Haptic Guided Exploration of Deformable Objects

Omar Arturo Domínguez Ramírez[1] and Vicente Parra Vega[2]

[1] Universidad Autónoma del Estado de Hidalgo
Centro de Investigación en Tecnologías de Información y Sistemas
Carretera Pachuca-Tulancingo Km 4.5, Pachuca, Hidalgo, México
[2] Robotics and Advanced Manufacturing Division-CINVESTAV
Carretera Saltillo-Monterrey Km 13.5 Ramos Arizpe, Coahuila 25900, México.
omar@uaeh.reduaeh.mx, omar@uaeh.edu.mx, vparra@cinvestav.mx

Abstract. Perception and interaction with virtual objects through kinesthetic sensation and visual stimuli is the basic issue of a haptic interface. If a real object is located at a remote station and explored (in contact) with a passive device, a haptic interface in a local station can be used to perceive its spatial and surface attributes. This is one type of haptic guidance. This problem has been addressed with undeformable object, and contact force modelled with the penalty-based method. However, this approach yields limited haptic properties of the object, and if the object is deformable, it is difficult to achieve stable contact. However, there exists relevant tasks for exploration of deformable objects, such as exploration of fruits, skin of animals and dermatological procedures. Motivated by these kind of tasks, an approach for guided remote exploration of deformable objects is proposed in this paper. A real object is explored in a remote location and object attributes and properties such as spatial location, shape, texture and roughness are perceived with a constrained Lagrangian-based decentralized force-position controller in the local station. Stable interaction is theoretical proved and experimental results using PHANToM 1.0A validate the approach.

1 Introduction

1.1 Haptic Interface

The kinesthetic perception is possible by means of the use of an electromechanical device (haptic device) in closed loop with the virtual object [1]. The high bandwidth of the tactile force-pressure physiological sensor of the operator requires high precision haptic interface to stimulate correctly the mechanoreceptors of the operator, while low bandwidth haptic rendering is required for visual stimuli. However, the haptic rendering graphics should convey deformation of the virtual world accordingly to the bilateral force-pressure stimulus [1]. In particular, the PHANToM haptic interface [1], [2] has successfully being used for this purpose, though its application programming interface GHOST has limited capabilities since only simple undeformable primitives can be programmed. Therefore, simple

© S. Torres, I. López, H. Calvo. (Eds.)
Advances in Computer Science and Engineering
Research in Computing Science 27, 2007, pp. 243-254

Received 24/02/07
Accepted 08/04/07
Final version 23/04/07

spring-based contact force models can be implemented. Though recent GHOST version allows simple dynamic properties to the virtual environments, and Phantom uses simple PID-based cartesian stiffness control, nowadays Phantom stands for a high end haptic interface, however this two facts further limits the scope of this haptic device for dynamic-based virtual environments, this device may become a powerful haptic interface if stable interaction with deformable objects can be established. On the other hand, some application for haptic teleoperation or haptic guidance have been proposed. In particular, new haptic guidance schemes are under research, wherein a master passive robot guides the remote haptic robot under different configurations.

1.2 Haptic Training

Haptic guidance can be used for training[12]. We identify four classes haptic guidance: **Configuration 1.** *Haptic Guidance:* The master sent only its position and contact force as desired references to the remote haptic interface. **Configuration 2.** *Haptic Guidance Control:* As configuration 1, but the master also controls the remote haptic interface. The difference between 1 and 2 is that in configuration 2 the master station controls directly the remote station, while configuration 1 implements an independent control loop in the remote station. **Configuration 3.** *Haptic Guided Exploration:* As definition 1, but the master performs a recognition task. **Configuration 4.** *Haptic Guided Exploration Control:* As definition 3, but the master controls the position and contact force of the remote haptic interface. The difference between 3 and 4 is that in configuration 4 the master station controls directly the remote station, while configuration 3 implements an independent control in the remote station. Finally, the difference between guidance and guided exploration is that a guided exploration configuration involves perception of shape, texture, and roughness, in contrast to a guidance configuration wherein this object attributes does not play a significant role. For instance, in some guided exploration tasks back and forth, and lateral motions might be important, while in guidance this movements are not important to complete the task. In this paper, we are interested in *Haptic Guidance Exploration* (configuration 3), which is useful for rapid training.

2 The Problem and A Solution

2.1 The Problem

How can haptic exploration of a deformable object be performed when an expert is training an inexpert? This interaction involves two haptic interfaces and two human operators, therefore compliant interaction arises. This new paradigm in haptic interfaces has been poorly explored, and [12] offers an extraordinary review on this subject. Haptic exploration involves contact to deformable object. This deformation may come from the deformation of the object itself due to the contact force, or, if the object is very stiff, deformation may occur due to the compliance of whole system. Remember that the human operator is driving the system, thus a compliant contact action occurs with deformation. It is evident that the solution of this problems requires contact force based on the dynamics of the whole system. From this viewpoint, it is also evident that Hooke´s Law-based contact force will not suffice since a static mapping is used. It was shown in our previous paper [9], [11] that that interaction with the constrained lagrangian allows stable interaction in contrast to the contact force model based on the Hooke´s Law (called penalty-based method, which is hugely popular among the haptic research community due to the simplicity, despite of its limited performance and prone to instability). The high-end kinesthetic coupling that arises using the constrained Lagrangian method yields a more realistic contact force as a function on the dynamical properties of the whole system. An illustrative example of haptic guided exploration could be an expert surgeon carrying out a surgical exploration (the master is in contact to a real object), and in a remote station a inexpert surgeon is holding a haptic display for training purposes. However, this scheme allows control to the inexpert surgeon to test its abilities. Or an expert painter training an candidate painter while the expert painter is painting. For this two cases, it is relevant not to implement direct control from the master to the remote station. The master can be real [13] or virtual.

2.2 The Solution

A haptic guidance scheme for guided exploration is implemented to yield an active haptic exploration with purposes of remote training, with simultaneous control of force and position on the remote station. Second order Lagrangian dynamics are assigned to the virtual objects, and to the PHANToM haptic device. Then, constrained Lagrangian algorithm is implemented to compute the reaction force based on the dynamic properties of the dynamical virtual world and the PHANToM device. The components of this contact force is used to reproduce object attributes such as shape, texture and roughness to allow a more realist contact force compliant to the real sensations of remote exploration.

3 Exploration of a Remote Real Object

There are two robotic systems involved in haptic guidance. In the remote station, the remote robot can be a passive linkage robotic arm exploring the real object in contact; this remote arm is equipped with angular position sensors and force sensor to measure angular displacement and real contact forces with the object. At the local station, a haptic display is required to generate the force contact coming from the real contact at the remote station. In this paper, we consider that two Phantoms are involved in each side.

3.1 Constraint Dynamics of PHANToM at Each Side

PHANToM 1.0A is a mechanism of articulate links, with n revolute joints described in generalized joint coordinates $(q^T, \dot{q}^T)^T \in R^{2n}$. The dynamics presents

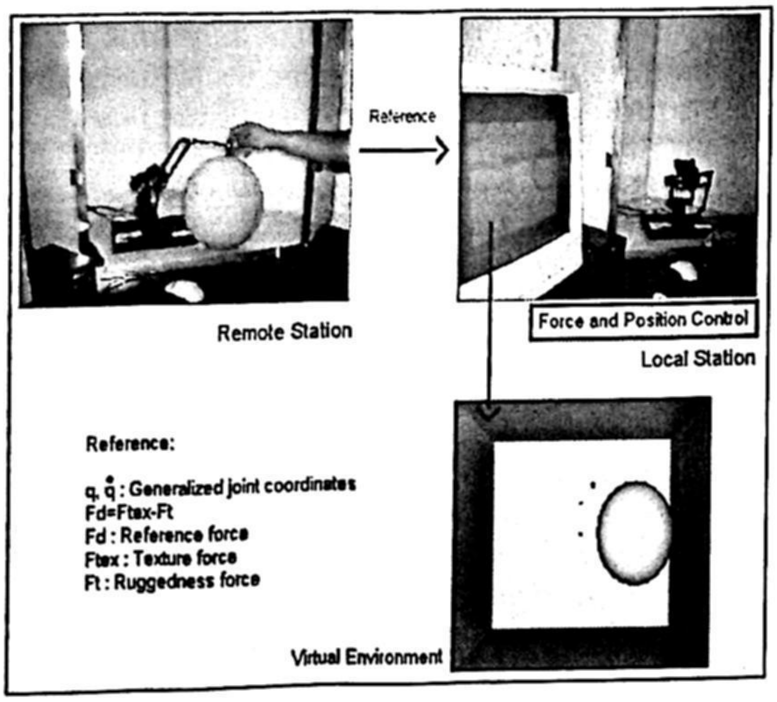

Fig. 1. Remote exploration of a real object through a haptic interface with haptic guidance controller

restriction in its movement, defined by the following algebraic and differential system of equations,

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + \frac{J_\varphi^T}{\left\|J_\varphi J_\varphi^T\right\|} f_r \tag{1}$$

$$\varphi(q) = 0 \tag{2}$$

where $M(q) \in \Re^{3\times 3}$ denotes a symmetric positive definite inertial matrix, $C(q,\dot{q}) \in \Re^{3\times 3}$ is a Coriolis and centripetal forces matrix, $g(q) \in \Re^n$ models the gravity forces, $\tau \in \Re^3$ stands for the torque input, $f_r \in \Re^r$ is (for r=1 is one point contact, a scalar) constrained Lagrangian representing the magnitude of the contact force, $\frac{J_\varphi^T}{\left\|J_\varphi J_\varphi^T\right\|}$ stands for the normalized projection of the jacobian $J_\varphi \in \Re^n$, $J_\varphi = J_\varphi(q) \equiv \left[\frac{\partial}{\partial q_1}\varphi(q)\ \frac{\partial}{\partial q_2}\varphi(q)\ \frac{\partial}{\partial q_3}\varphi(q)\right]$, which arises normal at the contact point. The following equation holds while the end-effector is moving on the constraint surface $\varphi(q) = 0$,

$$\dot{\varphi}(q) = J_\varphi \dot{q} \equiv 0 \tag{3}$$

and,

$$\ddot{\varphi}(q) = J_\varphi \ddot{q} + \dot{J}_\varphi \dot{q} \equiv 0 \tag{4}$$

These equations must be satisfied for consistency of the solution of the DAE system.

3.2 The Local Station

Real Remote Object The surface of the object is described by a geometric function $\varphi(q) = 0$. Based in the constrained dynamic model (1)-(2). The real object can be modelled in terms of the generalized coordinates q since $\varphi(q) = 0$ as a mass-spring-damper system as follows

$$m\ddot{\xi}(q) + b\dot{\xi}(q) + k\xi(q) = 0 \tag{5}$$

where m is the mass, b is damper and k is spring. This pointwise model is consistent to the formulation of one point contact of the DAE system (1)-(2).

Computation of Contact Force for Local Phantom It is assumed that there exists a force sensor that delivers f_r in the remote station.

3.3 The Remote Station

Virtual remote object Similar to subsection 3.2, where now the virtual object is assigned a lumped second order linear dynamics with respect to its inertial frame.

Computation of Contact Force for Local Phantom Phantom is not equipped with a force sensor. Then, we propose to compute it by solving the DAE system (1)-(2) for f_r as follows. First for stable interaction ($\varphi(q) = 0$), the haptic display must stay in contact to the virtual object, then the acceleration $\xi(q)$ must equal the acceleration $\varphi(q)$, that is $\xi(q) = \varphi(q)$, and then (5) becomes

$$m\ddot{\varphi}(q) + b\dot{\varphi}(q) + k\varphi(q) = 0 \tag{6}$$

Using (4), equation (6) becomes

$$m(J_\varphi \ddot{q} + \dot{J}_\varphi \dot{q}) + b\dot{\varphi}(q) + k\varphi(q) = 0 \tag{7}$$

Solving (6) by using (1) we obtain

$$\ddot{q} = M(q)^{-1} \left\{ -C(q,\dot{q})\dot{q} - G(q) + \tau + \frac{J_\varphi^T}{\left\|J_\varphi J_\varphi^T\right\|} f_r \right\} \tag{8}$$

Now, compute the constrained Lagrangian f_r from (7) and (8) as follows

$$\begin{aligned} f_r = \frac{\left\|J_\varphi J_\varphi^T\right\|}{m J_\varphi M(q)^{-1} J_\varphi^T} &\left\{ -b\dot{\varphi}(q) - k\varphi(q) - m\dot{J}_\varphi \dot{q} + \right. \\ &\left. m J_\varphi M(q)^{-1} (C(q,\dot{q})\dot{q} + G(q) - \tau) \right\} \end{aligned} \tag{9}$$

Notice that the constrained Lagrangian f_r is function of J_φ, and dynamics of the haptic device and the object.

3.4 Reproducing Object Properties in the Remote Station

Equation (9) represents the reaction force in terms of: **i)** the PHANToM dynamics; **ii)** the dynamics of the virtual object, and **iii)** the controller τ. Notice that acceleration is not required. In this way, the controller τ will track (reproduce) the desired trajectories, that is the real contact force $f_{r-local}$ of the local station becomes the desired contact force for the haptic device in the remote station, that is $f_{rd-remote} = f_{r-local}$, and thus $q_{d-remote} = q_{local}$ for position. Since the object in the remote station exhibit roughness and texture through the contact force f_{rd}, then if a controller τ guarantees that $f_{r-remote}$ converges to $f_{rd-remote}$, then it also guarantees that the real object properties are perceived in the remote station. Now, since there exists at least a three degree of freedom force sensor in the local station, then $f_{r-local} = [f_x, f_y, f_z]^T$, and in the next section we propose how to parameterize roughness, shape and texture in terms of $[f_x, f_y, f_z]$ and object parameters. Notice that these properties are parameterized by the operational contact forces at each unitary axis i, j, k, which are available from the force sensor and friction parameters. In this way, since τ generate tracking of $[f_x, f_y, f_z]$, it will guarantee also tracking of roughness, shape and texture.

4 Computation of Texture, Roughness, and Haptic Exploration

How to reproduce object properties with only force sensor measurement when sliding over a real remote object? In this section, we discuss an approach that synthesizes texture, roughness, and shape from f_x, f_y, and f_z measurements.

4.1 Roughness Perception

The sliding friction between two different materials with contact area defined by A, is equal to the load W divided by the flow stress P_m of the weaker of the two solids in contact. At this region of contact, the solid form a number of junctions as if they were welded together. Friction F represents the force required to shear these junctions apart. Mathematically, the theory is expressed as,

$$A = \frac{W}{P_m} \tag{10}$$

$$F = As \tag{11}$$

$$\mu = \frac{F}{W} = \frac{s}{P_m} \tag{12}$$

where s is the shear stress. Thus, the coefficient of friction $\mu \ll 1$ may be represented by the ratio of shear stress to flow stress of the material, and becomes its intrinsic property. Roughness arises as function of the sliding motion over the surface of the object, thus roughness is function of the tangential friction f_T.

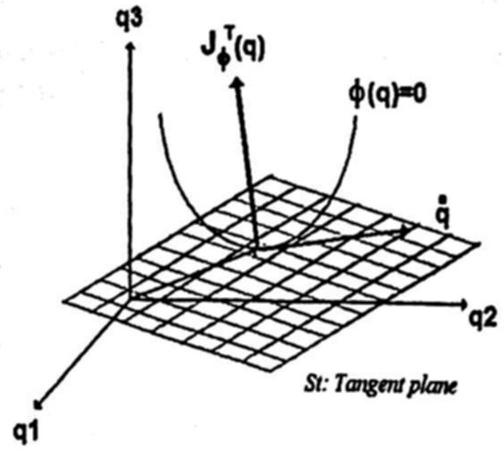

Fig. 2. Geometric decomposition in the contact point

Since f_T arises at the tangential plane at the contact point, see figure 2, it is then function of joint velocity.$\dot{q}$, in terms of $\dot{X} = J\dot{q}$ as follows

$$f_T = \mu\sqrt{(f_x^2 + f_z^2)}\dot{X}$$

where, $f_x, f_z \in S_t$. $\dot{X} = J\dot{q}$, with J as the Phantom jacobian matrix. The torques based on the tangential friction force is defined by the equation,

$$\begin{aligned} \tau_t &= J^T f_T \\ \tau_t &= \mu\sqrt{(f_x^2 + f_z^2)}J^T J\dot{q} \end{aligned} \tag{13}$$

In this way, we can model the roughness by simply assigning values to f_x, f_z, or these variables can be generated on line by the master station.

4.2 Texture Perception

The perception of surface texture is a specific design issue in force feedback interfaces. Manipulation of everyday objects, the perception of surface texture is fundamental to accurate identify contact points and apply the correct internal contact force. In a virtual environment also, haptic texture information can both increase the sense of realism of an object as well as convey information about what the object is and where it is. Phantom haptic device convey texture by actuating kinesthetic forces on the users fingers. In this work we model the texture property as a periodic function

$$T_{tex} = Amp\,(\sin(2\pi f t) + 1) \tag{14}$$

where Amp stands for half of the maximum value of texture torque, f stand for the frequency in hertz and t is the time in seconds.

4.3 Shape Perception

Shape is perceived by the normal contact force of an object. Thus, equation (9) directly provides this perception in absence of roughness and texture.

5 Haptic Exploration Control

Haptic guidance schemes are employed in tasks of remote training. The haptic device defines, in the station teacher, the position references (free motion) or position and forces (constrained motion) that will reproduce in the remote device (station remote). Experiment is shown in diagram of the figure 1. We use a nonlinear PID control [4], [7] for free movement experiments, and a simultaneous control of force and position for constrained movement experiments with the human on the loop [7], [8],[10].

5.1 Free Motion Control of the Remote Station

A nonlinear PID control [4] is proposal for haptic guidance task in free movement. This control compensate the nonlinear dynamics in continuous mechanical plants with tracking capability. The nonlinear PID controller given by

$$\tau = -k_p \Delta q - k_v \Delta \dot{q} + k_d S_d - k_i \int_{t_0}^{t} sgn(\Delta \dot{q} + \alpha \Delta q - S_d) d\varsigma \tag{15}$$

where $S_d = (\Delta \dot{q}(t_0) + \alpha \Delta q(t_0)) \exp^{-k(t-t_0)}$, for $k_p, k_v, k, \alpha > 0$, are positive feedback gains of appropriate dimensions. Tracking errors are defined as $\Delta q = q - q_d, \Delta \dot{q} = \dot{q} - \dot{q}_d$ for position and velocity, respectively. Desired values are the real position and velocity of the local station. This controller guarantees exponential tracking without using the model, see [4].

5.2 Constrained Motion Control of the Remote Station

We makes use of our previously proposed control law [7]

$$\tau = -\tau_p - \tau_f - \tau_d \tag{16}$$

where

$$\begin{aligned} \tau_p &= -K_p(t)\Delta q - K_v(t)\Delta \dot{q} - K_{ip}(t) I_p \\ \tau_p &= K_F(t)\Delta F + K_\lambda(t)\Delta\lambda - K_{iF}(t) I_f \\ \tau_d &= K_g \mathcal{N} + \zeta(t) \end{aligned} \tag{17}$$

and $K_p(t), K_v(t), K_{ip}(t), K_{iF}(t), K_F(t), K_\lambda(t), \dot{I}_F, \dot{I}_p, K_g(t), \mathcal{N}, \zeta(t)$ are time varying feedback gains that depends on matrix $Q(q) = I - J_\varphi^T(q)\left(J_\varphi(q) J_\varphi^T(q)\right)^{-1}$ stands for the orthogonal projection of the normal of a matrix $J_\varphi \in \Re^{1x3}$, and on J_φ^T. Gains α, β are positive constants, $\Delta F = \int (f_r - f_{rd}) dt$, $K_d = K_d^T \in \Re^{nxn}$, f_d are positive gains. This controller guarantees fast simultaneous tracking of position and force trajectories defined by the master operator. See [7].

5.3 A Stable Switching Algorithm

Remote exploration involves free and constrained motion, that at least two controllers are switching over time (it was shown that switching of these controllers is stable). The algorithm is as follows

- Phase a (*Without interaction*): $\varphi(q) > \varepsilon \to$ Free Motion Control
- Phase b (*Collision detection*): $-\varepsilon \leq \varphi(q) \leq \varepsilon \to$ Constrained Motion Control
- Phase c (*Stable interaction with deformation*): $\varphi(q) < -\varepsilon \to$ Constrained Motion Control

where $\varepsilon = 1 \to 10^{-6}\ m$. It can be seen that the applying the constrained Lagrangian method, in contrast to the penalty-based method, involves low frequencies over the virtual object. This allows a stable interaction, as proved in [14], without trembling for deformable objects.

6 Experiments

6.1 Experimental Setup

The conditions of the experiments are defined in a parallel plane S_t to the plane $X - Z$, the human operator of the remote station develops a circular trajectory on the plane S_t with texture and ruggedness (in way emulated by means of references to the controller of force and position in the local station). The constraint surface is $\varphi(q) = l_2 - l_2\cos(q_3) + l_1\sin(q_2) - y_0$, where $l_1 = l_2 = 139.7\ mm$. The parametric equations that define the trajectory are, $x = h + r\cos wt, y = y_0, z = k + r\sin wt)$, this equations correspond to a circumference in the plane S_t, with center in $C(h, y_0, k)$ and radio r. The Jacobian of PHANToM is given by

$$J = \begin{bmatrix} l_1c_1c_2 + l_2s_3c_1 & -l_1s_1s_2 & l_2s_1c_3 \\ 0 & l_1c_2 & l_2s_3 \\ -(l_1s_1c_2 + l_2s_1s_3) & -l_1s_2c_1 & l_2c_1c_3 \end{bmatrix} \tag{18}$$

where $c_* = \cos(*)$ and $s_* = \sin(*)$. The time in all the experiments is of $t = 5$ seconds. In all the experiments, the following parameters were used, $h = -25.0\ mm, y_0 = 20.0\ mm, k = 0.0\ mm, w = \frac{2\pi}{4} radsec^{-1}$. To define the texture the equation (14) is used, and to define f_x and f_z the following equation is implemented,

$$f_x = R\sin(2\pi f_R t)\left[\frac{J_{\varphi_{11}}}{\left\|J_\varphi J_\varphi^T\right\|}\right] \tag{19}$$

$$f_z = R\sin(2\pi f_R t)\left[\frac{J_{\varphi_{13}}}{\left\|J_\varphi J_\varphi^T\right\|}\right]$$

In the table 1 presents the parameters used in each one of the experiments,

Experiment	Amp	f	μ	R	f_R
1	0	0	0	0	0
2	150	0.5	0.015	50	0.5
3	150	1.5	0.015	50	1.5
$4 - deformation$	150	0.5	0.015	50	0.5

Table 1. Parameters used in experiments

6.2 Results

Fig. 3 describes the experiments of configuration 1, given in section 1. It can be seen that when there is not direct interaction of the master station over the local (inexpert) station, smooth haptic performance is obtained. Fig. 4 describes the experiments of configuration 2, given in section 1. Note that once texture and tangential friction is present over the path to be followed, the collision detection algorithm allows stable switching, while tracking is obtained. Fig. 5 describes the experiments of configuration 3, given in section 1. In this configuration local force-position control loops is implemented to allow kinesthetic stimuli of desired force-position trajectories, generated by the master. Texture does exhibit a frequency three fold of the previous case, and it is reproduced effortlessly with stable interaction. Fig. 6 describes the experiments of configuration 4, given in section 1. In this configuration direct control is performed through the master over the local station, wherein considerable deformation is achieved with stable contact, and even during deformation, texture and roughness is perceived seemingly.

7 Conclusions

A haptic system to allow remote exploration of a real object is proposed. A general framework based on constrained robot dynamics renders a Lagrangian-based contact force controller within a systematic way to produce shape, roughness and texture properties of the remote object under exploration. Even during deformation, these object properties can be perceived. The system is stable for free, collision and constrained motion by using a novel decentralized class of force-position robot control. Impedance can be easily incorporated, though it would not render tracking of both trajectories. This result has been supported theoretically, and experimental evidence suggest a successful exploration of dynamical (deformable) remote objects. Note that the lumped model of the object is calculated at each instant, and resembles the FEA since second order dynamics are computed in every point of the object. The computational cost is quite low, and yet formal stability arguments guarantee stability of the closed-loop system, critical for remote virtual training.

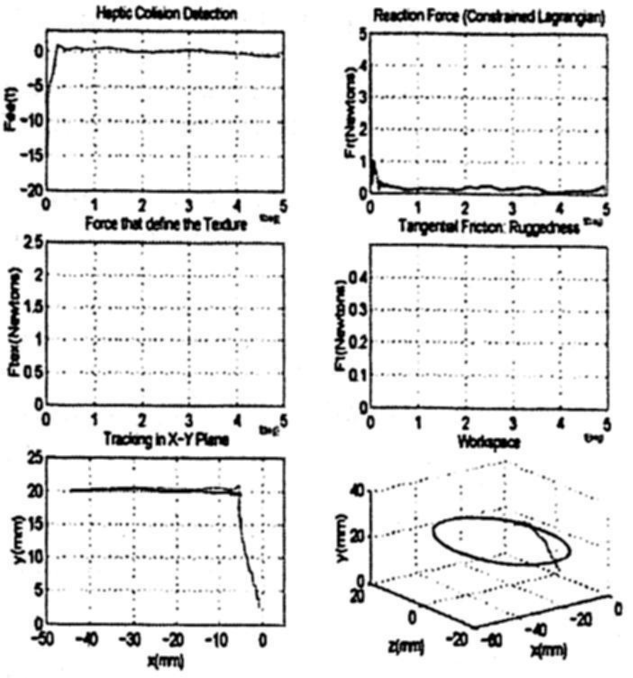

Fig 3. Experiment 1

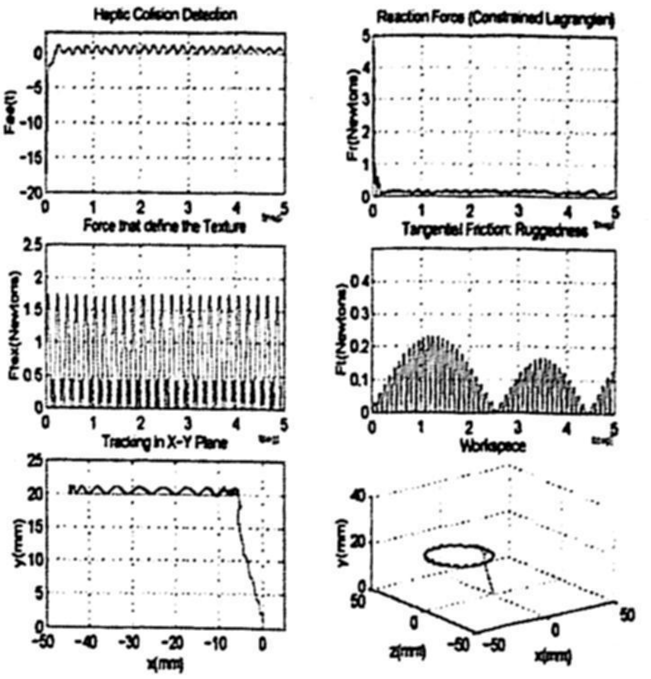

Fig 4. Experiment 2

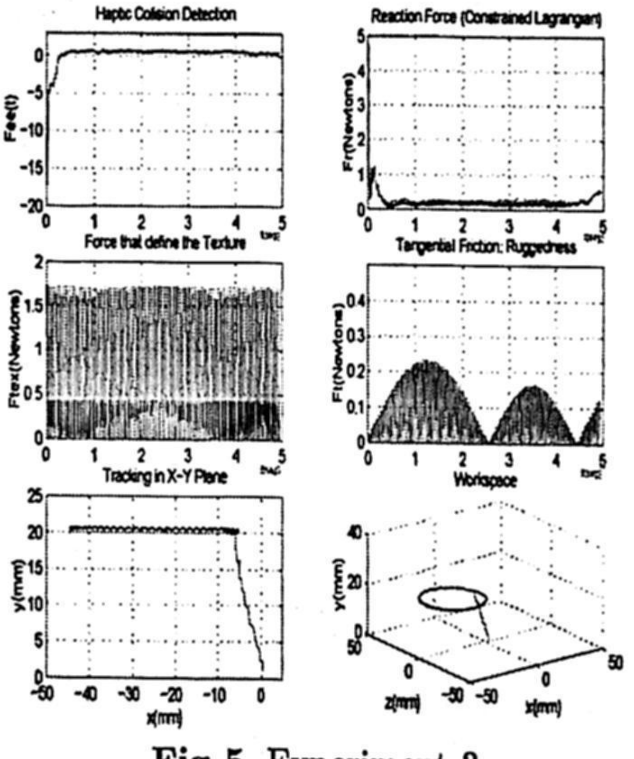

Fig 5. Experiment 3

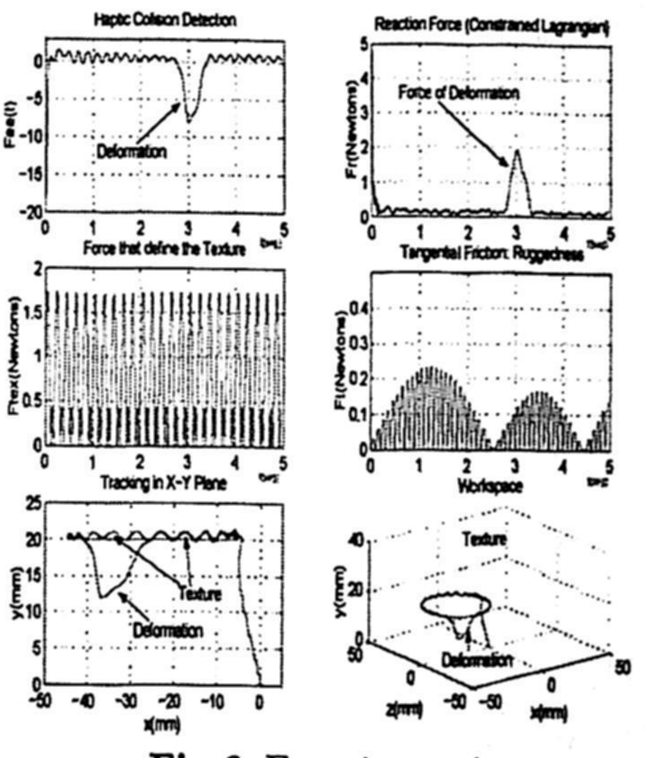

Fig 6. Experiment 4

References

1. G.C. Burdea, *"Force and Touch Feedback for Virtual Reality"*, John Wiley and Sons, Inc., Electrical and Computer Engineering Department, The State University of New Jersey, 1996.

2. Salisbury, J.K. and Mandayam A. Srinivasan. *"Phantom-Based Haptic Interaction with Virtual Objects"*, IEEE Computer Graphics and Applications; Volume 17, Number 5, pp. 6-10; September-October 1997.
3. M. Moreyra, B. Hannaford, *"A Practical Measure of Dynamic Response of Haptic Devices"*, International Conference on Robotics and Automation, Proceedings of the 1998 IEEE, pp. 369-374, Leuven Belgium, 1998.
4. V. Parra-Vega, S. Arimoto *"Nonlinear PID Control with Sliding Modes for Tracking of Robot Manipulator"*, Conference on Control Applications. Proceedings of the 2001 IEEE International.
5. C. Preusche, G. Hirzinger, *"Scaling Issues for Teleoperation"*, The Fifth Phantom user's Group Workshop, Massachusetts Institute of Technology, Cambridge, MA, pp. 39-42, 2000.
6. C.R. Carignan, K.R. Cleary, *"Closed-Loop Force Control for Haptic Simulation of Virtual Environments"*, The Electronic Journal of Haptics Research, vol. 1, No. 2, 2000.
7. V. Parra-Vega, A. Castillo-Tapia, *"Perfect Tracking of Force and Position for Constrained Robot Manipulators with Orthogonal Nonlinear PID Control"*, International Symposium on Robotics and Automation 03, Toluca, México 2003.
8. V. Parra-Vega,L.G. García-Valdovinos, A. Castillo-Tapia and Omar A. Domínguez-Ramírez, *"Sliding PID Control for Tracking in Finite Time for Robot Arms"*, The 11th International Conference on Advanced Robotics, pp. 1526-1531, University of Coimbra, Coimbra, Portugal, 2003.
9. Omar A. Domínguez-Ramírez and Vicente Parra-Vega, *"Constrained Lagrangian-Based Force-Position Control Haptic Guidance"*, pp. 444-450, EUROHAPTICS 2003, Trinity College Dublin and Media Lab Europe, Dublin, Ireland, 2003.
10. Omar A. Domínguez-Ramírez and Vicente Parra-Vega, *"Active Haptic Interface with Purposes of Remote Training"*, The 11th International Conference on Advanced Robotics, pp. 1588-1593, University of Coimbra, Coimbra, Portugal, 2003.
11. O. A. Dominguez-Ramirez, V. Parra-Vega, *"Texture, Roughness, and Shape Haptic Perception of Deformable Virtual Objects with Constrained Lagrangian Formulation"*, IIEEE-RSJ International Conference on Intelligent Robotts and Systems, October 27 - 31, 2003 Bally"s Las Vegas Hottell, Las Vegas„ NV, USA
12. D. Feygin, M. Keehner, and F. Tendick, *"Haptic Guidance: Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill"*, Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, part of IEEE Virtual Reality 2002, Orlando, FL, pp. 40–47, Mar. 2002
13. A. Okamura, M.R. Kutkosky, and J.T. Dennerlein, *"Reality-based Models for Vibration Feedback in Virtual Environments"*, IEEE/ASME Trnasactions of Mechatronics, Vol. 6, No. 3, september 2001, pp. 245-252.
14. P. Akella, V. Parra-Vega., Arimoto S. and T. Tanie, *"Discontinuous Adaptive Control for Robot Manipulators Executing Free and Contrained Tasks"*, Proc. of the IEEE Robotics and Automation, San Diego (1994), pages 3000-3007.