DESIGN AND INTEGRATION OF A HUMAN-ROBOT PHYSICAL INTERACTION PLATFORM WITH PURPOSES OF MEDICAL DIAGNOSIS AND REHABILITATION OF UPPER LIMB

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Abstract

In this paper a human-robot physical interaction system with purposes of diagnosis and rehabilitation of upper limb is proposed.Anunderactuatedhaptic device with six degrees of freedom is used, with low inertia and low joint friction.Adaptive control technique is used for passive haptic guidance and active exploration, in order to compensate the dynamic uncertainty of the human operator in the loop.To validate the experimental platform, a procedure is established with three steps: i) knowledge of the haptic interface (interaction with the kinematic virtual environment), ii) navigation in a virtual pipe with changes in the geometric characteristics (verification of position, velocity, collisions and runtime), and iii) haptic guidance in a structured path based on a clinical protocol (study of convergence and energy).Environmental conditions such as temperature, humidity, lighting and noise are characterizedwith purposes to define experimental conditions.In this work, we assess based on the NASA-TLX protocol,the workload perception of simple temporal-spatial tasks.

Keywords: Diagnosis, Rehabilitation, Hapitc guidance, Virtual training, Adaptive control

Introduction

Robotics has revolutionized the world of medicine being an assisting tool for analysis and physical therapy. Robots have systems that evoke movements through protocols which identify and evaluate dynamic movements and impaired coordination.For systems of human-robotphysical interaction, classic assessment schemes refer to the measurement of physical variables that describe the performance of the robotic system, particularly the convergence and energy exchange between the robot and the human operator.However, several experimental resultsin the Advanced Robotics and Haptic Interfaces Laboratory in the Hidalgo State University in Mexico, using different platforms for physical interaction has been possible to observe that the performance not only depends on the task defined in the robot (energy and convergence), also the human operator perception (mental or perceptual activity, physical demand, temporal demand, effort, performance and frustration). Haptic guidance and virtual exploration in diagnosis and rehabilitation provides tactile and kinaestheticstimuli on patients with neuromuscular disabilities. Effects of reactiveguidance depend essentially on the quality of the close loop controller andon its implementation where its design is subjected to human-centred engineeringcriteria such as stability, efficiency, bandwidth and latency. However,the dynamic action of the closed loop system is not necessarily ergonomic,affecting the user's perception of the guidance action and thus, the beneficesin a therapy. To this end, we assess based on the NASA-TLX protocol,the workload perception of simple temporal-spacial tasks on a haptic guidancesystem. With the human operator in the loop, under conditions in upper limb motor disability, the uncertainty in the control loop is high, for this reason is used an adaptive control that estimated the dynamics of the haptic device with the human operator in the loop. Resultsindicate that human-oriented assessment complies with and it is consistentto the advanced performance of the adaptive controller, becoming a viablealternative for haptic assisted rehabilitation.

Background in medical robotics in rehabilitation

In the past half century, research studies have focused on the effects generated by using biofeedback therapy (instrumentation applied to physiological processes) in the treatment of motor deficits in upper and lower extremities, caused from brain injury trauma, cerebral palsy or tendon injuries of the spine; all this in order to make comparisons between this type of therapy and conventional (based physiotherapy routine exercises) [1].Damage to the central nervous system can lead to alteration of motion control upper and lower limbs, face major difficulties in relation to the activities of daily life. Several studies showed that therapy-based rehabilitation oriented tasks repetitive motion helps improve movement disorder in these patients [2,3].Unfortunately, the repetitive nature of the therapy, which requires consistency and uniformity in the physical task demands precision and effective patient management by thephysiotherapist.This situation caused the need to employ new methods to be more economical and efficient procedure for neurorehabilitation. In order to enhance the relationship between the result and the cost of rehabilitation, robotic devices are being introduced in clinical rehabilitation, achieving more effective and convincing results [4,5].Neurorehabilitation based robotic devices has had a breakthrough in this field, as well as introducing greater accuracy and repeatability in the ratio of physiotherapy exercises. Precise quantitative measurement of parameters using robotic instrumentation in order to ensure the recovery of the patient. Another benefit is that robotic devices can be implemented for the purpose of enabling telerehabilitation exercises at home and make the rehabilitation treatment is more effective.People with a physical disability are demanding the benefits of dedicated actions in the field of prevention, promotion, care, rehabilitation and habilitation for maximum development of their potential as writing again, move objects on natural biomechanical performance as well as tasks involving coordination of both upper limbs; all with the purpose of achieving family and social integration and thus an adequate quality of life.Using haptics, physical therapy purposes, have been implemented in recent years in the area of neurorehabilitation, in order to reduce patient recovery time. The disability movement as a result of a neurological injury can be characterized by involuntary movement (biomechanical signals with changes in frequency and amplitude representative of abrupt changes of the limb), and limited movement of the hemiplegic type (biomechanical signals representing low frequency and amplitude of spastic conditions).In this article a haptic platform with OMNIhaptic device for virtual exploration and haptic guidance is proposed. Environmental conditions such as temperature, relative humidity, lighting and noise are characterized. The evaluation is carried out on 204 people, who were measured blood pressure and heart rate. After each stage of the experiment, were evaluated protocol NASA TLX.

Justification

Systems of physical human-robot interaction, technological tools represent high performance training; its applications in surgery, tool management, entertainment and remote operation of complex robotic systems and unmanned mobile vehicle for validating the interest of the scientific community to propose new and innovative strategies in construction, planning, control, decision under contingency operation in environments with uncertainty.In the literature various contributions in this regard are reported, as well as strategies that validate the performance, some refer to the measurement of physical interaction variables, however the vast majority of the proposals constitute the use of protocols that rely on subjective tendency perception user in developing a training task.To our problem, the neurorehabilitation of a disabled patient motion, which prevents the ability to perform controlled movements or volunteers, using a conventional rehabilitation (routine exercises) has benefits; however they are more limitations.The disadvantages are: i) The doctor provides a diagnosis based on their experience and personal opinion, but there is no clinical evidence based support.Despite the skill to determine physiotherapy exercise a particular patient does not guarantee that really the right neurorehabilitation [6] is induced; ii) The activity of conventional physiotherapy does not consider homogeneous biomechanical changes on the anatomical planes of the patient, as they depend on human error; and iii) There is no procedure for characterization and motion analysis to define the task of proper physical therapy and changes that should be subject during treatment.Furthermore, the interfaces used hitherto not consider the human operator in the loop and the uncertainty arising from disability, so stabilization techniques must adapt to changes in the dynamics of the system as a whole.Similarly, it is not considered the performance of the interface from the point of view of the human operator.

The problem and solution

The purpose of neurorehabilitation is to help a patient regain function and independence and improve their quality of life both in physical performance and socially. To do this, based on practice and repetition controlled and supervised; The patient performs a model-based learning a normal engine that affects neuromuscular activity eliminate abnormal with biofeedback, rehabilitation from neuroplasticity, and interaction between posture and movement program. The focus, which somehow is the scientific / technological problem and the proposed solution represents the design and build an experimental robotic platform in stable conditions, which ensure neurorehabilitation of patients with upper limb disabilities voluntary movement, the following characteristics:

a) To contribute to the characterization of anatomical movements (kinematic) and spatio-temporal from specific movement tasks involving biomechanical movements of the shoulder, elbow and wrist.
b) A method of motion analysis according to the form factor of the biomechanical signals (runtime, maximum and minimum, critical points and form factor) for defining the clinical condition of the patient.
c) A method for analyzing the performance of the patient - robot interaction from the energy involved in neurorehabilitation, and the effects of motion correction.
d) A planning strategy of the space-time taskas a reference of motion (position and velocity) for the controller used in the robotic device (haptic), and consider the motion analysis of the previous subsection.

e) A adaptive control technique for robust, stable and optimal that consider the dynamic of the haptic device, the uncertain dynamics of human operator bounded by the physiological limits of kinesthetic strength, high workability in the workspace and task-space neurorehabilitation, and allows path tracking.

The goal

Characterization and evaluation, based on the relationship between the user, the haptic interface and the environmental conditions during a physical task inlocal kinesthetic exploration and haptic guidance through a human-robot physical interactionusing the NASA TLX protocol to define the workload.

1. Design a virtual environment that allows the task of virtual navigation with local kinesthetic guidance for upper limb with involuntary movement, using the phantom omni haptic device.
2. Classify the elements necessary to carry out the task of kinesthetic guided navigation in the interface of an active 3D tube and a circumference of active and passive conditions.
3. Design a survey that allows mediate subscales of the NASA TLX protocol, during the subsequent evaluation to the task of kinesthetic guided navigation.
4. Develop navigation task kinesthetic guidance, obtaining vital signs before and after each experiment; apply the instrument to 248 persons performing the task, and NASA TLX assessment protocol.
5. Develop the interface, files and programs needed to capture, store and process the data collected in the application of the instrument based on NASA TLX protocol; environment (light, temperature, relative humidity and noise) and parameters of the platform (movement, strength and collision) during the navigation task with kinesthetic guidance by human-robot physical interaction.

The experimental platform and the task

The PHANToM Omni has 6 dof in position and 3 dof in force feedback. In each case,there are three actuators.The efficiency of the PHANToM haptic devices depends on factors such as low friction joint, low inertial dynamics and free movement of mechanical backlash, allowing them closer to realism touch interaction.

Figura. 6.1 Experimental platform based on PHANToM OMNI haptic device

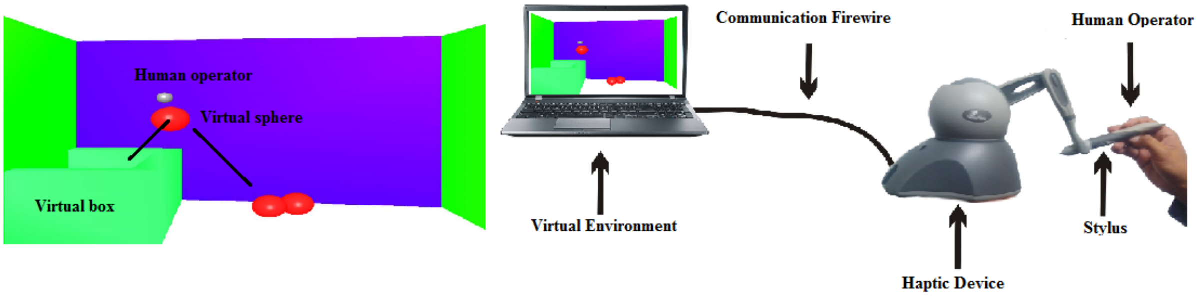
A) Phantom Omni haptic device **B) Haptic guidance platform** **C) Environmental parameters instrumentation**

The Figure 6.1 represents the experimental platform based on Omni Phantom haptic device (**A**), the defined task for haptic guidance (**B**), and the measurement of environmental parameters (**C**: temperature, humidity, lighting and noise).

To validate the experimental platform, a procedure is established with three steps:

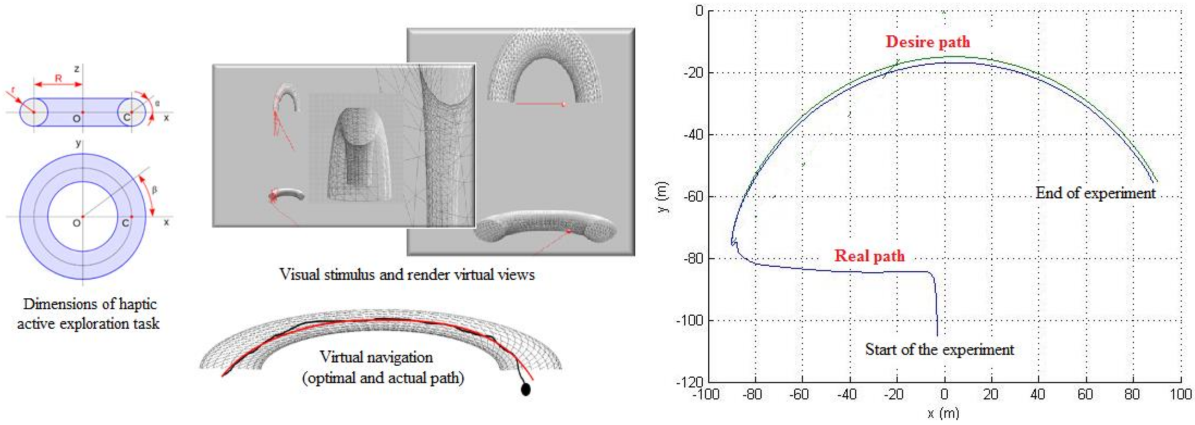
i) *Knowledge of the haptic interface (interaction with the kinematic virtual environment):* for the purpose of training in the use of a haptic interface, the user stores virtual spheres with programmable stiffness, sound synthesis and real-time visual stimulus.

Figura. 6.2T raining in the use of a Phantom Omni haptic device.



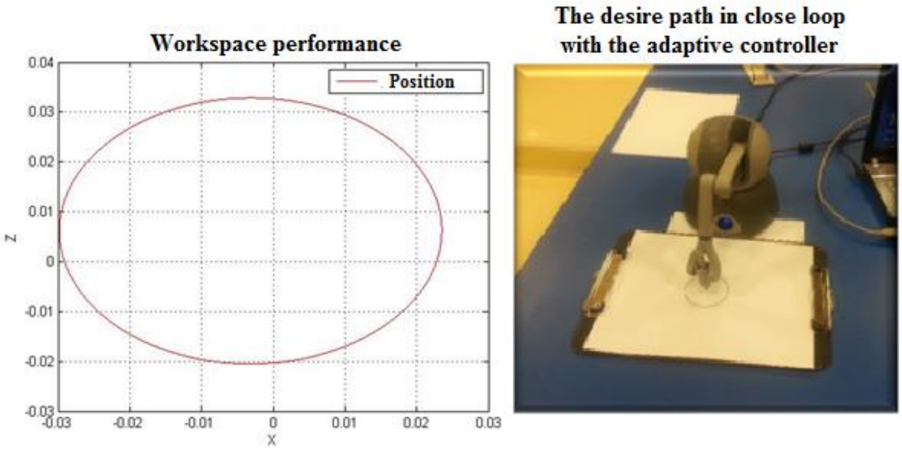
ii) *Navigation in a virtual pipe with changes in the geometric characteristics (verification of position, velocity, collisions and runtime):* the user attempts to resolve the virtual tube without contact or collision. The tube can be modified dimensions. Position, velocity, collisions and run time are evaluated.

Figura. 6.3Active haptic interface for virtual navigation.



iii) *Haptic guidance in a structured path based on a clinical protocol (study of convergence and energy):*

Figura. 6.4Adaptive tracking for haptic guidance task.



Environmental conditions such as temperature, humidity, lighting and noise are characterized with purposes to define experimental conditions.

Figura. 6.5Instrumentation station of environmental parameters

Virtual instrumentation of environmental parameters station

In this work, we assess based on the NASA-TLX protocol, the workload perception of simple temporal-spatial tasks.

Tabla. 6.1NASA Task Load Index

Title	**Points**	**Definition**	**Questioning**
Mental demand	Low / High	Corresponds to the characteristics of the task and planning	¿How much mental and perceptual activity was required? It was easy or demanding, simple or complex.
Physicaldemand	Low / High	Involveseffectsoneffort.	¿How much physical activity is needed? It was easy or demanding, slow or fast, loose or strenuous, repair or laborious task.
Temporarydemand	Low / High	It refers to the time in performing the task.	How much pressure sientio time to undertake the activity or more elements required for the activity? Is the pace was slow and quiet or fast and furious?
Effort	Low / High	Action physics to perform a task.	How hard you had to work (mentally and physically) to achieve the level of performance?
Frustration	Good / Bad	Emotional response related to anger and disappointment.	How insecure, discouraged, angry, happy, relaxed and complacent; how you felt during the task.
Perfomance	Good / Bad	Result in performing the task.	How successful was believed in meeting the objectives of the task set by the experimenter (or yourself)? How he felt satisfied with performance in achieving these objectives.

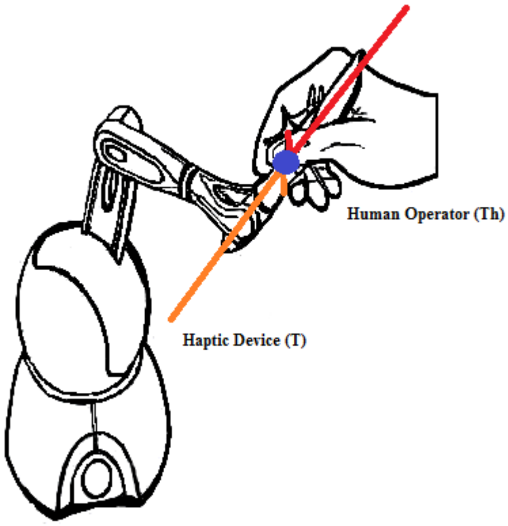
Dynamic model of the Phantom Omni Haptic Device

Based on Euler-Lagrange formulation, and the classical representation of the dynamic model with the human force interaction, de the dynamic of the human-robot physical interaction is given as

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + \tau_h \qquad (7.1)$$

Whereτ is the input torque in N, $\tau_h$represent the human torque in the physical interaction (Figure 7.1), $H(q)$ is the inertia matrix, $C(q,\dot{q})$ represent the Coriolis and centripetal matrix and finally $G(q)$is the gravity force vector; where$q$, $\dot{q}$ and $\ddot{q}$corresponds to the generalized coordinates and its derivatives.

Figura.7.1 Human and haptic forces interaction.



The equations of motion of the Phantom Omni haptic device are

$$\tau_1 = \theta_1\dot{q}_1 + \theta_2 C_{22}\ddot{q}_1 + \theta_3 C_{23}\dot{q}_1 + \theta_4 C_2 S_3 \ddot{q}_1 + \theta_5 S_2 \ddot{q}_2 - \theta_2 S_{22}\dot{q}_1\dot{q}_2 - \theta_3 S_{23}\dot{q}_1\dot{q}_3 - 0.5\theta_4 S_2 S_3 \dot{q}_1\dot{q}_2 + 0.5\theta_4 C_2 C_3 \dot{q}_1\dot{q}_3 - \theta_2 S_{22}\dot{q}_1 q_2 + \theta_5 C_2 q_2^2 - 0.5\theta_4 S_2 S_3 \dot{q}_1\dot{q}_2 - \theta_3 S_{23}\dot{q}_1\dot{q}_{33} + 0.5\theta_4 C_2 C_3 \dot{q}_1\dot{q}_3 \quad (7.2)$$

$$\tau_2 = \theta_5 S_2 \dot{q}_1 + \theta_6 \dot{q}_2 - 0.5\theta_4 S_{2-3}\dot{q}_3 + \theta_2 S_{22} q_1^2 + 0.5\theta_4 S_2 S_3 \dot{q}_1^2 + 0.5\theta_4 C_{2-3} q_1^2 + \theta_8 C_2 + \theta_{10} q_2 - \frac{\pi}{2} \quad (7.3)$$

$$\tau_3 = -0.5\theta_4 S_{2-3}\ddot{q}_2 + \theta_7 \dot{q}_3 + \theta_3 S_{23}\dot{q}_1^2 + 0.5\theta_4 C_2 C_3 \dot{q}_1^2 - 0.5\theta_4 C_{2-3} q_2^2 + \theta_9 S_3 \quad (7.4)$$

Where: $\cos q_1 = C_1, \cos q_2 = C_2, \cos q_3 = C_3, \sin q_1 = S_1, \sin q_2 = S_2, \sin q_3 = S_3$, $\sin 2q_1 = C_{21}, \cos 2q_2 = C_{22}, \cos 2q_3 = C_{23}, \sin 2q_1 = S_{21}, \sin 2q_2 = S_{22}, \sin 2q_3 = S_{23}$.
And the dynamic parameters are :

Table. 7.1Dynamic parameters of the haptic device.

Parameter	**Value**
θ_1	1.798 x 10-3
θ_2	0.864 x 10-3
θ_3	0.486 x 10-3
θ_4	2.766 x 10-3
θ_5	0.308 x 10-3
θ_6	2.526 x 10-3
θ_7	0.652 x 10-3
θ_8	164.158 x 10-3
θ_9	94.050 x 10-3
θ_{10}	117.294 x 10-3

To implement the adaptive control law, the linear parameterization of the dynamic model is required; particularly the regressor matrix of nonlinear elements, as follows

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Y\theta \quad (7.5)$$

$$Y\theta = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_{15} & Y_{16} & Y_{17} & Y_{18} & Y_{19} & Y_{110} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & Y_{25} & Y_{26} & Y_{27} & Y_{28} & Y_{29} & Y_{210} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & Y_{35} & Y_{36} & Y_{37} & Y_{38} & Y_{39} & Y_{310} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \\ \theta_7 \\ \theta_8 \\ \theta_9 \\ \theta_{10} \end{bmatrix} \qquad (7.6)$$

Where the regressor matrix parameters are:

$Y_{11} = \ddot{q}_1$

$Y_{12} = C_{22}\ddot{q}_1 - S_{22}\dot{q}_1\dot{q}_2 - S_{22}\dot{q}_1\dot{q}_2$

$Y_{13} = C_{23}\dot{q}_1 - S_{23}\dot{q}_1\dot{q}_3 - S_{23}\dot{q}_1\dot{q}_3$

$Y_{14} = C_2S_3\dot{q}_1 - 0.5S_2S_3\dot{q}_1\dot{q}_2 + 0.5C_2C_3\dot{q}_1\dot{q}_3 - 0.5S_2S_3\dot{q}_1\dot{q}_2 + 0.5C_2C_3\dot{q}_1\dot{q}_3$

$Y_{15} = S_2\ddot{q}_2 + C_2q_2^2$

$Y_{16} = Y_{17} = Y_{18} = Y_{19} = Y_{110} = Y_{21} = Y_{23} = Y_{27} = Y_{29} = Y_{31} = Y_{32} = Y_{35} = Y_{36} = Y_{38} = Y_{310} = 0$

$Y_{22} = S_{22}q_1^2$

$Y_{24\_}\{24\} = -0.5S_{2-3}\ddot{q}_3 + 0.5S_2S_3q_1^2 + 0.5C_{23}\dot{q}_1^2$

$Y_{25} = S_2\ddot{q}_1$

$Y_{26} = \dot{q}_2$

$Y_{28} = C_2$

$Y_{210} = q_2 - \frac{\pi}{2}$

$Y_{33} = S_{23}q_1^2$

$Y_{34} = -0.5S_{23}\ddot{q}_2 + 0.5C_2C_3\dot{q}_1^2 - 0.5C_{23}\dot{q}_2^2$

$Y_{37} = \ddot{q}_3$

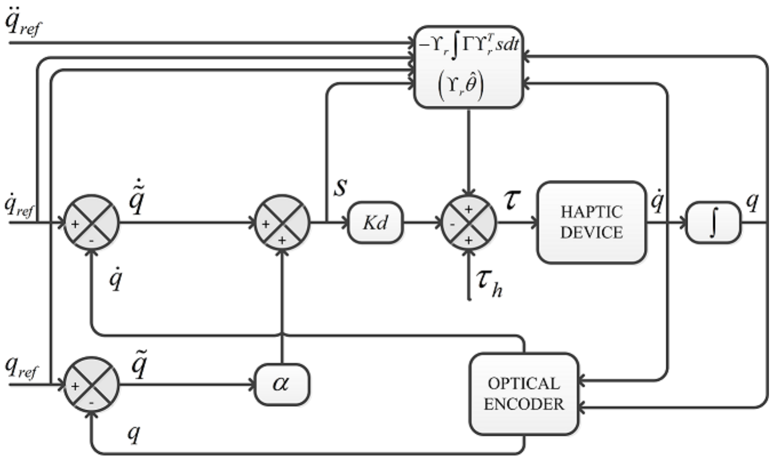
$Y_{39} = S_3$

The regressor matrix of nonlinear elements defined from the equations of motion of the haptic device allows the design of adaptive control law, employed in this research. As presented in the following section.

Adaptive control oh haptic device with the human in the loop

The problem of designing adaptive control laws for haptic interface in haptic guidance task with the human in the loop, that ensure asymptotic trajectory tracking has interested as a topic in training and rehabilitation. The development of effective adaptive controllers represents an important step toward high-speed/precision robotics and haptics applications. The control strategy used in this research is defined in the following scheme

Figura.8.1 Adaptive control squeme



Based on the motion equation defined in (7.1) , the control law is

$$\tau = Y_r^T \hat{\theta} - K_d S \qquad (8.1)$$

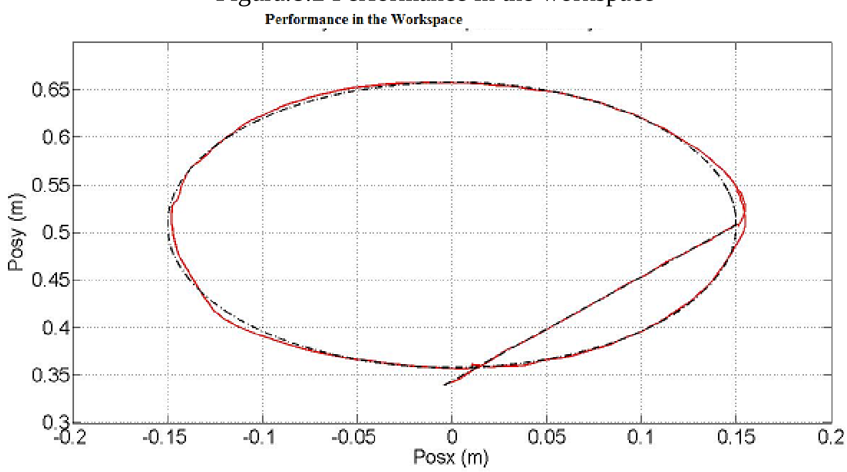
Subject to the law of adaptation

$$\dot{\theta} = -\Gamma Y_r^T S \qquad (8.2)$$

where$Y_r = Y_r(q, q_r, \dot{q}_r)$ is theno linear regressor as a function of the nominal reference; $\hat{\theta}$is the vector for parameter estimation; $\dot{q}_r = q_d - \alpha\tilde{q}$, $\tilde{q} = q - q_d$ y $\alpha = \alpha^T > 0$as a nominal reference; $K_d = {K_d}^T > 0$ y $\Gamma = \Gamma^T > 0$are the control gains; and $S = \dot{q} - \dot{q}_r$ is the extended error.

The experimental result with the human in the loop and the trajectory tracking is

Figura.8.2 Performance in the workspace



NASA TLX Method

The NASA TLX evaluation is subjective and weighted method, a tool for the evaluation of a Human Robot Physical Interaction System.This is a multidimensional assessment procedure gives an overall workload score, based on a weighted average of scores in six subscales, whose content is the result of research to empirically isolate and identify factors that are of relevance in the subjective experience of workload.

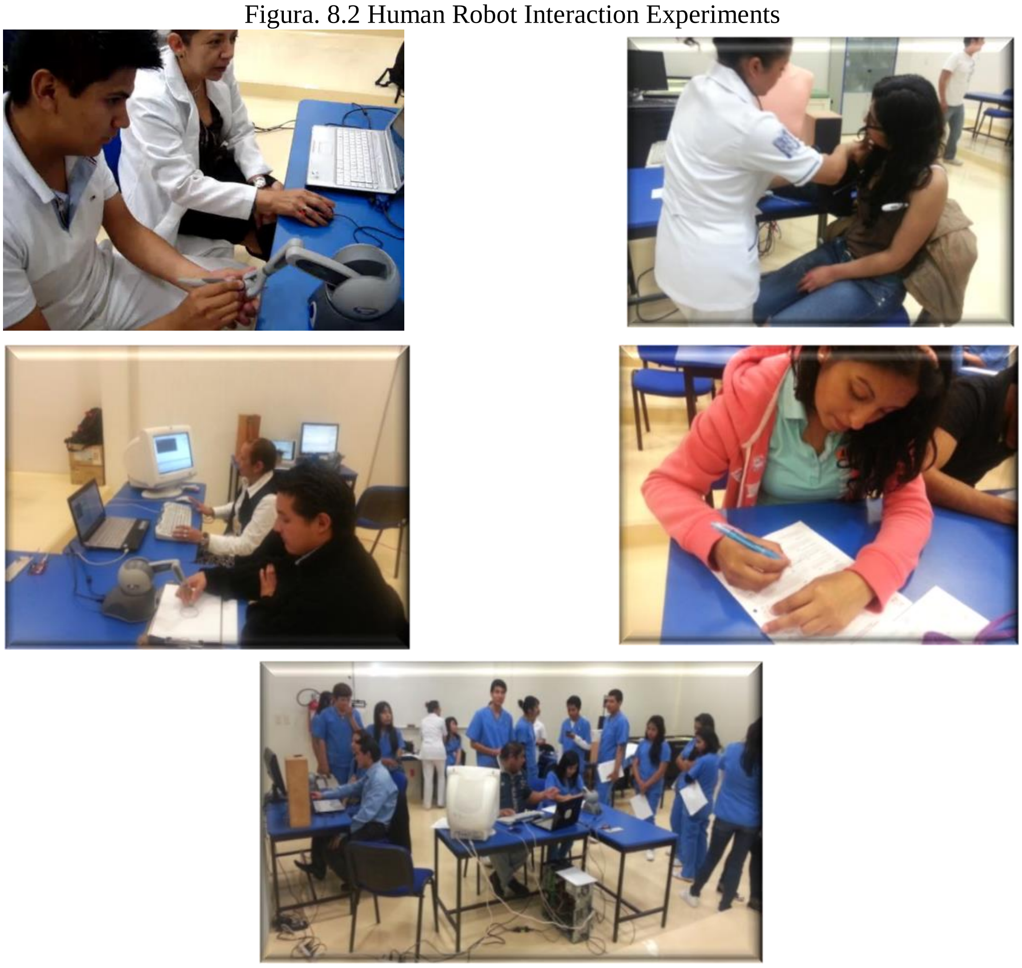
The NASA TLX (Task Load Index) is a multidimensional assessment procedure gives an overall workload score, based on a weighted average of scores in six subscales, of these, three relate to the demands imposed on the person (mental demands, physical and temporal) and the other three relate to the interaction of the person with the task (effort, frustration and performance); with a scale of 20 intervals of each 5 ranging from Low / High.

The assumption that the subjective experience of loading summarizes the influences of various factors, besides the objective demands imposed by the task. Loading is not an inherent characteristic of the task but is the result of interaction between the requirements of the task; the circumstances under which develops and skills, behaviors and perceptions of the operator.

Experimental results

Physical interaction studies, medical measurement and evaluation protocol variables of NASA TLX, during haptic task are described in the following images

Figura. 8.2 Human Robot Interaction Experiments



Conclusion

The purpose is: to provide a platform for virtual navigation and guidance prospects kinesthetic training, entertainment, simulation, physical therapy and more. For this it is essential to check the performance of the interface, from the point of view of the robot (inherent in the device status variables: Hamiltonian, convergence of position error and operational velocity, kinematic and dynamic manipulability, robustness and practical stability); and also verify the performance from the point of view of the user (NASA TLX Protocol: effort, stress, fatigue, frustration, physical and mental demands).

In the various systems of human-computer interaction, usability and utility are used when the interaction is not physical; it is possible to verify the performance through the protocol NASA TLX (exclusive or established for that specific purpose). This is not enough when the interaction is physical. It is the case of this study, many of the results allow to verify the crossing or correspondence between physical robot signals and indicators protocol NASA TLX, so that the latter wins objective evaluation system of Human-Robot Physical

Interaction. The measurement of environmental parameters and vital signs aims to discriminate false readings users whose underperforming this given by a motivated by extreme or uncomfortable environment and disease conditions in the user effort.

Variable	Frequency	Percentage	Variable	Frequency	Percentage
Gender			**Educational Program**		
Masculine	81	39.7	Medicine	42	20.6
Feminine	123	60.3	Odontology	121	59.3
Total	**204**	**100.0**	Nursing	41	20.1
Age			**Total**	**204**	**100.0**
18	24	11.8	**Marital Status**		
19	40	19.6	Stag	186	91.2
20	20	9.8	Free union	12	5.9
21	36	17.6	Married	6	2.9
22	36	17.6	**Total**	**204**	**100.0**
23	25	12.3			
24	14	6.9			
25	4	2.0			
26	1	.5			
27	2	1.0			
35	1	.5			
37	1	.5			
Total	**204**	**100.0**			

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