Continuous Impulsive Force Controller for Forbidden-Region Virtual Fixtures

D. Hennekens, D. Constantinescu and M. Steinbuch

***Abstract*— Forbidden-Region Virtual Fixtures (FRVFs) are traditionally imposed on users via proportional-derivative (PD) control. To reduce user penetration into the forbidden region, this paper proposes a new controller, hereafter called Continuous Impulsive Force (CIF) controller. The CIF controller generates passive impulsive forces throughout users' motion into the forbidden region. These impulsive forces annihilate users' velocity into the forbidden region. Superimposed on typical PD control forces, the CIF control forces reduce users' incursion into the forbidden region, and render the feel of fully plastic collisions.**

I. INTRODUCTION

Alongside visual and audio feedback, force feedback improves the interaction between a human and a remote environment (RE) in teleoperation applications, or between a human and a virtual environment (VE) in haptics applications. Typically, the goal of force feedback is to faithfully relay to users the slave - RE interaction in teleoperation systems, or the virtual tool (VT) - VE interaction in haptics applications, respectively. More recently, force feedback control algorithms have been proposed to implement virtual fixtures (VFs). First introduced in [1], VFs improve users' performance in telemanipulation tasks via providing users with abstract sensory information overlaid on a workspace of interest. In addition to teleoperation applications, VFs may also improve users' performance in virtual reality-based training applications. For example, medical residents training for surgical procedures on haptic setups may learn faster to avoid critical anatomic features if VFs preventing users from intruding into sensitive tissue are implemented in the VE.

Virtual fixtures fall into two categories: Guidance Virtual Fixtures (GVFs) and Forbidden-Region Virtual Fixtures (FRVFs). When the slave robot of a master/slave teleoperation system or the virtual object (VO) controlled by the user in a haptics application needs to follow a prescribed path within the RE or within the VE, respectively, GVFs are implemented in order to assist the user with the desired task. Various techniques for designing and implementing GVFs can be found in [2], [3], [4], [5], and [6]. FRVFs are designed in order to hinder slave incursions into specific RE areas, or VO motions into predefinded VE regions. Traditionally, FRVFs are implemented via high gain PD controllers which compliantly oppose users' motion into the restricted areas. Examples of PD-based FRVF design can be found in [3], [7], and [8]. The stability of this type of FRVFs is considered in [9]. According to [8], FRVFs implemented via PD control can reduce the magnitudes of incursions into forbidden regions by up to 80%. While this represents outstanding performance, the following remarks suggest that room for improvement may still exist:

- *Magnitude of penetration:*
  Minimizing undesirable intrusions into forbidden areas requires increased gains of the PD controller in REs and stiffer virtual constraints in VEs. However, due to factors like the sampling frequency of the force control loop and the physical damping in the system, these gains are limited or the interaction becomes unstable. In addition, FRVF implemented via PD control require users to have intruded into the restricted region in order to counteract users' motion.
- *Users' perceptual experience:*
  PD control renders the feeling of intruding into compliant environment. Moreover, because the FRVFs implement discretized unilateral constraints, they may be active and cause the slave in the RE or the VO in the VE to bounce.

A smaller magnitude of penetration is favorable in teleoperation tasks, where delicate tissues or objects are at risk. Examples are of course teleoperation surgery, but also working with nano-scale devices through a teleoperator. A realistic haptic feedback is crucial when simulating interactions with rigid objects. As [10] points out, when it comes down to exploration of hard surfaces such as surface deformations, sharp edges, and other small discontinuities, the sense of touch becomes the dominant source of information. In recent work, [11] designs a Dynamically-Defined Virtual Fixture whereby the virtual constraint changes position interactively, depending on the velocity of or the force applied by the user. In other words, the Dynamically-Defined Virtual Fixture moves closer or further away from the forbidden area and thus, creates a safe zone. While this approach does not change the haptic experience or the penetration into the VF, it reduces users' penetration into the real forbidden area. Implementing Event-Based Haptic Feedback [10] improves the users perception significantly, but does not affect the magnitude of penetration into the forbidden area. When Impulsive Force (IF) control is implemented upon VO contact with the VF as proposed in [12], not only the magnitude of penetration decreases considerably, but also the haptic

D. Hennekens is student of the Faculty of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands d.w.t.hennekens@student.tue.nl

D. Constantinescu is with the Faculty of Mechanical Engineering, University of Victoria, Victoria BC, Canada danielac@me.uvic.ca

M. Steinbuch is with the Faculty of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands m.steinbuch@tue.nl

experience of the user improves. The counteracting impulsive force dissipates most of the kinetic energy of the VO at the moment of impact. As a result, less energy is transferred to the compliant VF and VO penetration into the VF is reduced. Furthermore, the excess energy returned to the VO by the discrete-time implementation of the VF is typically less then the energy dissipated by the impulsive force, and the user bounces off the VF less. The FRVF implementation via IF control also changes users' perceptual experience, as it increases the perceived stiffness of the VF through increasing its rate hardness [13]. Although the implementation of IF control within the FRVF framework improves both users' perceptual experience and the control effectiveness as measured by the depth of VO incursion into the forbidden region, further improvements are still possible.

In this report, a new control scheme, hereafter called the Continuous Impulsive Force (CIF) control, is developed for implementing FRVFs. The proposed algorithm is designed such that unwanted user motions into the protected regions are shallower and such that users perceive intrusions into sensitive areas as fully plastic collisions. Specifically, the passive impulsive forces applied to users through CIF control are computed similarly with the impulsive forces applied through IF control. However, the CIF control forces are computed throughout users' motion inside the FRVF and users feel them regardless whether the VO moves into the FR or outside it as long as users push the VO into the FR. The proposed algorithm is validated experimentally for haptic interaction within VEs. While the extension of the algorithm to telemanipulation is straightforward when an accurate dynamic model of the slave is available, work in progress investigates its implementation in the presence of slave model inaccuracies.

The paper starts by introducing the proposed CIF control implementation of FRVF in Section II. The experimental validation of the CIF controller is presented in Section III through comparing its efficacy both with that of typical PD control and with that of IF control. Conclusions and future work end this report in Section IV.

II. CONTINUOUS IMPULSIVE FORCE CONTROL FOR FRVF IMPLEMENTATION

The haptic rendering of rigid body collisions introduced in [12] forms the basis of the CIF control proposed herein for implementing FRVFs. This haptic rendering method translates directly into IF control in the implementation of FRVFs. In other words, IF control models a FRVF as a virtual constraint that is infinitely stiff upon VO intrusion into it, and has a limited stiffness thereafter. This IF control implementation of FRVFs is physically based and applies passive impulsive forces to users when the VO enters the forbidden region. In contrast, CIF control lacks a physical interpretation. It simply aims to reduce to zero the velocity of the VO along the direction normal to the restricted area (i.e., the VO normal velocity) during VO incursions into this area.

To achieve its goal, CIF control avails of the passivity of the impulsive forces computed using Newton's restitution law in the IF control implementation of FRVFs. It employs a Newton's restitution law-like method to compute the impulsive forces to restrict VO motions into critical zones. Since the goal is to eliminate the VO normal velocity throughout violation of restricted areas, the "coefficient of restitution" used to compute the impulsive force that drives this velocity to zero in one control step is assumed to be zero. Moreover, the impulsive feedback is applied regardless of whether the VO approaches or separates from the forbidden region provided users push the VO into it. Under these assumptions, the impulsive forces $\boldsymbol{F}_{CIF}$ become (see [12] for a detailed derivation):

$$\boldsymbol{F}_{CIF} = \frac{-\left(\boldsymbol{\mathcal{J}}_c \boldsymbol{M} \boldsymbol{\mathcal{J}}_c^T\right)^{-1} \boldsymbol{\mathcal{J}}_c \boldsymbol{v}_0}{\Delta t}, \qquad (1)$$

where $\boldsymbol{\mathcal{J}}_c =$ is the Jacobian of the VF, $\boldsymbol{M}$ is the mass matrix of the VO, and Δt is the step of the force control loop. All quantities in (1) are computed as described in [12].

The impulsive forces are superimposed on traditional PD control forces in the CIF implementation of FRVFs. This is because impulsive forces alone control only the VO velocity and cannot prevent drift. As discussed above, they are designed to reduce to zero the normal velocity of the VO and thus, of the user as long as the user pushes the VO into a forbidden region. A favorable side-effect of this design is that they decrease unwanted incursions into protected areas. These features of the proposed CIF controller are illustrated via an experiment in the next section.

III. EXPERIMENTS

A. Experimental setup

In this section, the efficacy of CIF control is compared experimentally to the efficacy of typical PD control and of IF control for the implementation of FRVFs. The planar haptic device shown in Fig. 1 is used in the experiments.

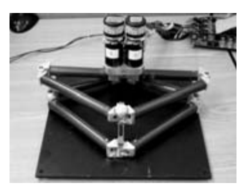


Fig. 1. 3 DOF haptic device

All control schemes are implemented using the architecture shown in Fig. 2. In this architecture, the VE is generated synchronously with the force control loop at a frequency of 512Hz, on a computer which runs the VxWorks real-time operating system. Users are provided with visual feedback by a client Windows machine at a frequncy of 30Hz.

For simplicity, the FRVFs are implemented as virtual constraints that form a square enclosure around the rectangular VO controlled by the user (see Fig. 3). The mass of the VO is 2kg, and its dimensions are 2.1cm and 4.2cm, respectively.

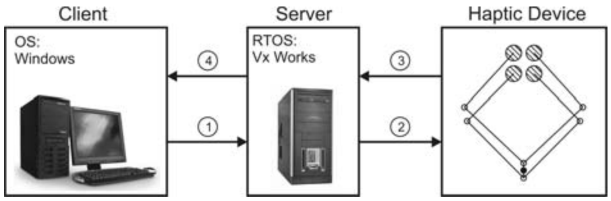


Fig. 2. Computer architecture used to implement FRVFs.

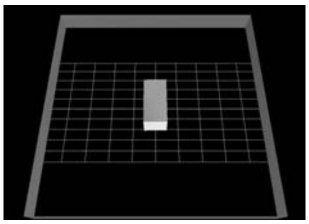


Fig. 3. Testbed VE. The forbidden region is represented as a square enclosure around the rectangular VO controlled by the user.

B. Implusive Force (IF) Control Implementation of FRVFs

In the experiments presented in this and in the following sections, the user repeatedly pushed the VO into the right FRVF until the desired VO normal velocity upon violation of the forbidden region was achieved. This desired normal velocity was equal to 50mm/s, 100mm/s or 150mm/s, respectively. These velocities are chosen because they represent a velocity domain, that covers merely all impacts with the FRVFs, using this haptic setup. Almost similar velocities are used in experiments of [8], and [10]. Furthermore, the VO was kept perpendicular to the restricted zone while moving into it. Just before the start of the unwanted VO motion, the user retracted their hand from the haptic device and thus, had no inflence on the dynamics during the FRVF violation itself. The gains of the PD control forces are 15000N/m for the proportional component and 100Ns/m for the derivative component in all experiments.

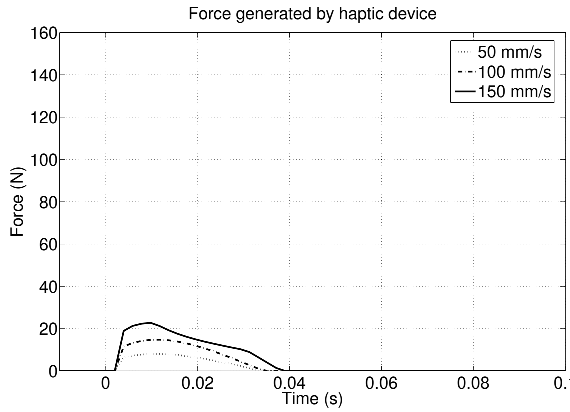
The effect of IF control on the VO violation of FRVFs is shown in Fig. 4. In particular, Figs. 4(a) and 4(b) illustarte the forces applied to users during their incursions into the forbidden region when the FRVF is implemented via typical PD control and via IF control, respectively. In these figures, a positive force represents a force perpendicular to the boundary of the critical area and directed out it. Note that both control algorithms counteract the VO motion until the VO exists the FRVF. The impulsive force seeks to dissipate all kinetic energy of the VO within one time step and hence, it is much larger than the initital force generated via PD control. After this first control step, the IF control is equivalent to the traditional PD control. The magnitude of the VO violation of the forbidden region is depicted in Figs. 4(c) and 4(d). These figures show that IF control more than halves the undesired motion compared to conventional PD control. Lastly, Figs. 4(e) and 4(f) plot the kinetic energy of the VO due to its normal velocity. This is done in order to exclude the effect of the (small) velocity along the FRVF boundary and of the (small) angular velocity of the VO. Fig. 4(f) illustrates the sudden drop in the VO kinetic energy upon the start of the unwanted motion. Another advantage of the IF control is that the kinetic energy of the VO is much lower when it leaves the forbidden region. In other words, besides reducing the magnitude of the undesirable incursion, IF control makes the FRVF feel less elastic. This is particularly advantageous when the forbidden region geometry is such that users have only a narrow clearance through which they are allowed to move.

C. Continuous Implusive Force (CIF) Control Implementation of FRVFs

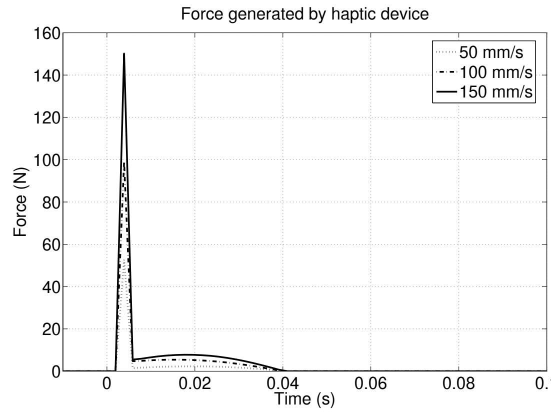
Since IF control is able to bring the normal velocity of the VO to zero within one time step, CIF control seeks to keep the normal velocity zero throughout the time that users intrude into a forbidden region. As discussed in Section II, CIF computes a new impulsive force at each control step during unwanted user motions. Hence, CIF control drives the normal velocity of the VO to zero until the VO leaves the forbidden region or the users pulls it away. This ensures that users do not perceive a sticky FRVF and can move out of the protected area when they choose to. Because CIF control dissipates the kinetic energy of the VO as soon as it is generated by the PD component of the controller, the VO does not bounce off of the VF. In turn, users perceive their offending motion as fully plastic contact with the VF.

To validate the proposed implementation of FRVFs, the experiments described in Section III-B and depicted in Fig. 4 are performed again using CIF control. Fig. 5 contrasts the performance of CIF control to that of IF control. This figure illustrates several differences between CIF and IF control. In particular, Figs. 5(a) and 5(b) depict the following:

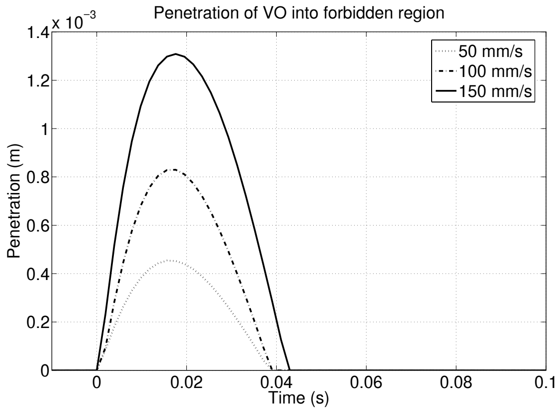
- The initial force generated by CIF control is larger than the initial force generated by the IF control because of the additional PD component.
- The VO violates the forbidden region longer when the FRVF is implemented via CIF control then when it is implemented via IF control. This is because the energy generated by the discrete time PD controller is dissipated continuously via CIF control. As noted in Section III-B, this may be advantageous when users must navigate through narrow permissible regions.
- The CIF controller applies forces that both push users away from the restricted area and pull users in this area, while IF control only pushes users away. This demonstrates that CIF control not only counteracts the motion of the VO into the forbidden region, but also the VO bouncing off of the VF caused by PD control. Hence, CIF control allows users to perceive their incursion into a forbidden region as fully plastic contact with the VF.
- The damped sinusoidal VO path after the larger initial impulsive forces indicates the existence of a damped mass/spring system. During undesirable user motions, the VO under PD control can indeed be considered a mass/spring system. Because the mass of the VO m_{vo} is



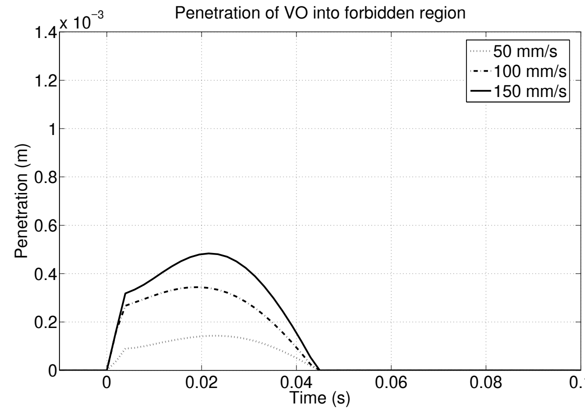
(a) Force applied to user via PD control.



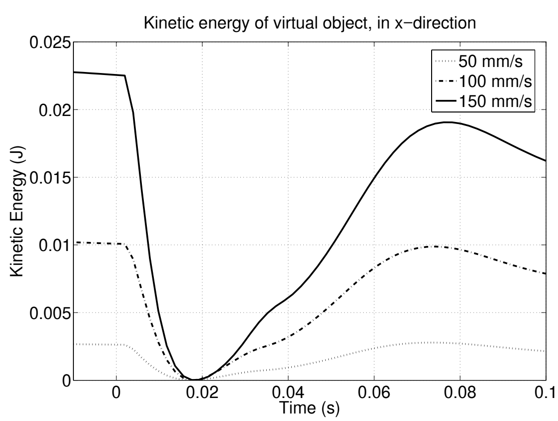
(b) Force applied to user via IF control.



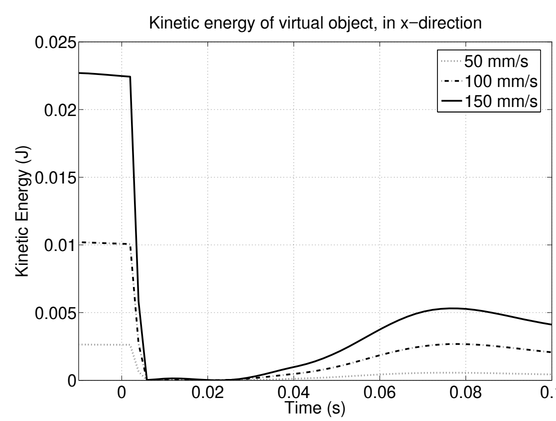
(c) FRVF violation under PD control.



(d) FRVF violation under IF control.



(e) Kinetic energy of the VO under PD control, x-direction.



(f) Kinetic energy of the VO under IF control, x-direction.

Fig. 4. Experimental data collected during violation of the FRVF under traditional proportional-derivative (PD) and under impulsive force (IF) control.

2kg and the stiffness of the PD controller is 15000N/m, the natural frequency ω_0 of this system is:

$$\omega_0 = \sqrt{\frac{K_{pd}}{m_{vo}}} = \sqrt{\frac{15000}{2}} \approx 86.6 \text{ rad/s}, \qquad (2)$$

and the period of oscillation is:

$$T = \frac{2\pi}{\omega_0} \approx 0.073 \text{ sec}. \qquad (3)$$

The VO penetration into the forbidden region is depicted in Figs. 5(c) for IF-control and 5(d) for CIF-control, respectively. These plots support the conclusions drawn from the plots of forces applied to users by CIF and IF control, including those concering the duration of unwanted motion, the mass/spring system and the larger initial force applied to users by the CIF controller. Additionally, Figs. 5(c) and 5(d) show that CIF control slightly decreases users' travel into the restricted zone compared to IF control. The smaller maximum penetration comes at the price of a longer penetration time. Thus, the FRVF designer needs to decide which VF controller is more suitable for their specific application. Figs. 5(e) and 5(f) show the kinetic energy of the VO during violation of a VF implemented via IF control and via CIF control, respectively. The key conclusion that can be drawn from these plots is that CIF imparts negligible kinetic energy to the VO while the VO moves out of the forbidden area. Thus, CIF control enables users to experince violation of a FRVF as fully plastic collision. The experimental results are summarized in Table I.

	vel. (mm/s)	**PD**	**IF**	**CIF**
max. magnitude	50	0.45	0.15	0.12
of	100	0.82	0.34	0.24
penetration (mm)	150	1.31	0.49	0.42
max. duration	50	0.04	0.045	0.20
of	100	0.04	0.045	0.27
penetration (s)	150	0.04	0.045	0.29
max. KE	50	2.5	1.0	0.0
after	100	10.0	2.5	0.0
penetration (mJ)	150	19.0	5.0	0.0

TABLE I

EXPERIMENTAL RESULTS

IV. CONCLUSIONS AND FUTURE WORK

The experiments described in this work validate that the proposed CIF control has several advantages compared to IF and to PD control for implementing FRVFs. The main advantages are: (a) the decrease in the magnitude of the incursion into the forbidden region; and (b) users' perception of the intrusion as fully plastic collision with the VF.

One drawback of CIF control is the increased time that the users spend inside the protected region. For example, an impact at the highest initial normal velocity of 150mm/s results in a penetration of approximately 0.3secs. This is three times longer than the penetration time during PD control or during IF control. However, because the bandwidth of the human voluntary motions is approximately 10Hz, this unwanted effect is not felt by users and may not be a problem in all applications. Another weakness of CIF control for FRVF implementation is that its stability is not yet proven. Work in progress seeks to eliminate this problem.

In addition to investigating the stability of CIF control, future work will pursue several directions. First, the application of CIF control to telemanipulation will be investigated. Then, the proposed CIF control may be combined with the Dynamically-Defined Virtual Fixtures proposed in [11]. For example, an user motion into a FRVF could be predicted based on position and speed. The prediction could trigger a CIF controller before the actual offending motion begins. In turn, users' kinetic energy would partially be dissipated in advance, and a smaller magnitude and sorter duration of the unwanted motion could result without sacrificing users' perceptual experience.

V. ACKNOWLEDGMENTS

The authors thank Professor Tim Salcudean of UBC for kindly providing the haptic setup used for the experiments.

REFERENCES

[1] L. B. Rosenberg, "Virtual fixtures: Perceptual tools for telerobotic manipulation", *Proc IEEE Annual Int Symp Virt Real*, 1993, pp. 76-82.

[2] D. Aarno, S. Ekvall, and D. Kragic, "Adaptive Virtual Fixtures for Machine-Assisted Teleoperation Tasks", *Proc IEEE Int Conf Robotic Autom*, Barcelona, Spain, 2005, pp. 1139-1144.

[3] J.J. Abbott, P. Marayong, and A.M. Okamura, "Haptic Virtual Fixtures for Robot-Assisted Manipulation", *Robotic Res, Springer Tracts in Adv Robotic*, Vol. 28 (Proc Int Symp Robotic Res, 2005), S. Thrun, H. Durrant-Whyte, and R. Brooks, Eds., 2007, pp. 49-64.

[4] A. Bettini, P. Marayong, S. Lang, A.M. Okamura, and G.D. Hager, "Vision-assisted control for manipulation using virtual fixtures", *IEEE T Robotic*, vol.20, no.6, Dec. 2004, pp. 953-966.

[5] A.B. Kuang, S. Payandeh, Bin Zheng, F. Henigman, and C.L. MacKenzie, "Assembling virtual fixtures for guidance in training environments", *Proc Int Symp Haptic Interf Virt Envir Teleop Syst (HAPTICS'04)*, Chicago, IL, March 2004, pp. 367-374.

[6] J.T. Nolin, P.M. Stemniski, and A.M. Okamura, "Activation cues and force scaling methods for virtual fixtures", *Proc Symp Haptic Interf Virt Env Teleop Syst (HAPTICS 2003)*, Los Angeles, CA, March 2003, pp. 404-409.

[7] S. Park, R.D. Howe, and D.F. Torchiana, "Virtual Fixtures for Robotic Cardiac Surgery", *Medical Image Computing and Computer-Assisted Intervention (MICCAI 2001)*, Utrecht, The Netherlands, pp. 1419-1420.

[8] C.R. Wagner and R.D. Howe, "Mechanisms of performance enhancement with force feedback", *First Joint Eurohaptics Conf Symp Haptic Interf Virt Env Teleop Syst (World Haptics 2005)*, Pisa, Italy, March 2005, pp. 21-29.

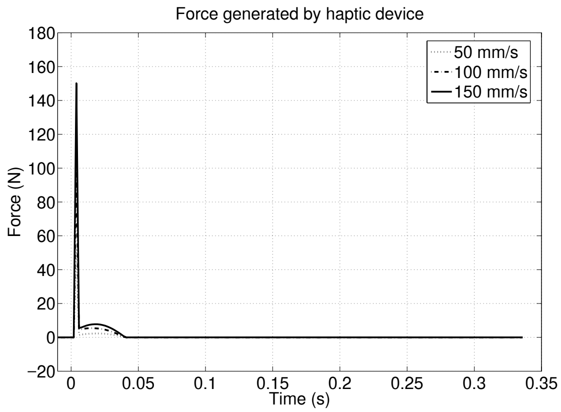
[9] J.J. Abbott, and A.M. Okamura, "Stable Forbidden-Region Virtual Fixtures for Bilateral Telemanipulation", *ASME J Dyn Syst-T ASME*, vol.128, no.1, March 2006, pp. 53-64.

[10] K.J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving Contact Realism through Event-Based Haptic Feedback", *IEEE T Vis Comp Gr*, vol.12, no.2, March 2006, pp. 219-230.

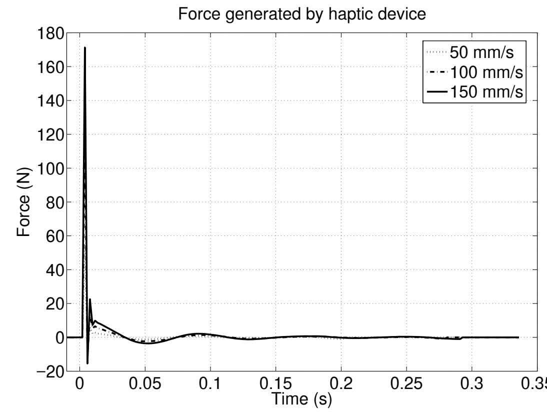
[11] P. Marayong, Hye Sun Na, and A.M. Okamura, "Virtual Fixture Control for Compliant Human-Machine Interfaces", *Proc IEEE Int Conf Robotic Autom*, Rome, Italy, April 2007, pp. 4018-4024.

[12] D. Constantinescu, S.E. Salcudean, and E.A. Croft, "Haptic rendering of rigid contacts using impulsive and penalty forces", *IEEE T Robotic*, vol.21, no.3, June 2005, pp. 309 - 323.

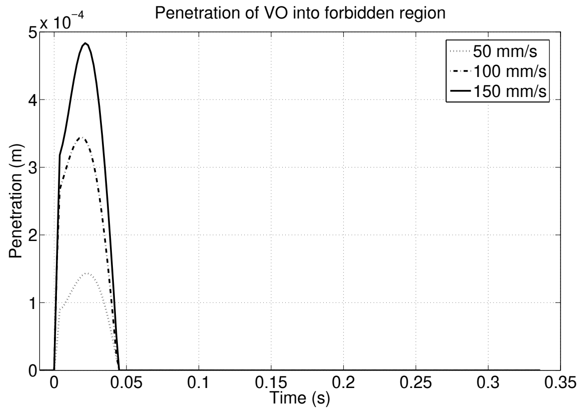
[13] D.A. Lawrence, L.Y. Pao, A.M. Dougherty, M.A. Salada, Y. Pavlou, "Rate-hardness: a new performance metric for haptic interfaces", *IEEE T Robotic Autom*, vol.16, no.4, Aug. 2000, pp. 357-371.



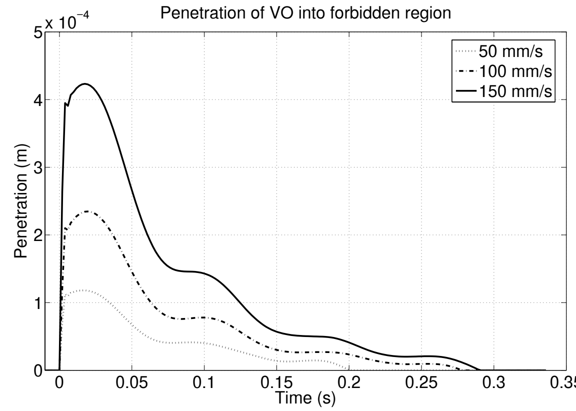
(a) Force applied to user by the IF controller.



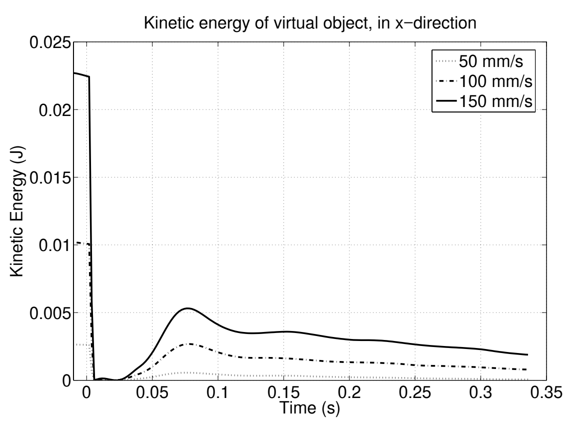
(b) Force applied to user by the CIF controller.



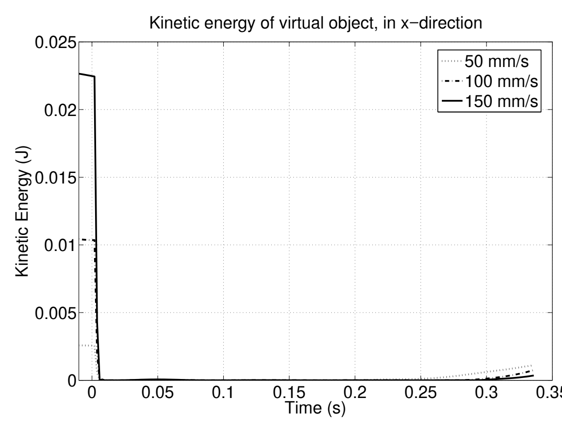
(c) FRVF violation under IF control.



(d) FRVF violation under CIF control.



(e) Kinetic energy of the VO under IF control, x-direction.



(f) Kinetic energy of the VO under CIF control, x-direction.

Fig. 5. Experimental data collected during violation of the FRVF under impulsive force (IF) and under continuous impulsive force (CIF) control.