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Haptic Training Method Using a Nonlinear Joint Control

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Abstract— There are many research works on robotic devices to assist in movement training following neurologic injuries such as stroke with effects on upper limbs. Conventional neurorehabilitation appears to have little impact on spontaneous biological recovery; to this end robotic neurorehabilitation has the potential for a greater impact. Clinical evidence regarding the relative effectiveness of different types of robotic therapy controllers is limited, but there is initial evidence that some control strategies are more effective than others. This paper consider the contribution on a haptic training method based on kinesthetic guidance scheme with a non linear control law (proxybased second order sliding mode control) with the human in the loop, and with purpose to guide a human user´s movement to move a tool (pen in this case) along a predetermined smooth trajectory with finite time tracking, the task is a real maze. The path planning can compensate for the inertial dynamics of changes in direction, minimizing the consumed energy and increasing the manipulability of the haptic device with the human in the loop. The Phantom haptic device is used as experimental platform, and the experimental results demonstrate.

Index Terms—Diagnosis and rehabilitation, haptic guidance, sliding mode control, path planning, haptic interface, passivity and control design.

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1 Introduction

IN the least decade the number of patients who have suffere accidents stroke or traumatic brain injuries have increase considerably [1]. The central nervous system damage can lea to impaired movement control upper extremities, which ar facing major difficulties in relation to the activities of daily life. Several studies showed that the rehabilitation therapy which is based on motion-oriented tasks repetitive, it help to improve the movement disorder of these patients [2], [3]. Unfortunately repeatability therapy requires consistency, time for physicians and therefore money.

Conventional neurorehabilitation appears to have little impact on impairment on spontaneous biological recovery. Robotic neurorehabilitation has potential for a greater impact on impairment due to an easy deployment, its applicability across of a wide range of motor impairment, its high measurement reliability, the capacity to deliver high dosage of training protocols and high intensity in the exercises. This situation economic rehabilitation. With the purpose of enhance the relationship between outcome and the costs of rehabilitation robotic devices are that being introduced in clinical rehabilitation [4], [5]. Rehabilitation using robotic devices not only has had an important contribution in this area but also has introduced greater accuracy and repeatability of rehabilitation exercises. Accurate measurement quantitative parameter using robotic instrumentation is a tool that accomplishes the goal of the patient's recovery.

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1.1 Justification

As care is decentralized and moves away the inpatient settings to homes, the availability of technologies can provide effective treatment outside, the acute care of the hospital would be critical to achieve sustainable management of such diseases. In the field of neuromotor rehabilitation, skilled clinical managers and therapists can achieve remarkable results without using technological tools or with rudimentary equipment, but such precious human capital is in very short supply and, in an case, is totally insufficient to sustain the current demographic.

Robots are particularly suitable for both rigorous testing and application of motor learning principles to neurorehabilitation. Computational motor control and learning principles derived from studies in healthy subjects are introduced in the context of robotic neurorehabilitation. There is an increasing interest in using robotic devices to provide rehabilitation therapy following neurologic injuries such as stroke and spinal cord injury. The general paradigm to be explored is to use a robotic device to physically interact with the participant's limbs during movement training, although there is also work that uses robot that do not physically contact the patients [6].

1.2 The Problem

Some of the problems presented by a motor rehabilitation of patients who have suffered a brain injury, is the time rehabilitation takes place, the cost that this entails, poor information that the specialist has to determine the diagnosis of a patient in rehabilitation, and the lack of platforms for rehabilitating patients who cannot assist to the hospital and require continued rehabilitation.

1.3 Our Proposal

One technique used to solve the problem of generating rehabilitation platforms using robotic systems is haptic guidance, this technique is based on the use of haptic devices, which allow human-machine interaction. These haptic devices are programmed under certain considerations, such as considering the safety of the patient during the interaction, the physiology of the patient in order to generate tracking trajectories that allow proper rehabilitation, and so on. In this paper is proposed to generate a trajectory based on the solution of mazes in 2D and the haptic device guides the patient under a control law, which is designed with certain characteristics that allow coupling among the patient, the device and the trajectory. The haptic device is equipped with optical encoders, this allows obtaining data such as position, velocity, acceleration, force and torque, these data in combination with other data allow to the specialist to generate a clinical diagnosis, which has therapeutic support based on the patient's movements in eac exercise performed on the platform.

1.3 Organization

In section 2, we introduce the human-haptic interaction, including the haptic scheme, the dynamic model of the haptic device and the guidance control law implemented in the experimental platform. The description task and the path planning for guiding to the experiments are given in section 3; experimental results are discussed in 4. Finally, we presen the conclusions in section 5.

3 Human-Haptic Interaction

The haptic feedback has also been developed for task oriented biofeedback studies [7]. Haptic interfaces allow the patient to interact with and to manipulate a virtual object or real. Results [8] have shown that haptic information provides knowledge of results (KR) and kinaesthetic fed back, sensation that are important for task performance.

3.1 Haptic Guidance Sheme

For the human participation in the system, there are two haptic guidance applications: active and passive. The first allows the user to guide the robotic system (haptic device) in the workspace to explore. However, in the passive haptic guidance, the user is guided in the workspace with the position and velocity control strategies. On the other hand, kinesthesis is the human sense of position and movement, which is created from proprioceptive cues arising from receptors in the joints and muscles [9]. Thanks to kinesthetic memory, or the ability to remember limb position and velocity, humans have a remarkable ability to remember positions of their limb quite accurately and for long periods [10].

3.2 Haptic Device Dynamics

Consider a mechanism of articulate links (PHANToM 1.0 [11]), with n revolute joints described in the generalized join coordinates $(q^T, \dot{q}^T)^T \in R^{2n}$. Physically, the robot is never in touch with a physical object, thus robot dynamics in free motion describe properly the haptic device, as fol lows

$$D(q)\ddot{q} + (C(q,\dot{q}) + B)\dot{q} + G(q) = \tau \qquad (1)$$

Where $D(q) \in R^{3x3}$ denotes a symmetric positive definite inertial matrix, $C(q,\dot{q}) \in R^{3x3}$ is a Coriolis and centripetal forces matrix, $G(q) \in R^{3x1}$ models the gravity forces vector, $B \in R^{3x3}$ denotes a symmetric positive definite viscous coefficient matrix, and $\tau \in R^{3x1}$ stands for the torque input. In our case the human operator is driving the system, therefore $\tau = \tau_c + \tau_h$, and $\tau_c \in R^{3x1}$ stands for the guidance control, and $\tau_h = J^T f_h$ denotes the human-haptic interaction, where J^T stands for the transpose Jacobian of the haptic device, an fh represents the human performance force vector.

3.3 Guidance Control Law

The design of a control strategy applied to haptic guided must meet certain objectives such as: giving stability in human-machine interaction, presenting high robustness against disturbances generated by the human operator and currently meeting the objective to rehabilitate, this can be corroborated with an analysis clinical examined by specialists.

3.4 Properties of Euler-Lagrange Systems

The dynamic equation for manipulator robots (1) has instrusting follow properties [12]:

- There exists some positive constant α such that

  $$D(q) \geq \alpha I \quad \forall q \in R^n$$

  Where I denotes the nxn identity matrix. The $D(q)^{-1}$ exist and this is positive definite.

- The matrix $c(q,\dot{q})$ have a relationship with the inertial matrix as:

  $$\dot{q}^T \left[\frac{1}{2}\dot{D}(q) - C(q,\dot{q}) \right] \dot{q} = 0 \ \ \forall q, \dot{q} \in R^n$$

((

- The Euler-Lagrange system have the total energy as:

  $$\varepsilon = k + u \qquad (2)$$

Where k is the kinetic sum for each coordianate, and u are the potencial energy respectively.

The kinetic energy is obtained by:

$$k = \frac{1}{2}\sum_{i=1}^{n} m_i v_i^2 = \frac{1}{2}\dot{q}^T D(q)\dot{q} \qquad (3)$$

Where $m_i \in R$ are the *i* mass of the *i* link, $v_i \in R^n$ are the *i* velocity of the *i* link.

The potencial energy is obtained by:

$$u = \sum_{i=1}^{n} m_i h_i g \tag{4}$$

Where $h_i \in R^n$ are the *i* height of the *i* link respect to mass center and g is a gravitational constant. By differentiating (2) we obtain

$$\begin{aligned}\dot{\varepsilon} &= \dot{q}^T D(q)\dot{q} + \frac{1}{2}\dot{q}^T \dot{D}(q)\dot{q} + \dot{q}^T G(q)\\ &= \dot{q}^T\left[-C(q,\dot{q}) - G(q) + \tau\right] + \frac{1}{2}\dot{q}^T \dot{D}(q)\dot{q} + \dot{q}^T G(q)\\ &= \dot{q}^T \tau\end{aligned} \tag{5}$$

- From the passivity property we have that:

$$V(x) - V(0) \le \int_0^t y^T(s)u(s)ds \tag{6}$$

Where $V(x)$ is a storage function, $y(s)$ is the output, and $u(s)$ is the input of the system, and *s* is a variable change. Using (5) for the Euler-Lagrange system, energy function ε as the storage function, and we have the passivity property as:

$$\varepsilon(t) - \varepsilon(0) \le \int_0^t \dot{q}^T \tau \, dt \tag{7}$$

Where $\dot{q}$ is the output, and τ is the input of the sys tem.

3.5 Passivity of the Dynamic Error

The described passivity property presents an interesting property in the regulation problem on Euler-Lagrange systems, however this property can be extended for the trajectory tracking problem solution, [13] drive this passive erro dynamic property, as follow for:

$$D(q)\dot{s} + \left[C(q,\dot{q}) + K_d(q,\dot{q})\right]s = 0 \tag{8}$$

Where s denotes an error signal that we want to drive to zero, $k_d(q,\dot{q}) = k_d(q,\dot{q})^T > 0$ is a damping injection matrix. Based on this property and the skew-symmetric properly we follow the next lemma:

Lemma 1: The differential equation:

$$D(q)\dot{s} + \left[C(q,\dot{q}) + K_d(q,\dot{q})\right]s = \psi \tag{9}$$

Where $D(q)$ and K_d are positive matrices and $C(q,\dot{q})$ satisfies (8) it defines an output strictly passive operator $\sum_d : \psi \to s$. Consequently, if $\psi \equiv 0$ we have $s \in L_2$;

With the Lemma 1, and the dynamic properties, we can follow a control law design. In this paper we obtain the control technique via Lyapunov theory, dynamical and passivity properties.

4 DESIGN OF A NONOLINEAR JOINT CONTROL BASED ON PASSIVIT

Given a designated trajectory $q_d(t)$, can be considered as a Lyapunov function as follows [14]:

$$V(s) = \frac{1}{2}s^T D(q)s + \int s^T K_L \int \tanh(s)dsds + c \tag{10}$$

Where c >>1, $s = [s1, s2, .., sn]^T$ denote dynamic error, the function $\tanh(s) = [\tanh(s1), .., \tanh(sn)]^T$ and K_L are a symeyric positive definite matrices.

Given that (10) is a positive semidefinite function, obtain the derivative of the Lyapunov candidate function, so that is follows [1]:

$$\dot{V}(s) = \frac{1}{2}s^T D(q)\dot{s} + \frac{1}{2}s^T \dot{D}(q)s + \frac{1}{2}\dot{s}^T D(q)s + s^T K_L \int \tanh(s)ds \tag{11}$$

Simplifyng (11)

$$\dot{V}(s) = s^T D(q)\dot{s} + \frac{1}{2}s^T \dot{D}(q)s + s^T K_L \int \tanh(s)ds \tag{12}$$

As saw in (12), we applied lemma 1, and use the follow result:

$$D(q)\dot{s} = \psi - \left[C(q,\dot{q}) + K_d\right]s \tag{13}$$

Where ψ are the system dynamics

$$\begin{aligned}\psi &= \tau - \left[D(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + F(\dot{q})\right]\\ &= \tau - Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\phi\end{aligned} \tag{14}$$

Where $\dot{q}_r$ and $\ddot{q}_r$ are the nominal references, $Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r) \in R^{nxp}$ is the regressor of known nonlinear terms $\phi \in R^p$ is the vector of unknown parameters, so that (13) is as follows:

$$D(q)\dot{s} = \tau - Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\phi - \left[C(q,\dot{q}) + K_d\right]s \tag{15}$$

Using (15) and (12) as follows:

$$\dot{V}(s) = s^T\left[\tau - Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\phi - \left[C(q,\dot{q}) + K_d\right]s\right] + \frac{1}{2}s^T \dot{D}(q)s + s^T K_L \int \tanh(s)ds \tag{16}$$

$$\dot{V}(s) = s^T\left[\tau - Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\phi - K_d s\right] - s^T C(q,\dot{q})s + \frac{1}{2}s^T \dot{D}(q)s + s^T K_L \int \tanh(s)ds \tag{17}$$

Applying the antisymmetric property in (17), it reduces to the following expression:

$$\dot{V}(s)=s^T\left[\tau-Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\phi-K_d s+K_L\int\tanh(s)ds\right] \quad (18)$$

For asymptotic convergence (Lyapunov stability theorem) is required $\dot{V}(s)\le 0$, in this case a function is designed $\dot{V}$ as follows:

$$\dot{V}(s)=-s^T K_D s\le 0 \quad (19)$$

$$\dot{V}(s)=-s^T K_D s=s^T\begin{bmatrix}\tau-Y_r(q,\dot{q}.\dot{q}_r,\dot{q}_r)\phi-K_d s\\ +K_L\int\tanh(s)ds\end{bmatrix} \quad (20)$$

In (20), can be reduced to the following expression:

$$-s^T K_D s=s^T\begin{bmatrix}\tau-Y_r(q,\dot{q}.\dot{q}_r,\ddot{q}_r)\varphi-K_d s\\ +K_L\int\tanh(s)ds\end{bmatrix} \quad (21)$$

Solving for τ in (21) is obtained:

$$\tau=Y_r(q,\dot{q}.\dot{q}_r,\dot{q}_r)\phi+K_d s-K_D s$$
$$-K_L\int\tanh(s)ds \quad (22)$$

Where $K_D > k_d$, so that $K_d s-K_D s$ can be written as $-k_{ds}s$, therefore the control law for systems n degrees of freedom can be written as:

$$\tau=Y_r(q,\dot{q}.\dot{q}_r,\dot{q}_r)\phi-K_{ds}s-K_L\int\tanh(s)ds \quad (23)$$

Given that $Y_r(q,\dot{q}.\dot{q}_r,\dot{q}_r)\phi$ is upper bounded, we propose modified control law as:

$$\tau=-K_{ds}s-K_L\int\tanh(s)ds \quad (24)$$

5 EXPERIMENTAL PLATAFORM FOR DIAGNOSIS AND REHABILITATION

The purpose of this paper is to generate the experimental platform, which permit an effective medical rehabilitation in the shortest time possible, also provide information for a medical diagnosis. The experimental platform consists of the patient with physical disability doing recovery exercises, these exercises are based on the solution maze. The desired trajectory is programmed into the device PHANToM háptico premium 1.0 [11], this device guides the patient on the maze.

The patient is stimulated in a kinesthetic way (related to muscle and tendons) by the haptic device, however the environment with which interacts is real, the labyrinth is made of wood but the desired trajectory is programmed into th device.

In the Fig.1 presents the haptic guidance system, where X_r is the reference position of the desired trajectory, $\dot{X}_r$ determines the reference velocity of the trajectory, previously evaluated under the best conditions for interaction. Because the design control signal was

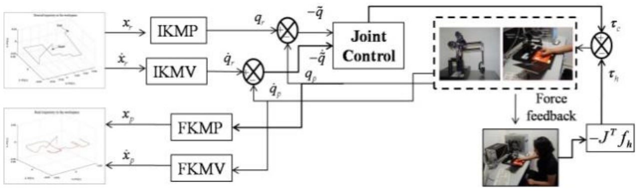

Fig. 1. Haptic guidance system[15]

performed with the joint space required to use models IKMP (Inverse Kinematic Model Position) and IKMV (Inverse Kinematic Model Velocity), so qr is obtained which represents the vector of desired joint positions and $\dot{q}_r$ is the vector of desired joint velocity, in this way is obtained qp which represents the vector of real joints position and $\dot{q}_r$ represents the vector of real joints velocities. By getting the joint position errors and velocity articulated errors , they are used in the joint control to generate the vector of torques. The patient is manipulated by the haptic device, but the patient disrupts desired tracking trajectory, the perturbation (in position and velocity) is obtained by reading optical encoders mapping is performed after the joint space to the operational space to display the operational positions and velocities.

5.1 Phantom Haptic Device Platform

The experimental platform consists of a PC running at 1.4 GHz with two AMD Athlon processor, 1 Gb RAM, 64 Mb NVIDIA GeForce 4Mx and Visual C++ as a programming language over Windows XP. The haptic device used is PHANToM premium [11], provide 3 degrees of freedom positional sensing and 3 degrees of freedom force feedback, and connects to the PC via the parallel port (EPP) interface.

5.2 Phat Planning For Guidance

The patient is guided in the real world by the end effector of PHANToM 1.0, in order to solve a maze constructed of wood, the guidance in the maze has a duration is 23.5 seconds. In the Fig. 2 shows the workspace where they are

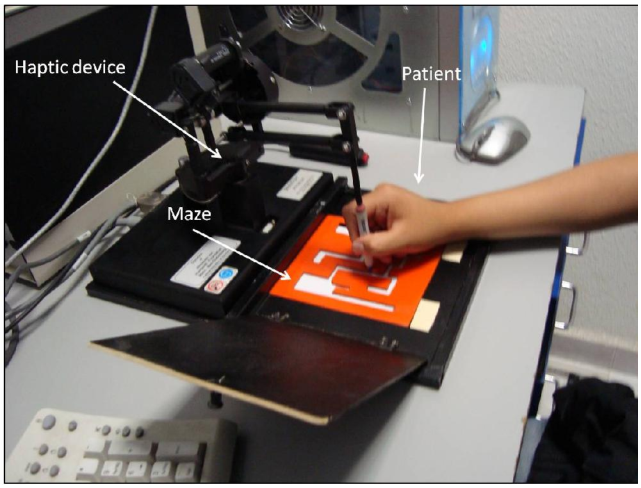

Fig. 2. Experimental platform

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held on the rehabilitation of patients.

The polynomials that represent the trajectories of the solution maze (see Fig. 3) are based on equations; they represent the position, velocity and acceleration of the trajectory. The polynomial of the position is as follows,

$$\xi(t) = a_3 \frac{(t-t_0)^3}{(t_b-t_0)^3} - a_4 \frac{(t-t_0)^4}{(t_b-t_0)^4} + a_5 \frac{(t-t_0)^5}{(t_b-t_0)^5} \tag{25}$$

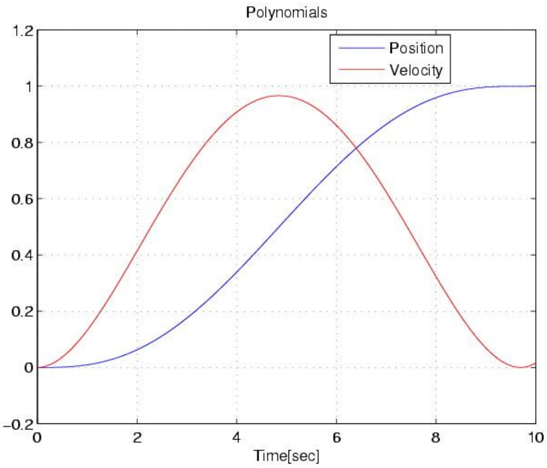

Fig. 3. Performance of polynomials ξ and $\dot{\xi}$.

The polynomial $\xi(t)$ corresponds to a smooth trajectory to the start and end time, which breaks with the inertial effects due to the state of repose and movement (see Fig. 3), t is the time, t_0 represents the initial time and tb determines at the time of convergence. To obtain the velocity is necessary to derive the polynomial $\xi(t)$ with respect to time, and the acceleration has to derive the polynomial twice with respect to time. To determine the values of a_3; a_4 and a_6 is done as follows, with the conditions $\xi(t_0)=0$, $\dot{\xi}(t_0)=1$, $\xi(t)=0, \dot{\xi}(t_b)=0$ and $\ddot{\xi}(0.5t_b)=0$, so solving the equations and is obtained that $a_3=10$, $a_4=15$ and $a_5=6$.

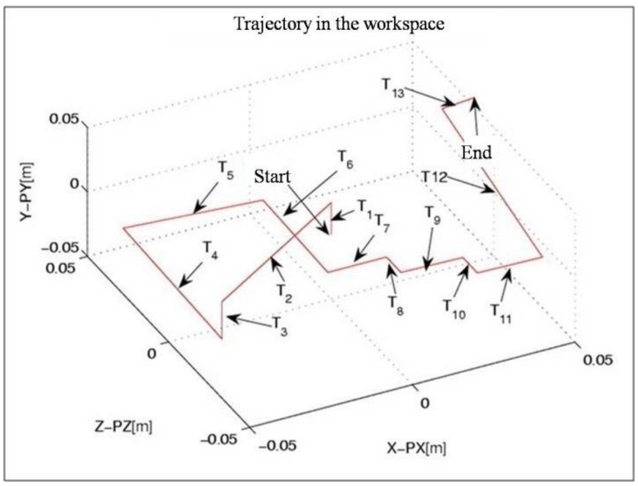

Fig. 4. Path planning

This way we perform the task planning considering convergence in finite time (see Fig. 3). The characteristics that have the polynomials design allows a patient to be guided at the beginning of the exercise: smoothly increasing velocity and decreasing when the trajectory is about to end. In Table I is presented the start and the end time for each trajectory represent in the Fig.4.

TABLE 1
INITIAL AND CONVERGENCE TIME OF THE TASKS PRESENTED IN FIG. 4

Task	Initial time	Finite time convergence
T_1	0 sec.	t_{b1}=1 sec.
T_2	1 sec.	t_{b2}=3 sec.
T_3	5 sec.	t_{b3}=1 sec.
T_4	6 sec.	t_{b4}=2 sec.
T_5	8 sec.	t_{b5}=1.5 sec.
T_6	9.5 sec.	t_{b6}=1 sec.
T_7	10.5 sec.	t_{b7}=1 sec.
T_8	11.5 sec.	t_{b8}=1 sec.
T_9	12.5 sec.	t_{b9}=1 sec.
T_{10}	13.5 sec.	t_{b10}=1 sec.
T_{11}	14.5 sec.	t_{b11}=1 sec.
T_{12}	15.5 sec.	t_{b12}=4 sec.
T_{13}	19.5 sec.	t_{b13}=3 sec.

5.3 The Inertial Dynamics Effects

Convergence in finite time by the position and velocity trajectory is reflected in accelerating $\ddot{q}_r$, this benefits the task planning. Fig.5 shows the inertial torque $\tau_H = D(q)\ddot{q}$ using the patient acceleration generated in the exercise.

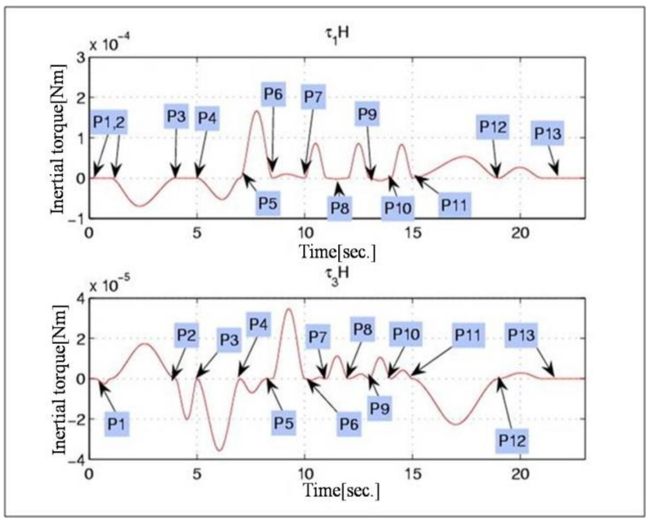

Fig. 5. Inertial torques one and trhee

However D(q) corresponds to the matrix of inertia of the haptic device. In P0, P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12 and P13 inertia is minimal due to the benefit of the task planning, and the design of the control law that allows stable tracking [16].

6.1 The Experiments

Rehabilitation process consists on patient performance of ten exercises, which have different characteristics under certain parameters. Here are the characteristics of each exercise:

1. Exercise 0.-The patient is guided to follow up the trajectory, in this exercise haptic device actuators are zero, and this way the patient voluntarily moves the PHANToM end effector (see Fig.6).

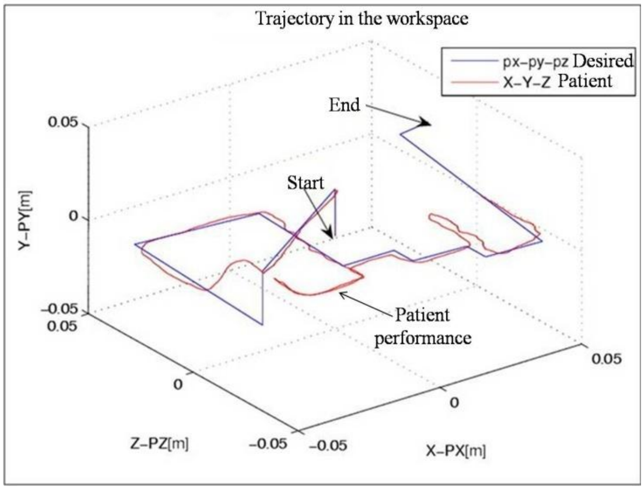

Fig. 6. Exercise 0 (uncontrolled).The patient's performance in the first experiment without control. The patient is not guided by the haptic device PHANToM.

2. Exercise 1-10.-The patient is guided by PHANToM considering the control signal in (24). The constants have the following value $K_{ds} = 0.03$ and $K_L = 0.009$.
3. Exercise 11.-The patient performs the last exercise with the same features as the first, without control in the actuators (see Fig.8). The patient is free movement during the experiment. He controls his movements.

The Fig.7 shows the performance PHANToM 1.0 workspace, the patient has a certain disturbance index during the haptic guidance. Finally, Fig.8 illustrates the performance of the last exercise of patient, this to control the actuators.

6.2 Stability Analysis

The nonlinear control design described in 24 is a robust control that allows a stable man-machine interaction. Control design is based on Lyapunov theory (second method) and passivity. It is well known that one of the techniques to analyze stability is through the behavior of the Lyapunov function (10) and their respective derivative (20).

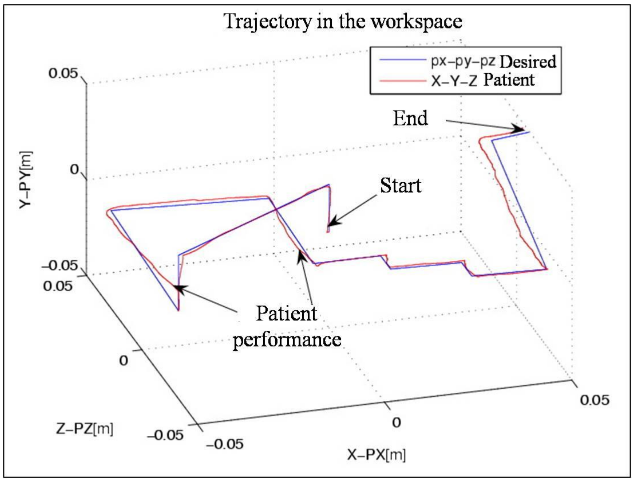

Fig. 7. Exercise 1 (with control) . The patient is guided for 10 times continuously. This allows for success in motor performance

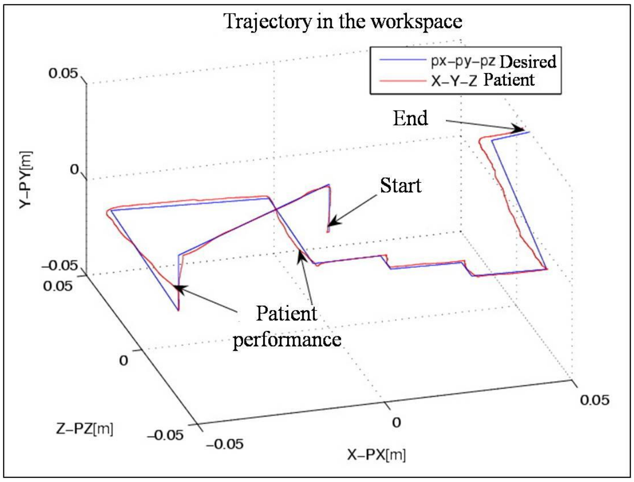

Fig. 8. Exercise 1 (with control) . The patient is guided for 10 times continuously. This allows for success in motor performance

If the candidate Lyapunov function is defined postive in every instant of time and also the derivative with respect to time of the Lyapunov function is negative semidefinite then the system is stable. In order to know if the system (human machine interaction) was stable it is necessary to consider the behavior of the functions described above.

In Fig 9 shows the behavior of the Lyapunov function of Exercise 1. The function is always positive definite, therefore the system is stable with the patient in the control loop.

On the other hand the derivative of the Lyapunov function is shown in Fig 10. The function is negative semidefinite at all times, so that the system is stable at all times. Disturbances of the patient during the interaction are reflected in the impulses that show the functions.

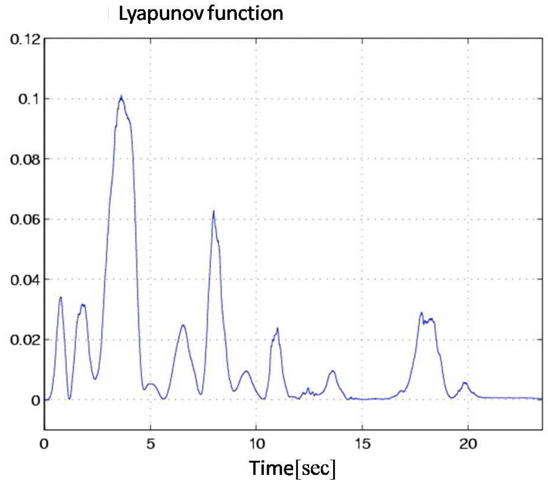

Fig. 9. The graph that describes the behavior of the Lyapunov function permirte note that the function was always positive definite, but at certain moments presented impulses, this is due to disturbances of the patient

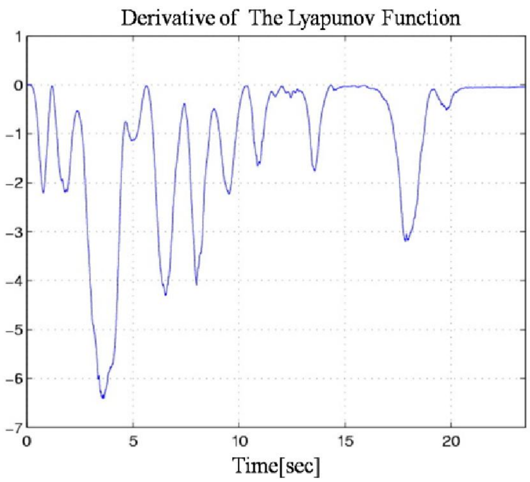

Fig. 10. The high disturbances generated by the patient did not prevent the system was unstable.

Considering the forces on individual fingers, which should be under 30 to 50N in total and the average force that humans can exert on the index finger is 7N, 6N middle finger and ring finger without experiencing 4.5N discomfort or fatigue. It is important that the control signal in the actuators of the haptic device does not exceed the force of 7N. Thus patient safety prevails in closed loop and increasing the useful life of the device. In order to ensure patient safety is necessary to observe the behavior of the nonlinear control law.

In Fig 11 shows the control signal of the three actuators which does not exceed 7N. Because the design of the control law is based on theories that allow for energy analysis and pasivisar the system with the patient in the control loops.

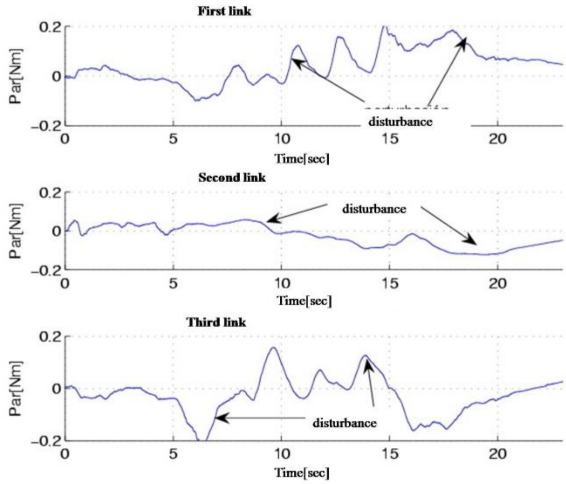

Fig. 11. The interference generated by the patient is reflected in instantaneous changes of the control signal in the three actuators.

6.3 Discussions

In the Fig.12 and Fig.13 present the graphs representing the rehabilitation of the patient during each of the 10 exercises. In each of the experiments $\sum|\tau|$ were performed, measuring the disturbance index that the patient generated during each exercise and then assess the performance and learning via the control signals (see Fig. 9A). The disturbance of the patient influences the dynamic error signals S, in each exercise is calculated $\sum|S|$ and is plotted as shown in Fig. 13.

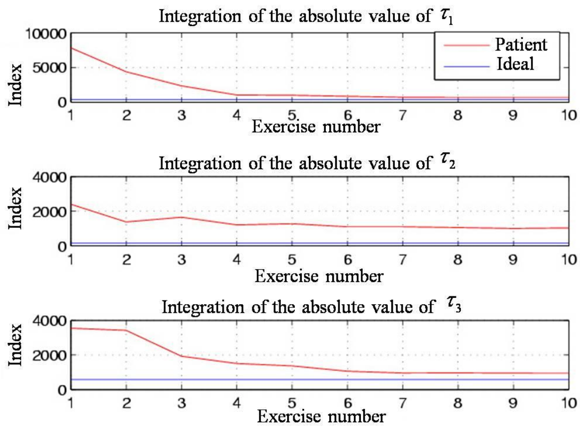

Fig. 12. The performance of the patient in the rehabilitation process is presented in this graphic.

Based on the data obtained, the comparison between the initial results (exercise 1) and the end (exercise 10) results, shows that the patient acquires the ability to solve the maze and also that her motor movements are recovered gradually as the number of exercises is increased.

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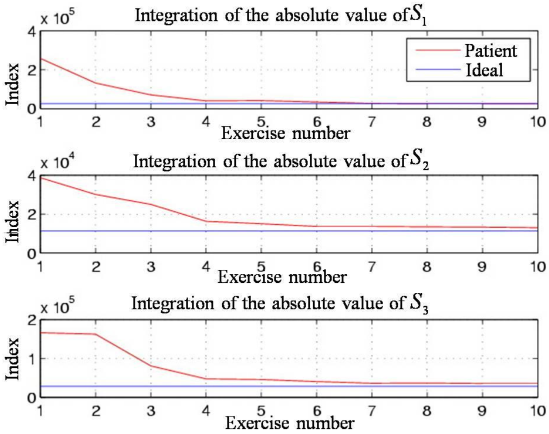

Fig. 13. The absolute value of the error spread in the patient's rehabilitation is important. Reflects the progress of the patient at all

4 CONCLUSIONS

The experimental platform design presented in this work demonstrates the importance of using the technique of haptic guidance for rehabilitation and medical diagnosis. One of the factors that influence the experimental platform for the stability of the system is the design of the control law, which promotes stability and robustness in human-machine interaction, this allows the patient tracking task. This will take care of the patient's physical integration and partial or total damage of the device. Another relevant factor is the high performance that has the haptic device, which in this case is very high due to the high resolution optical encoders as well as the under backlash that presents PHANToM.

The patient, gradually rehabilitated, using haptic guidance platform leads to reduction in motor rehabilitation time, which reduces the cost that this implies. Data provided by the platform are evaluated by specialists to determine a diagnosis based on the performance of the patient.

REFERENCES

[1] T. Truelsen, B. Piechowski-Jwiak, R. Bonita, C. Mathers, J. Bogousslavsky, and G. Boysen, "Stroke Incidence and Prevalence in Europe: a Review of Available Data", *European journal of neurology*, vol.13(6), pp. 581-598, June 2006.

[2] R. Colombo, F. Pisano, S. Micera, A. Mazzone, C. Delconte, M. C. Carrozza, P. Dario, and G. Minuco, "Robotic Techniques for Upper Limb Evaluation and Rehabilitation of Stroke Patients", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.13, no. 3, pp.313- 324, September 2005.

[3] P. S. Lum, C. G. Burger, P. C. Shor, M. Majmundar, and M. van der Loos, "Robot-Assisted Movement Training Compared with Conventional Therapy Techniques for the Rehabilitation of Upper Limb Motor Function After Stroke",*Arch. Phys. Meical. Rehabilitation*. vol. 83, pp. 952-959, 2002.

[4] H.I. Krebs, J.J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, K. Rannekleiv, B.T. Volpe, and N. Hogan, "Rehabilitation Robotics: Performance-Based Progressive Robot-Assisted Therapy", *Autonomous Robots*, vol. 15, no. 1, pp. 7-20, 2003.

[5] W.S. Harwin, J. Patton, and V.R. Edgerton, "Challenges and Opportunities for Robot Mediated Neurorehabilitation", *Proceedings of the IEEE Special issue on medical robotics*, vol. 94, no. 9, pp. 1717 1726, September 2006.

[6] MJ, Eriksson J, Feil-Seifer DJ, Winstein CJ, "Socially assistive robotics for post-stroke rehabilitation", *J Neuroeng Rehabilitation*, 2007, 4:5.

[7] P. Metherall, EA. Dymond, N. Gravill, "Posture control using electrical stimulation biofeedback: a pilot study", *J Med Eng Technol* 1996, 20:53-59.

[8] D. Jack, R. Boian, AS. Merians, M. Tremaine, GC. Burdea, SV. Adamovich, M. Recce, Z. Poizner, "Virtual reality-enhanced stroke rehabilitation", *IEEE Trans Neural Syst Rehabil Eng,* 2001, 9:308-318.

[9] D. Feygin, M. Keehner and F. Tendick, "Haptic Guidance: Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill",*Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002. HAPTICS 2002, pp 40-47, Orlando, FL, 2002.

[10] F. Clark and K. Horch, "Kinesthesia: in Handbook of Perception and Human Performance", *v.1 Sensory Processes and Perception*, New York: Wiley, 1986.

[11] SensAble Technologies, Inc., "PHANTOM PREMIUM 1.0/1.5A, 3D Touch Components": *Hardware Installation and Technical Manual*, Revision 6.5, 18 August,2000.

[12] V. S. Rafael Kelly. Control de Movimiento de Robots Manipuladores. Prentice-Hall, pp 15-37, 2003.

[13] P. J. N. Romeo Ortega, Antonio Lora and H. Sira- Ramrez. Pasivity-based Control of Euler-Lagrange Systems. Springer-Verlag, 1998.

[14] A. Jarillo-Silva and O.A. Domínguez-Ramírez, "Joint Control Strategy for Haptic Guidance", *2010 Electronics, Robotics and Automotive Mechanics Conference,*pp 411-416, 2010.

[15] A. Jarillo Silva and O.A. Domínguez Ramírez, "Diseño e Implementación de Técnicas de Control No Lineal Basadas en Pasividad Aplicadas a Guiado Háptico", Master, Research Center on Information Technologies and Systems, Autonomous University of Hidalgo State, Hidalgo, México, 2009.

[16] A. Jarillo-Silva, O.A Domínguez-Ramírez and V. Parra-Vega, "Haptic Training Method for a Therapy on Upper Limb", *3rd International Conference on Biomedical Engineering and Informatics (BMEI 2010),* pp. 1750-1754, 2010.