Constrained Lagrangian-Based Force-Position Control for Haptic Guidance

O. A. Domínguez-Ramírez and V. Parra-Vega

Mechatronics Division - CINVESTAV, México.
(omar,vparra)@mail.cinvestav.mx

Abstract. A methodology, and its experimental validation, is presented to compute the contact force as the solution of the differential algebraic equations that arise from the dynamical haptic display (PHANToM) and a dynamical (deformable) virtual object. Based on this dynamics, a reaction force based on the constrained Lagrangian is computed to reproduce a realistic contact force as a function on the dynamical properties of the whole system. Then, a haptic guidance scheme is implemented to yield an active haptic guidance with purposes of remote training, with simultaneous control of force and position on the remote station. Key words: Haptic Guidance, Control, Constrained Lagrangian.

1 Introduction

Force reflecting human-machine interfaces provides the operator with useful kinesthetic information in teleoperation task and virtual reality applications. The kinesthetic and tactile perception is possible by means of the use of an electromechanical device (haptic device) in closed loop with the virtual environment [1], [2]. However, contact force computed with Hooke's Law (penalty method) does not guarantee a realistic interaction with the operator because this contact force is computed with a kinematic model while the system is immersed into a dynamical world. Since operator is accustomed to a realistic dynamical deformation of objects when interacted with, then the key to establish a realistic interaction is to assign dynamics to the virtual objects, and to compute the contact force based on this dynamics, as well as the dynamics involved with the haptic device, the PHANToM in our case. The effect that the dynamic-based reaction force has in the immersion process of a haptic guidance interface is the main purpose of this paper. It is shown that interaction with the constrained Lagrangian allows better interaction in contrast to the hugely popular among the haptic research community contact force model based on the Hooke's Law called penalty-based method. A haptic guidance scheme is implemented to yield an active haptic guidance with purposes of remote training, with simultaneous control of force and position on the remote station.

2 Dynamic Constraints of PHANToM

When PHANToM is in contact to a kinematic-based virtual world $\varphi(q) = 0$ the following algebraic differential system of equations arises [5], [6]

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

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

For definitions and details see [5] and [6].

3 Dynamical Object and Lagrangian-based Contact Force

A virtual object model can be modeled in terms of the generalized coordinates q as a mass-spring-damper system as $m\ddot{\xi}(q) + b\dot{\xi}(q) + k\xi(1) = 0$, where m is the mass, b is viscous coefficient of the damper and k is the stiffness coefficient of the spring. For stable interaction, 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 the virtual object can be represented by $m\ddot{\vartheta}(q) + b\dot{\vartheta}(q) + k\vartheta(q) = 0$, thus (2) becomes

$$m(J_\vartheta\ddot{q} + \dot{J}_\vartheta\dot{q}) + b\dot{\vartheta}(q) + k\vartheta(q) = 0 \tag{3}$$

Solving by using (1) and (3), the constrained Lagrangian force f_r can be computed as follows

$$f_r = \frac{\left\| J_\vartheta J_\vartheta^T \right\|}{m J_\vartheta M(q)^{-1} J_\vartheta^T} \left\{ -b\dot{\vartheta}(q) - k\vartheta(q) - m\dot{J}_\vartheta \dot{q} + m J_\vartheta M(q)^{-1} D_p \right\} \tag{4}$$

where $D_p = C(q,\dot{q})q + G(q) - \tau$. The experiment consists on a random sliding over the surface of a virtual sphere. The object (sphere) is rounded without tangential friction, thus buzzing or trembling should not appear, otherwise it would not be realistic. That is contact frequency F_{sc} must be 0KHz . A collision detection algorithm is implemented to determine either free or constrained motion or impact. The benefit of applying the constrained Lagrangian method, in contrast to the penalty-based method, can be observed through F_{sc} . Experiments results shows that using (4) stable interaction is established without trembling, F_{sc} = 0Hz , see figures 3 and 4), in contrast to the F_{sc} = (0.11,1)KHz of the penalty method, see figures 1 and 2.

4 A Proposal for Active Haptic Guidance

A haptic guidance scheme consists of a trainer (master) and a student (slave). The trainer generates the position references (free motion) or position and forces (constrained motion) to be followed by the student (the PHANToM in this paper). The student is the haptic PHANToM interface. Both, the trainer and the student share the same virtual environment. To control the student, a nonlinear sliding PID control [5] and a nonlinear force-position sliding PID control [6] are proposed for free and constrained motion, respectively, This controller compensates the nonlinear dynamics of continuous mechanical plants with very fast tracking capability, see figure 5. Experimental results shows that deformation on the virtual object arises, and stable interaction is established with F_{sc} = 0Hz, see figure 6.

5 Conclusions

First, a constrained Lagrangian based contact force is proposed to guarantee realistic interaction between a human operator and a virtual environment. This allows us experimentally to verify that dynamic interaction is established effortlessly without buzzing or trembling. Then, this contact force is used in a haptic guidance scheme. Advanced haptic control is implemented in the student station to be trained affectively by a behavior determined by the trainer in the master station. Experiments verifies our proposed haptic guidance scheme.

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. B. Gillespie and J. E. Colgate. "A Survey of Multibody Dynamics for Virtual Environments",Proceedings of the ASME IMECE, DSC-Vol. 61, Dallas, TX. Nov 15-20, 1997. pp. 45-54.
3. 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.
4. 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.
5. 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.
6. 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.

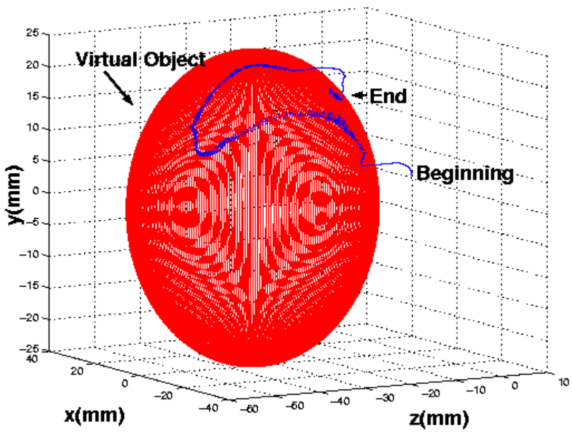

Fig. 1. Penalty Method. With k = 2000 N/m buzzing arises.

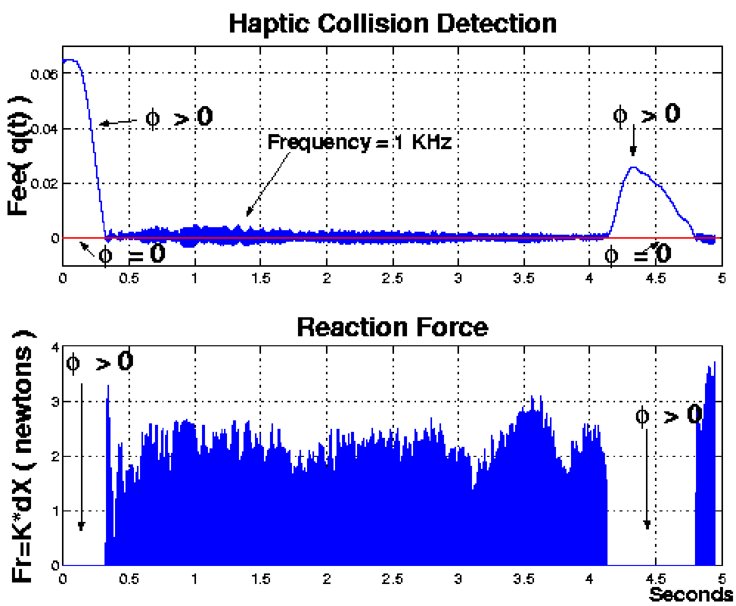

Fig. 2. Penalty Method. Collision Detection and Reaction Force.

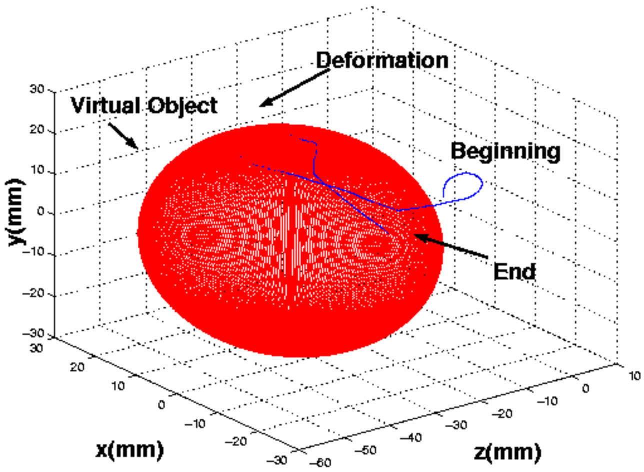

Fig. 3. Constrained Lagrangian. m = 1.25 kg, b = 100 Ns/m, yk = 2000 N/m. No buzzing appears.

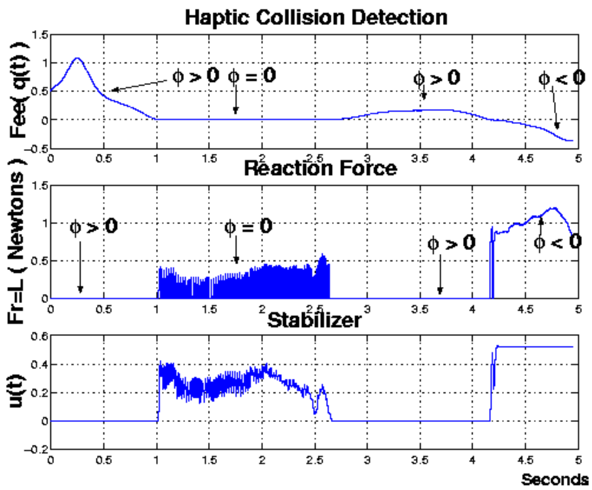

Fig. 4. Constrained Lagrangian. Collision Detection and Reaction Force.

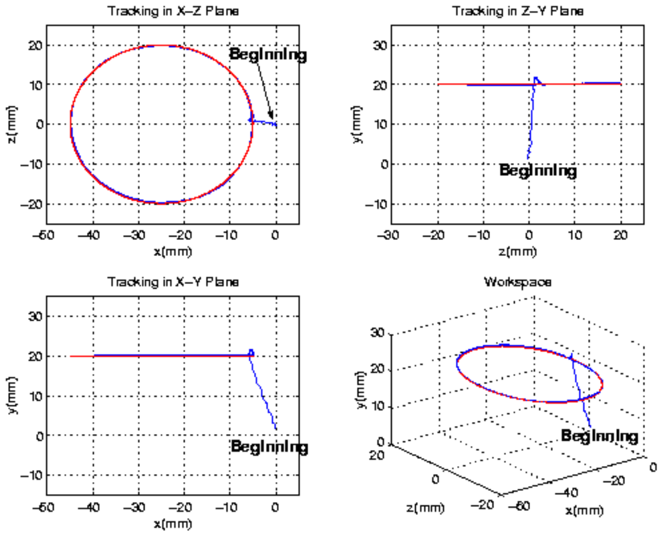

Fig. 5. Experimental behavior of the real and desired trajectory (Free Motion).

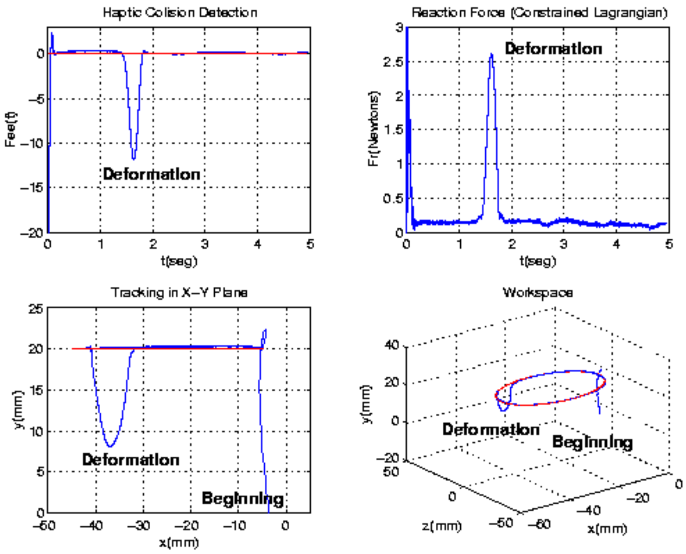

Fig. 6. Experimental behavior of the real and desired trajectory with deformation (Constrained Motion).