PHANToM OMNI Haptic Device: Kinematic and Manipulability

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***Abstract*—The haptic device kinematics (position and its derivates) allows evaluate the virtual representation of the human operator in a virtual visualization at the same form defines the interaction with virtual objects programs across of a contact and deformation algorithm. The PHANToM OMNI haptic device, allows the kinematic interaction with complex virtual environments, and the potentials of application require of the available of its mathematical models. In this paper we present the kinematic results and the experimental proofs across of knowledge trajectories, such as the evaluation of the kinematic manipulability allows verify the limits of inherent admissible operation at admissible configuration space or workspace, and to this end allows the free architecture to more applications on different engineering fields.**

***Keywords*-PHANToM OMNI; Virtual Environment; Forward Kinematic; Manipulability; Human-Machine Interaction**

I. INTRODUCTION

How introduce the tact sense in the Virtual Environment (VE) has been studied by the haptic for 20 years ago. The recent problem of the virtual reality is the limitation of sense tact stimulus. The contact force feedback or kinesthetic is a haptic research field, works with interaction devices on muscles and tendons and allows at the human operator the sensation that a force is applicated in a virtual world. The tact feedback works with interaction devices on skin terminals nervous, that indicate the presence of heat, pressure and texture (propioreceptors). The PHANToM OMNI is a design of electromechanical device with purpose in kinesthetic feedback, there are many applications to this device, for example: entertainment, teleoperation and medical applications of diagnostic and rehabilitation. The contributions of this haptic device require of the forward and inverse kinematic models, the models allows know the human operator performance and his representation in the virtual world, such as the evaluation of contact detection technics and deformation in particular cases. In this paper we present the approach of the PHANToM OMNI kinematic chain and the position and differential kinematic models, this expression is used to define the torque input vector as a function of the reaction force, this information is compute in the VE to recreate of real form in the end effector (EE) of the haptic device with the human operator in the loop. And finally, a experimental proof of cartesian coordinate trajectory is showed, to this purpose we used the application program interface for this haptic device.

The contribution of this paper is to provide the explicit mathematical models for application development haptic and motion control with the PHANToM OMNI haptic device. The work is organized in 7 sections, section II is a detail technical specifications for the PHANToM OMNI, section III presents the position and differential kinematic models, section IV the study of the PHANToM OMNI device as a haptic interface and the procedure for the synthesis of a VE based on the kinematics obtained, in the section V includes the experimental verification, section VI corresponds to the analysis of operational efficiency and manipulability study applied to the experimental results described in section V and finally the section VII we present the conclusions.

II. TECHNICAL SPECIFICATIONS OF PHANTOM OMNI

The most important technical features of the PHANToM OMNI haptic device correspond to a nominal resolution of 0.055 mm offset in its workspace, a total equivalent weight of 3lb with 5oz, a EE force nominal of 3.3 N (such that the safety limit to be considered by software this magnitude). PHANToM OMNI is a device for kinesthetic active force feedback on the axis x, y and z from the measurement of instantaneous position and velocity to use of joint proprioceptive sensors (optical encoders). The communication interface is IEEE-1394 Fire Wire port and allows real-time programming through class ToolKit 3D Touch at work with Visual C++.

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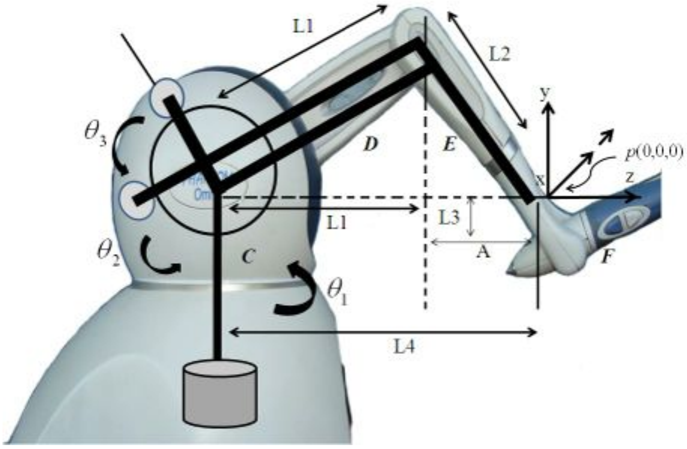

Figure 1. Initial condition of PHANToM OMNI.

III. Kinematic model

A haptic device is designed basen on the work kinematic and dynamic considerations, conventionally attributed in robot manipulators, so the design of models apply to corresponding haptic interfaces, and the methodologies for the synthesis of their mathematical models. The kinematics of the haptic device allows the relationship between the operational coordinates and joints coordinates.

A. Forward kinematic model of position (FKMP)

The FKMP establishing the relations between the operational coordinates (position and orientation of the end effector) and the joint coordinates (joint angles) as shown in (1) [3], [4],

$$x = f(q) \tag{1}$$

where $x \in R^{3x1}$ denote the operational coordinates vector and $q \in R^{3x1}$ is the vector of joint coordinates.

The kinematics chain of the PHANToM OMNI haptic device, and it representation of variables and constants involved in the model are displayed in Fig. 1

Where L1=L2=0.135m represent the length of its links, A=0.035m, L4=L1+A and L3=0.025m same that represent auxiliary variables to obtain the kinematic model. The vector describes the position of the EE is determined from SCC (Source Coordinate Center) until the EE of the manipulator. Initially, the SCC is in the element C (see Fig. 1) where to cut the axes of rotations θ_1 and θ_2, after performing a coordinate transformation to translation from the point (0,0,0) of the device.

The elements of the position vector corresponding to the operational FKMP, is given as:

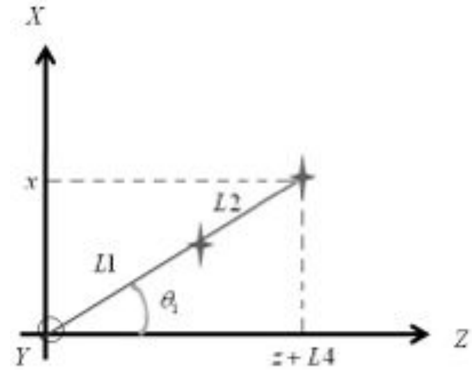

Figure 2. Higher sight of the Kinematic chain of PHANToM OMNI.

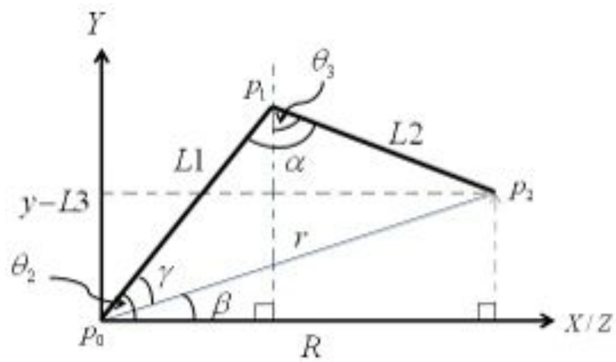

Figure 3. Inverse kinematic of PHANToM OMNI.

$$\begin{aligned} x &= -s_1(L1c_2 + L2s_3) \\ y &= L3 - L2c_3 + L1s_2 \\ z &= -L4 + c_1(L1c_2 + L2s_3) \end{aligned} \tag{2}$$

where $c_x = \cos\theta_x$ and $s_x = \cos\theta_x$.

B. Inverse kinematic model of position (IKMP)

The IKMP is the compute of the angles θ_i of each joint as a function of the EE position in cartesian coordinates and is defined by (3).

$$\theta = f^{-1}(x) \tag{3}$$

The solution to define θ_1, θ_2 and θ_3 as a function of the cartesian coordinates x, y and z, and contribute in the path planning with haptic guidance purposes [7], [5].

Where θ_1, can be determined by simple inspection using Fig. 2, is expressed as follows

$$\theta_1 = -atan2(x, z + L4) \tag{4}$$

For θ_2 and θ_3 makes use of the scheme in Fig. 3, Where:

$$R = \sqrt{x^2 + (z + L4)^2} \quad (5)$$
$$r = \sqrt{x^2 + (z + L4)^2 + (y - L3)^2} \quad (6)$$
$$\beta = atan2(y - L3, R) \quad (7)$$

Applying the cosines law to the triangle with base $\triangle P_0 P_1 P_2$, we obtain the following expression.

$$L2^2 = L1^2 + r^2 - 2L1r\cos(\gamma) \quad (8)$$
$$\gamma = \cos^{-1}\left(\frac{L1^2 + r^2 - L2^2}{2L1r}\right) \quad (9)$$

The physical characteristics of PHANToM OMNI, require that $\gamma > 0$. Accordingly, we obtained θ_2 is,

$$\theta_2 = \gamma + \beta \quad (10)$$

To compute θ_3 using the cosines law for the same triangle $\triangle P_0 P_1 P_2$ and applied to obtain angle α as follow

$$r^2 = L1^2 + L2^2 - 2L1L2\cos(\alpha) \quad (11)$$
$$\alpha = \cos^{-1}\left(\frac{L1^2 + L2^2 - r^2}{2L1L2}\right) \quad (12)$$

This angle is positive according to real workspace PHANToM OMNI. Then:

$$\theta_3 = \theta_2 + \alpha - \frac{\pi}{2} \quad (13)$$

C. Forward kinematic model of velocity (FKMV)

The FKMV is defined as:

$$\dot{x} = J\dot{\theta} \quad (14)$$

Where $\dot{x} \in R^{3x1}$ denote the operational velocities vector, $J \in R^{3x3}$ and represents the Jacobian matrix of the haptic device, and $\dot{\theta} \in R^{3x1}$ defines the joint velocities vector. Deriving (2) and ordering in a matrix form we have [3], [4]:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} J11 & J12 & J13 \\ J21 & J22 & J23 \\ J31 & J32 & J33 \end{bmatrix} \begin{bmatrix} \dot{\theta_1} \\ \dot{\theta_2} \\ \dot{\theta_3} \end{bmatrix} \quad (15)$$

Where, $J11 = -(L1c_1c_2 + L2s_3c_1)$, $J12 = L1s_1s_2$, $J13 = -L2c_3s_1$, $J21 = 0$, $J22 = L1c_2$, $J23 = L2s_3$, $J31 = -L1c_2s_1 - L2s_3s_1$, $J32 = -L1s_2c_1$ and $J33 = L2c_3c_1$.

Technically, the Jacobian matrix is used path and motion planning during haptic guided tasks, and is also used for mapping the vector in a real reaction force on VE to a torques vector necessarily be applied by the joints actuators of the haptic interface device.

D. Inverse kinematics model of velocity (IKMV)

The IKMV is defined by (16) [3], [4].

$$\dot{\theta} = J^{-1}\dot{x} \quad (16)$$

where $J^{-1} \in R^{3x3}$ corresponds to the inverse of the Jacobian matrix and is given as:

$$J^{-1} = \frac{adj(J)}{det(J)} \quad (17)$$

where $adj(J) \in R^{3x3}$ define the Jacobian matrix adjunct and $det(J)$ denotes its determinant, described by:

$$det(J) = -L1L2(L1c_2s_2s_3 + L1c_2^2c_3 + L2s_2 + d) \quad (18)$$

where $d = -L2s_2c_3^2 + L2s_3c_2c_3$, and under the condition of existence: $\theta_3 \neq \theta_2 + \pi/2$, than represents the solution within the space of admissible configurations or nonsingular regions.

IV. PHANToM OMNI haptic interface

A haptic interface is constituted by a human operator, a haptic device and VE. The human operator is stimulated by visual, tactile and kinesthetic information. Based on the initial condition of the tactile and visual, the human operator to modify the VE and with force signals response and the changes in the visual display [2], thereby enabling new dynamic conditions of the interaction. Prospects implementation of a haptic interface are many, particularly purpose of this paper is to report the haptic device in haptic guidance [7], [5], [6] with application on neuroscience in particularly in diagnosis and medical rehabilitation of patients with motor disability, as has previously worked with devices with less efficient [6]. To achieve the compute of the force feedback that stimulates to the human operator kinesthetic is used the force to mapping the torque in each joint.

A. Kinesthetic force feedback

The generalized torque to be supplied to the joint actuators in articulated link mechanism of the haptic device is defined by the following equation [2]:

$$\tau = J^T F \quad (19)$$

where $\tau \in R^{3x1}$ defines the torques vector, J^T is the transpose of the Jacobian matrix and $F \in R^{3x1}$ is the forces vector defined by the interaction in the VE. According (19), the forces vector at the contact point if is defined as $\overrightarrow{F} = (Fx_i + Fy_i + Fz_i)N$ then $\tau_1 = (J11Fx + J21Fy + J31Fz)Nm$, $\tau_2 = (J12Fx + J22Fy + J32Fz)Nm$ and $\tau_3 = (J13Fx + J23Fy + J33Fz)Nm$ and define the torque in each joint. The force that is generated on actuators to provide a sense of presence of a virtual object to this end different algorithms can be used, for example: constrained Lagrangian [5] penalty method (Hooke law), etc. [8].

In the PHANToM OMNI interface, the human operator applies a force F_h to the pencil by changing its joint coordinates, these signals are recorded by sensors or optical encoders. With the use of FKMP and FKMV, is possible to obtain the operational coordinates that to define the position and velocity of the human operator in the VE. Instantly the contact point detector algorithm is evaluated to know the time value at the contact point between the human operator represented in the environment and virtual object. The human operator and the virtual object interactions is used to defined the reaction force (penalty method [2]). With this reaction force f_r is computed the joints torque based on the transformation that define by (19) to recreate the kinesthetic stimulus in the PHANToM OMNI pencil.

V. Experimental verification

For validation purposes and kinematic manipulability studies we present two different experiments. The first is to make a trajectory based on the real environment the top of an aluminum cylinder bottle as shown in Fig. 5, the time of the experiment is 5 s and whole this allows to define of the man-machine interaction systems. The second experiment is based on solving a labyrinth in the plane $x - z$ as shown in Fig. 6, human operator find the labyrinth solution in a time of 10 s. To develop these experiments, it is essential to have a experimental platform with technology requirements to a stable interaction.

A. Characteristics of the workstation

We used a PC Pentium 4 with 1Ghz and 1Gb of RAM, two Intel processors and a GForce3 video card under Windows XP and as programming language is Visual C++ 6.0 using the OMNI class [2], and graphic effects and data analysis test was used MatLab 7.0.

B. Experimental validation of the kinematics

Experimental validation of the algorithm for the validation kinematics corresponds to the flow scheme of Figure 4. 1. Read the operational coordinates x_{dh} and $\dot{x}_{dh}$ through OMNI classes (defined voluntarily by human operator). 2. These results are used in the IKMP and IKMV for to define θ and $\dot{\theta}$. 3. Subsequently, these vectors are evaluated at FKMP for FKMV x_m and $\dot{x}_m$, and are compared with those obtained in step 1 thereof which have been in $\Delta = 0.005mm$ and $\dot{\Delta} = 0.005mm/seg$ with graphical display purposes.

- **Experiment 1**

According to the flow scheme of the Fig. 4, the operational path during the human operator tracking and define by the aluminium cylinder bottle is based on the PHANToM OMNI classes [2], the real trajectory in the workspace is illustrated in Fig. 7.

The Fig. 8 and Fig. 9 represent to the experimental results that validate the functionality of the models FKMP and FKMV, and its variation instant is constant and defined

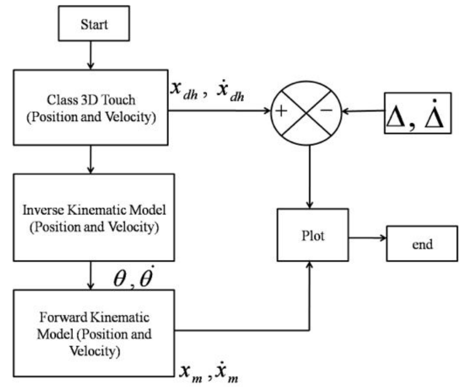

Figure 4. Kinematic chain of PHANToM OMNI.

Figure 5. Experiment 1.

Figure 6. Experiment 2.

by the increases previously described for purposes of comparative graphical display.

- **Experiment 2**

In the Fig. 10 there are two paths that are developed by a human operator with two different condition: acceptable health and a patient with motriz disabilities in the upper limbs, the task corresponds in solve the labyrinth (Fig. 6). In the Fig. 11 and Fig. 12 presents the validation of kinematic position and velocity respectively, because this real labyrinth path is on the plane $x - z$, and the component over y there is

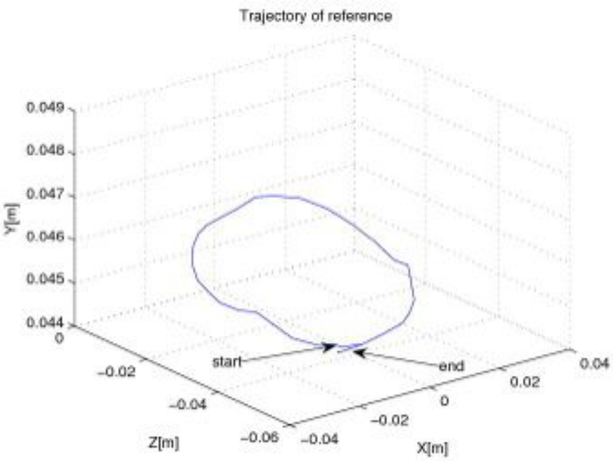

Figure 7. Trajectory of the experiment 1.

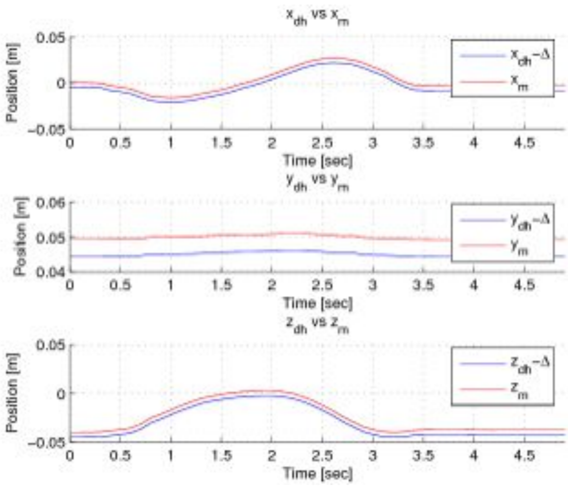

Figure 8. Validation of the FKMP experiment 1.

constant (Fig. 11b), in this condition the velocity is tending to zero (Fig. 12b).

VI. Manipulability

Manipulated index (MI) is used to compute the efficiency of the PHANToM OMNI haptic device when the task there is operating over the workspace and thus able to define the singular zones of the device that somehow represent a mechanical effort. Yoshikawa [1] proposes an strategy as a function of the Jacobian J of the device that is defined in (20),

$$MI = \sqrt{|JJ^T|} \tag{20}$$

The MI of the experiment 1 is presented in Fig. 13, with the operational navigation of the EE PHANToM OMNI based on the real human evolution and its position with respect to the singular zones in its workspace. In the Fig. 14

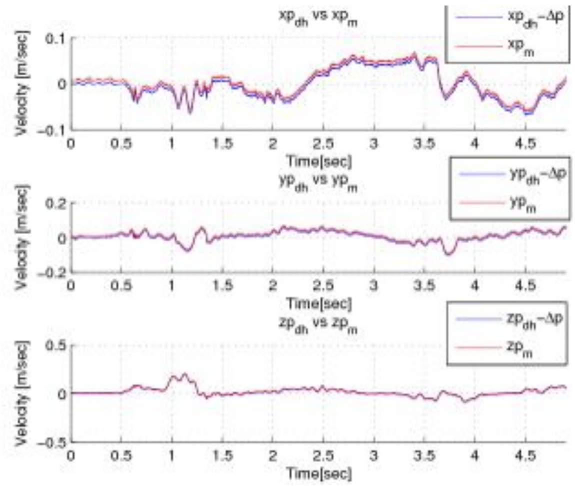

Figure 9. Validation of the FKMV experiment 1.

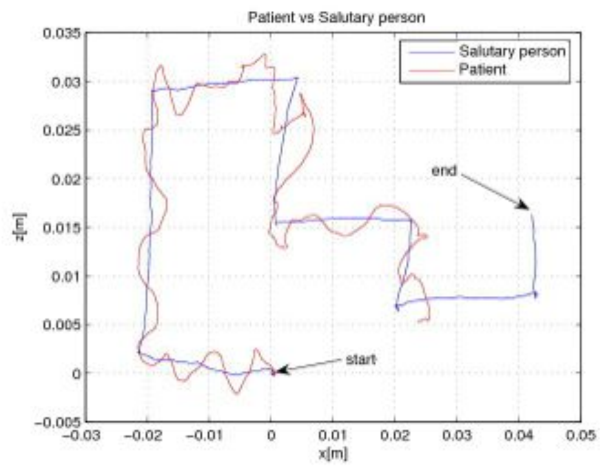

Figure 10. Trajectory of the experiment 2.

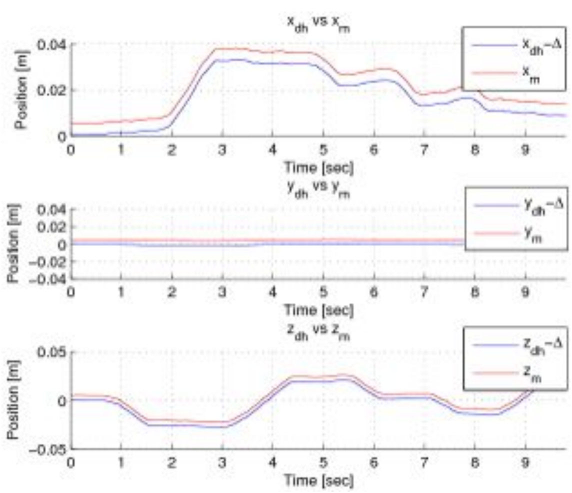

Figure 11. Validation of the FKMP experiment 2.

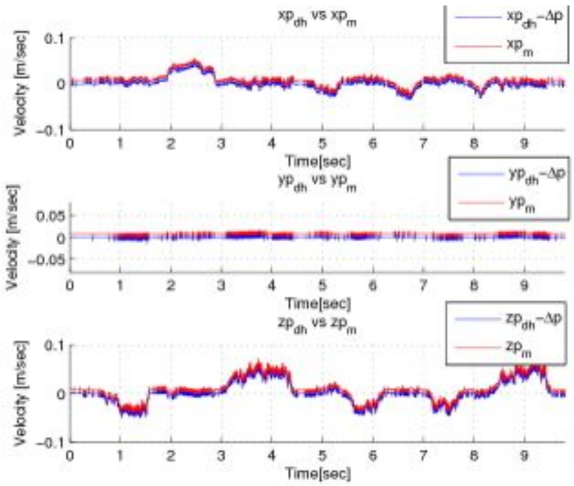

Figure 12. Validation of the FKMV experiment 2.

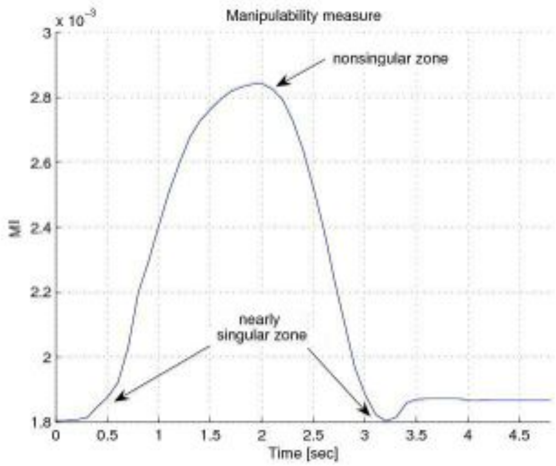

Figure 13. MI: Experiment 1.

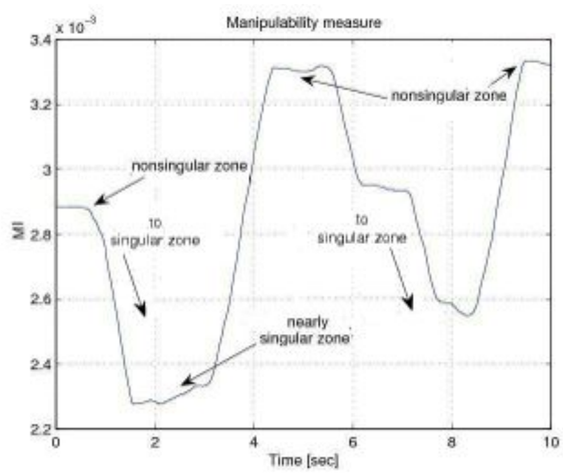

Figure 14. MI: Experiment 2.

presents the MI very different that the show in the Fig. 13 there are significant changes, since it represents significant motion in different workspace configuration.

VII. Conclusions

The final results that we represent in this paper allow to evaluate the PHANToM OMNI in different experiments applications as a haptic device to human-machine interaction with VE or robotic mechanism with the haptic guidance purposes for example in training, teleoperation and medical applications. The experiments that are present allows verify the performance of the device and confirm the mathematic models. The MI show the admissible configuration without mechanical effort that contribute to life long and excellent performance.

VIII. Acknowledgments

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References

[1] Yoshikawa,T., *Foundations of Robotics:Analisys and Control* Cambridge, MIT Press, 1990.

[2] SensAble Technologies, *PHANTOM OMNI, 3D Touch Components: Hardware Installation and Technical Manual* Revision 6.5, Massachuset, 2000.

[3] Mark W. Spong, M. Vidyasagar, *Robot Dynamics and Control*, John Wiley Sons, Canada, 1989.

[4] Richard M. Murrey, Zxiang Li and S. Shonkar Sastry, *Robotic Manipulation*, 3 edition CRC Press, Florida, 1994.

Articles

[5] Dominguez-Ramirez, O. A. and V. Parra-Vega, *Texture, Roughness and Shape Haptic Perception of Deformable Virtual Objects with Constrained Lagrangian Formulation*,IEEE/RSJ International Conference on Intelligent Robots and Systems, Proceedings of IROS 2003 ISBN 0-7803-7861-X, Vol. 4, pp. 3106-3111, 2003.

[6] Dominguez-Ramirez, Omar. A. and L. R. Samperio-Llano, *Technology of Haptics Interfaces with Purposes of Diagnosis of Patient with Neuropsychological Illnesses*, Proceedings of the Fifth Mexican International Conference in Computer Science (ENC04), September, pp. 262- 267, Las Vegas, Nevada, 2004.

[7] Dominguez-Ramirez Omar A. and Vicente Parra-Vega, *Haptic Remote Guided Exploration of Deformable Objects*, International Mechanical Engineering Congress and Expositiona November, Washington DC, USA, 2003.

[8] Dominguez-Ramirez, O. A. and V. Parra-Vega, *Constrained Lagrangian-Based Force-Position Control for Haptic Guidance*, Proceedings of Eurohaptics 2003, Incorporating the PHANToM Users Research Symposium. Trinity College Dublin and Media Lab Europe, Dublin, Ireland pp. 444-450, 2003.