accurately and effectively with humans [2]. For this reason, a wide number of systems, used for their rehabilitation, have been developed last years. Indeed, exoskeletons have the advantage of allowing a real control of the joint level of limbs. Exoskeletons have been developed for a wide range of applications [3] and initially from military applications [4]. Currently, these robotic orthoses are considered as the most efficient way in the walking rehabilitation [5]. Indeed, it can be defined relatively as the application of manual and/or instrumental therapeutic methods whose objectives are to restore and to recover functional abilities [6]. Hence, the objective is to consume less energy for a longer movement through space and time. Moreover, it decreases the consequences of brain damage to motor functions. The aim is, therefore, to allow the patient to re-find his independence as much as possible and to be able to move in the safest and most cost-effective way. We are interested in the following to kids [7] with the age range from 2 to 13 years old. For this reason, an augmented L_1 adaptive controller is implemented in order to take into account parameter variations. Moreover, the implementation of this control law offers the possibility of an online estimation without any requirement for any further information. In this paper, two advanced controller laws have been developed to overcome the problem of the parameter variations. The first approach consists to apply an augmented L_1 adaptive control [8] which combines the L_1 adaptive control with proportional-integral control in order to eliminate the time lag. The second approach is also based on L_1 adaptive control, but instead of the PI control, a PID control action is added. Then, a comparison study between these two approaches has been established. Besides, in order to not exceed torque limits while ensuring track desired trajectories, a fuzzy logic supervisor has been added [9]. Different scenarios have been performed dealing with parametric uncertainties to test the controller robustness. The first one deals with kids' masses uncertainties $\pm 50\%$. In the second scenario length uncertainties of $\pm 25\%$ are carried out [10]. Simulation results have been presented. Finally, brief concluding remarks and future works are detailed.

2 Description and modeling of exoskeleton

Walking is a physical activity that allows people to move from one point to another in their environment. It requires a long and a challenging learning process that eventually becomes almost automatically [11].

Walking can also be defined as a cyclical and alternative rhythmic activity lower and upper limbs requiring the mobilization of many body segments that promote the displacement of the human body in a given reference frame and for a specific purpose. In this paper, we study the walking of children with neurological disorders, known as Cerebral Palsy (CP) [7]. These children show different topographies of motor disorder, either a diplegia, hemiplegia or even a tetraplegia [12]. We focus only on children with spastic diplegia, the most common form of CP. To recover physical and social activities and the most independent way of life of these children, we are interesting in their rehabilitation [13]. For this purpose, there are currently several methods of gait rehabilitation by robotic assistance like lokomat system [14] which is based on an automatic process of the cyclical movement through intensive repetition training, carried out on a treadmill synchronized with two lower limb exoskeletons, with a partial suspension of the body [15]. In this paper, we focus just on the control of exoskeletons using adaptive controllers.

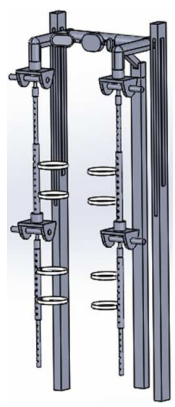

Figure 1: Design of 2 DOF exoskeletons

The condensed form of the two degrees of freedom robotic system, described in Fig.1 is written as follows:

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

with,

$$\begin{aligned} M_{11} &= J_1 + J_2 + m_2(l_1^2 + d_2^2 + 2l_1 d_2 \cos q_2) + m_1 d_1^2 \\ M_{12} &= M_{21} = J_2 + m_2(d_2^2 + l_1 d_2 \cos q_2) \\ M_{22} &= J_2 + m_2 d_2^2 \end{aligned}$$

$$\begin{aligned} C_1 &= -\Big[2m_2 l_1 d_2 \dot{q}_2 \sin q_2\Big]\dot{q}_1 - \Big[m_2 l_1 d_2 \dot{q}_2 \sin q_2\Big]\dot{q}_2 \\ C_2 &= \Big[m_2 l_1 d_2 \sin q_2\Big]\dot{q}_1^2 \end{aligned}$$

$$\begin{aligned} G_1 &= (m_1 d_1 + m_2 l_1) g \sin q_1 + m_2 d_2 g \sin(q_1 + q_2) \\ G_2 &= m_2 d_2 g \sin(q_1 + q_2) \end{aligned}$$

and where:
$q = [q_1\ q_2]^T \in \mathbb{R}^2$ is the position vector,
$\dot{q} = [\dot{q}_1\ \dot{q}_2]^T \in \mathbb{R}^2$ is the speed vector,
$\ddot{q} = [\dot{q}_1\ \dot{q}_2]^T \in \mathbb{R}^2$ is the acceleration vector,

3 Proposed Control Solution

L_1 adaptive control is divided into four principal parts which are : the controlled system, the state predictor, the adaptation mechanism and the control law including a low pass filter. The control input vector $\tau(t)$ is compound of two parts namely a fixed state-feedback term that defines the evolution of the transient response and an adaptive term that cancels system nonlinearities. Its expression is:

$$\tau(t) = A_m r(t) + \tau_{ad}(t) \tag{2}$$

where:
$A_m \in \mathbb{R}^{2\times 2}$ is a Hurwitz matrix,
$\tau_{ad} \in \mathbb{R}^{2\times 2}$ is the adaptive component.

The tracking error is expressed as:

$$r = (\dot{q} - \dot{q}_d) + \Lambda(q - q_d) \tag{3}$$

with $\Lambda \in \mathbb{R}^{2\times 2}$ is a diagonal positive and definite matrix.
The state predictor is based on estimated parameters obtained from the adaptation mechanism:

$$\dot{\hat{r}} = A_m \hat{r}(t) + \tau_{ad}(t) - \hat{\eta}(t) - K[\hat{r}(t) - r(t)] \tag{4}$$

where:

$$\hat{\eta}(t) = \hat{\theta}(t)\|r_t\|_\infty + \hat{\sigma}(t) \tag{5}$$

and the matrix gain $K \in \mathbb{R}^{2\times 2}$ is used to reject high frequency noises.
The estimate of $\theta(t)$ and $\sigma(t)$ are expressed as

$$\dot{\hat{\theta}}(t) = \Gamma\, \mathrm{Proj}\,(\hat{\theta}(t), P\hat{r}(t)\|r_t\|_\infty) \tag{6}$$

$$\dot{\hat{\sigma}}(t) = \Gamma\, \mathrm{Proj}\,(\hat{\sigma}(t), P\hat{r}(t)) \tag{7}$$

where Γ is the adaptive gain
Let's P the solution of the algebraic Lyapunov equation

$$A_m^T P + P A_m = -Q \tag{8}$$

The adaptive control is as follows:

$$\tau_{ad}(s) = C(s)\hat{\eta}(s) \tag{9}$$

where $\hat{\eta}(s)$ is the Laplace transform of $\hat{\eta}(t)$:
$C(s)$ is a bounded input, bounded output stable strictly proper transfer matrix.

3.1 Augmented L_1 Adaptive control based on a PI control

In order to eliminate the time lag [17, 18] which appears using the classical L_1 adaptive control, we propose an augmented L_1 adaptive based on PI control which is illustrated in Fig. 2.

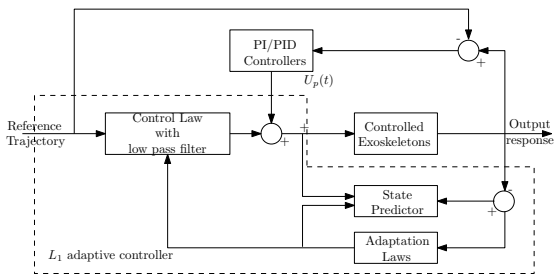

Figure 2: Block diagram of augmented L_1 adaptive control

Hence, the control input $\tau(t)$ will be expressed by:

$$\tau(t) = A_m r(t) + \tau_{ad}(t) + K_p e(t) + K_i \int e(t)dt \quad (10)$$

where K_p and K_i are diagonal positive definite matrices, and are the proportional and integral gains, respectively. $e(t)$ is the tracking error, defined by:

$$e(t) = q(t) - q_d(t) \quad (11)$$

with $q(t)$ is the system output and $q_d(t)$ is the desired trajectory.

3.2 Augmented L_1 Adaptive Control based on a PID controller

The main idea is to replace the PI controller with PID [16]. Hence, the expression of the control input $\tau(t)$ becomes:

$$\tau(t) = A_m r(t) + \tau_{ad}(t) + K_p e(t) + K_i \int e(t)dt + K_d \dot{e}(t) \quad (12)$$

where K_p, K_i and K_d are diagonal positive definite matrices, and are the proportional, integral and derivative gains, respectively. $e(t)$ is the tracking error and $\dot{e}(t)$ its differential defined by:

$$\dot{e}(t) = \dot{q}(t) - \dot{q}_d(t) \quad (13)$$

3.3 Fuzzy logic supervisor used for torque limitations

It is to be noted that when the error is large (in particular at the beginning) torques are too high in such a way they exceed their limits. For these reasons, we propose to use two fuzzy systems as supervisors which deliver adequate torques.

The input x_i of the fuzzy system i (i =1,2) is the absolute value of the torque τ_i (x_i=$|\tau_i|$).
Its output is the applied torque: τ_{ai}. x_i is quantified into two fuzzy logic subsets as indicated in Fig. 3 (S: Small, L: Large) Then, two fuzzy rules are described as:

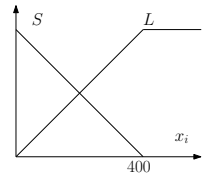

Figure 3: Fuzzy logic supervisor

- If (x_i is S) then $\tau_{ai} = \tau_i$
- If (x_i is L) then $\tau_{ai} = \alpha_i \tau_i$

with α_1=0.1 and α_2=0.05.

4 Simulations Results

In this section, simulation results of the proposed control are presented and compared. Two different scenarios have been accomplished: The first one deals with the nominal case and the second one deals with the parametric uncertainties.

- Scenario 1: Nominal case. In this scenario, a comparison study between augmented L_1 adaptive control with PI control and PID control is established in nominal cases and applied for the mean value of masses and lengths.
- Scenario 2: Robustness towards parameter uncertainties. In this scenario, variations of ±50% on masses and ±25% on lengths variation have been considered with the limitation of the control input using fuzzy logic approach. The objective is to investigate the robustness of this controller against parametric uncertainties.

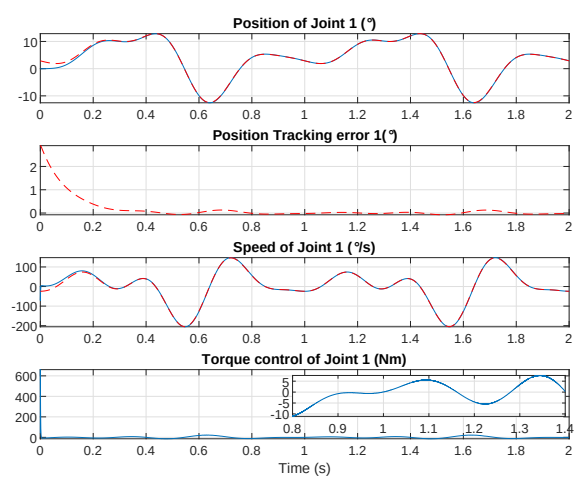

Figure 4: Augmented L_1 adaptive control of hip joint with PI control in the nominal case, dashed line: desired trajectory, continuous line: actual trajectory.

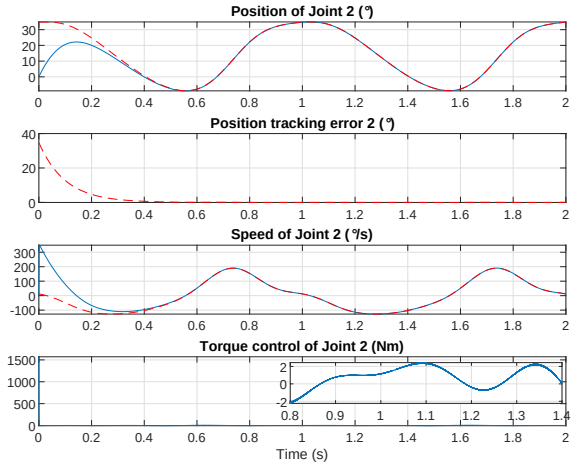

Figure 5: Augmented L_1 adaptive control of knee joint with PI control in the nominal case, idem as Fig. 4.

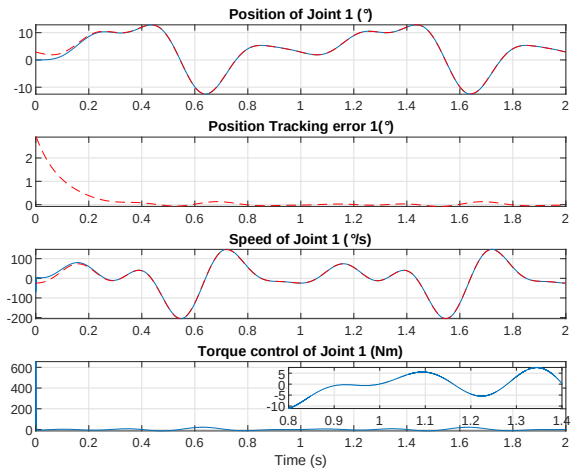

Figure 6: Augmented L_1 adaptive control of hip joint with PID control in the nominal case, dashed line: desired trajectory, continuous line: actual trajectory.

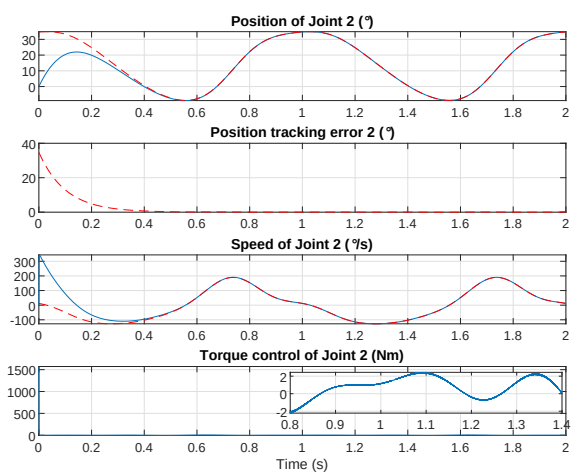

Figure 7: Augmented L_1 adaptive control of knee joint with PID control in the nominal case, dashed line: desired trajectory, continuous line: actual trajectory.

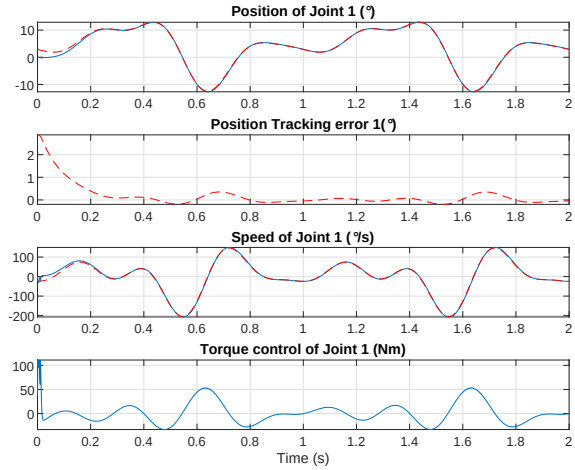

Figure 8: Robustness against 50% of masses and 25% of length uncertainties using Fuzzy logic of hip joint, idem as Fig. 6.

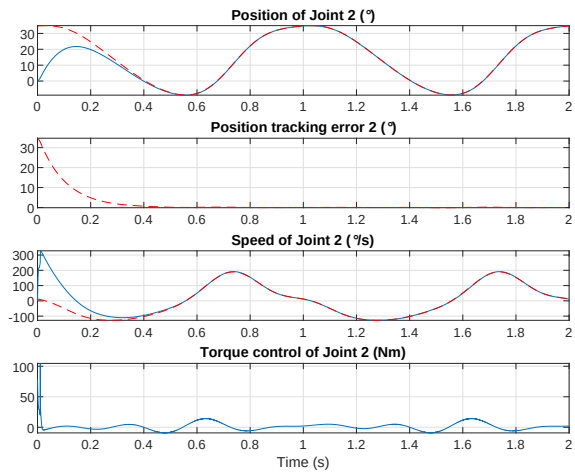

Figure 9: Robustness against 50% of masses and 25% of length uncertainties using Fuzzy logic of knee joint, idem as Fig. 6.

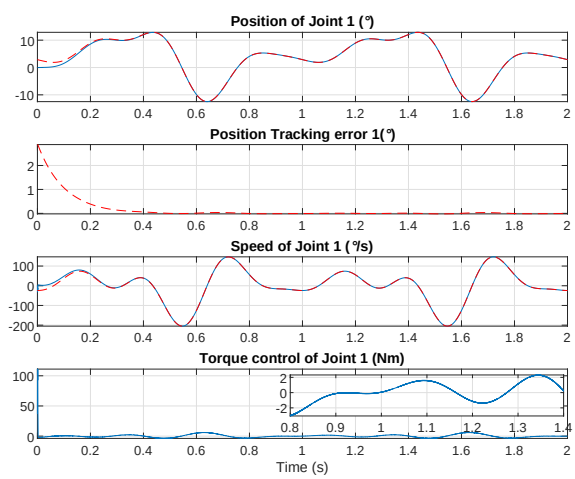

Figure 10: Robustness against –50% of masses and –25% of length uncertainties using Fuzzy logic of hip joint, idem as Fig. 6.

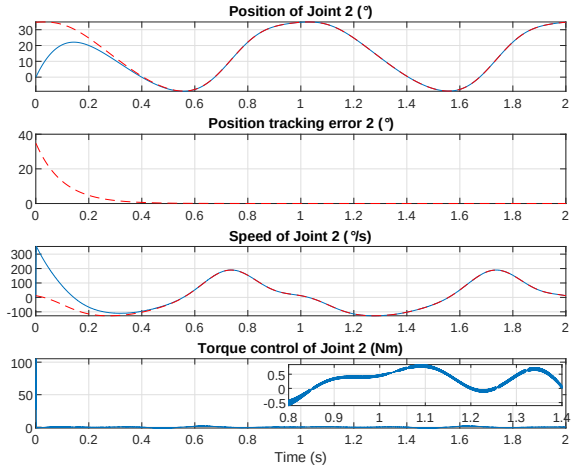

Figure 11: Robustness against –50% of masses and –25% of length uncertainties using Fuzzy logic of knee joint, idem as Fig. 6.

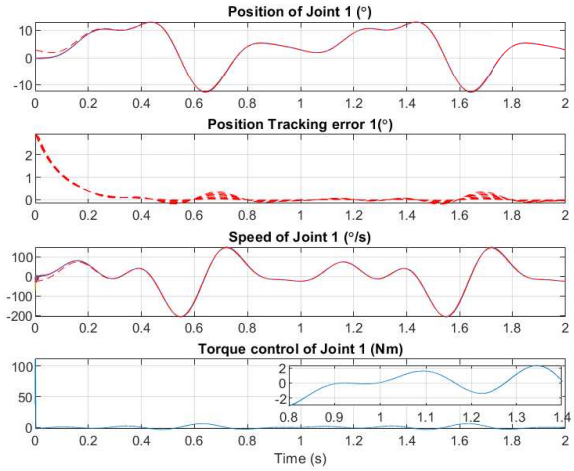

Figure 12: Robustness against –50%, –40%, –30%, –20% of masses and –25%, –20%, –15%, –10% of length uncertainties using Fuzzy logic for hip joint.

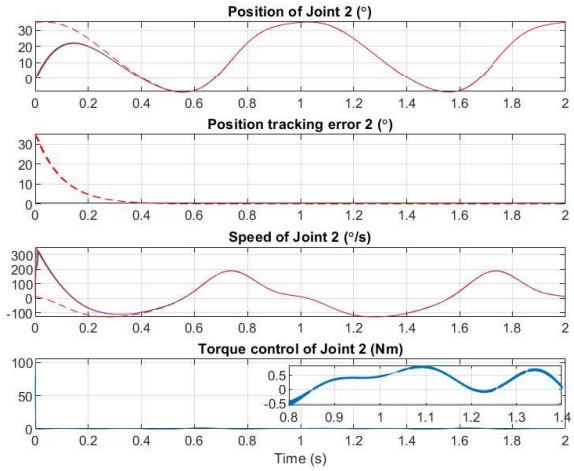

Figure 13: Robustness against –50%, –40%, –30%, –20% of masses and –25%, –20%, –15%, –10% of length uncertainties using Fuzzy logic for knee joint.

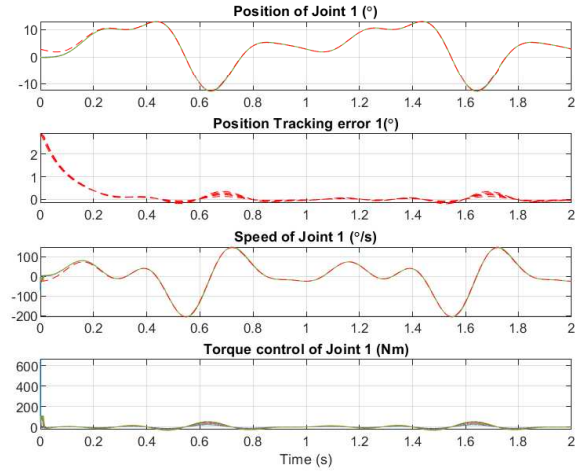

Figure 14: Robustness against 50%, 40%, 30%, 20% of masses and 25%, 20%, 15%, 10% of length uncertainties using Fuzzy logic for hip joint.

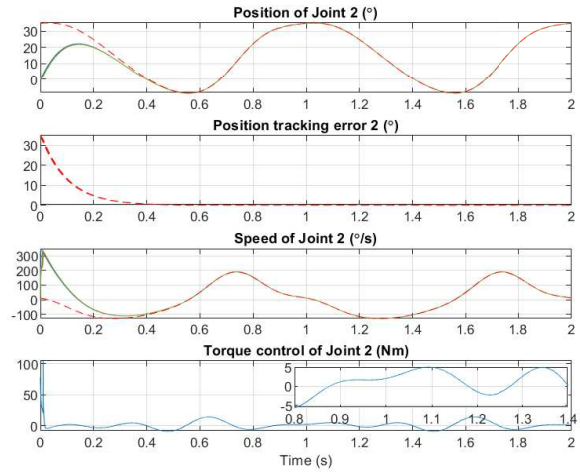

Figure 15: Robustness against 50%, 40%, 30%, 20% of masses and 25%, 20%, 15%, 10% of length uncertainties using Fuzzy logic for knee joint.

In these figures, we can observe the evolution of the position of hip and knee joints, their speed and their applied torques. Moreover, we have drawn the evolution of position errors. Figures. 4, 5, 6 and 7 present the evolution of positions, speeds, applied torques and position errors in the nominal case. In fact for both PI and PID controllers, we obtain a well-tracked trajectory with the same tracking error values.
In the following, we will focus on the augmented L_1 adaptive control based on PI controller.
Figures. 8, 9, 10 and 11 show the evolution of positions, speeds, applied torques and position errors via $\pm 50\%$ uncertainties on the total masses and $\pm 25\%$ uncertainties on the lengths. In order to check the robustness of the augmented L_1 adaptive control, several cases corresponding to uncertainties of $\pm 50\%$, $\pm 40\%$, $\pm 30\%$ and $\pm 20\%$ on the masses and of $\pm 25\%$, $\pm 20\%$, $\pm 15\%$ and $\pm 10\%$ on lengths, have been estab-

lished and simulation results are shown in figures 12, 13, 14, 15. Moreover, to limit the applied torque, the use of a fuzzy logic supervisor gives adequate results shown on figures. 8, 9, 10, 11, 12, 13, 14, 15.
Thus, it is well obvious the good performances observed by the augmented L_1 adaptive control.

5 Conclusions

In the present paper, two controllers have been combined with L_1 adaptive control aiming to eliminate the time lag. Through simulations, it has been shown that PI and PID yield the same performances. For this reason, a PI-augmented L_1 adaptive control is considered as the better controller regarding performances. Moreover, two fuzzy systems have been proposed as supervisors in order to achieve adequate torques. Indeed, the tracking error decreases rapidly. This method guarantees the robustness against parametric uncertainties such as lengths and masses since kids' age range is between 2 and 13 years old.

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