Haptic Virtual Fixtures for Robot-Assisted Manipulation

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Summary. Haptic virtual fixtures are software-generated force and position signals applied to human operators in order to improve the safety, accuracy, and speed of robot-assisted manipulation tasks. Virtual fixtures are effective and intuitive because they capitalize on both the accuracy of robotic systems and the intelligence of human operators. In this paper, we discuss the design, analysis, and implementation of two categories of virtual fixtures: guidance virtual fixtures, which assist the user in moving the manipulator along desired paths or surfaces in the workspace, and forbidden-region virtual fixtures, which prevent the manipulator from entering into forbidden regions of the workspace. Virtual fixtures are analyzed in the context of both cooperative manipulation and telemanipulation systems, considering issues related to stability, passivity, human modeling, and applications.

1 Introduction

Haptic virtual fixtures are software-generated force and position signals applied to human operators via robotic devices. Virtual fixtures help humans perform robot-assisted manipulation tasks by limiting movement into restricted regions and/or influencing movement along desired paths. By capitalizing on the accuracy of robotic systems, while maintaining a degree of operator control, human-machine systems with virtual fixtures can achieve safer and faster operation. To visualize the benefits of virtual fixtures, consider a common physical fixture: a ruler. A straight line drawn by a human with the help of a ruler is drawn faster and straighter than a line drawn freehand. Similarly, a robot can apply forces or positions to a human operator to help him or her draw a straight line. However, a robot (or haptic device) has the additional ability to provide assistance of varying type, level, and geometry.

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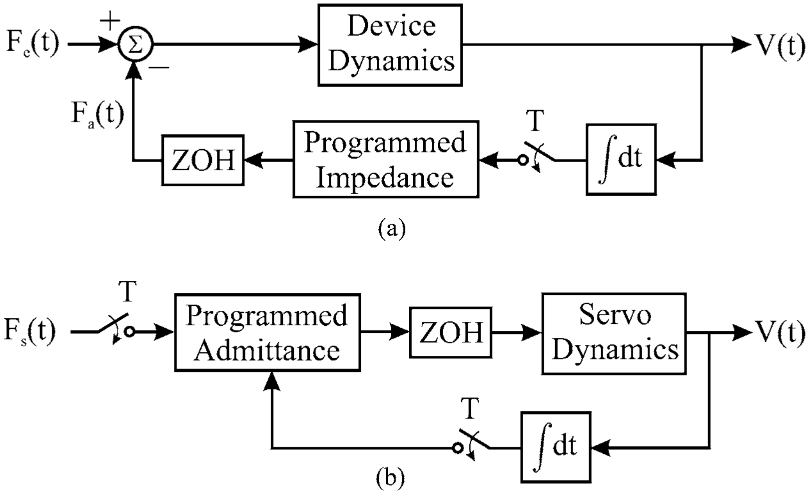

Fig. 1. Models of robots of the (**a**) impedance and (**b**) admittance types. For the impedance-type robot, F_a is the actuator force and F_e is the sum of all externally applied forces. For the admittance-type robot, F_s is the component of the externally applied force that is sensed. V is the robot velocity, and T is sampling period of the control system.

Virtual fixtures show great promise for tasks that require better-than-human levels of accuracy and precision, but also require the intelligence provided by a human directly in the control loop. Human-machine manipulation systems make up for many of the shortcomings of autonomous robots (e.g., limitations in artificial intelligence, sensor-data interpretation, and environment modeling), but the performance of such systems is still fundamentally constrained by human capabilities. Virtual fixtures, on the other hand, provide an excellent balance between autonomy and direct human control. Virtual fixtures can act as safety constraints by keeping the manipulator from entering into potentially dangerous regions of the workspace, or as macros that assist a human user in carrying out a structured task. Applications for virtual fixtures include robot-assisted surgery, difficult assembly tasks, and inspection and manipulation tasks in dangerous environments.

Virtual fixtures can be applied to two types of human-machine robotic manipulation systems: *cooperative manipulators* and *telemanipulators*. In cooperative manipulation, the human uses a robotic device to directly manipulate an environment. In telemanipulation, a human operator manipulates a master robotic device, and a remote slave robot manipulates an environment while following the commands of the master. In general, the robots used in these systems can be of the *impedance* or the *admittance* type [6]; basic models for these robot types are shown in Fig. 1.

Robots of the impedance type, such as typical haptic devices, are backdrivable with low friction and inertia, and have force-source actuators. An example of an impedence-type robot familiar to many is the PHANToM® from SensAble Technologies, Inc. [32]. Robots of the admittance type, such as typical industrial robots, are modeled as being nonbackdrivable with velocity-source actuators. This is due to either large inertia and joint friction from gear reduction in electric-motor systems, or valves and incompressible fluid in hydraulic systems. The velocity is controlled with a high-bandwidth low-level controller, and is assumed to be independent of applied external forces. This model loses validity when the admittance-type robot interacts with a very stiff environment.

Figure 2(a) shows the Johns Hopkins University Steady-Hand Robot [33], an admittance-type cooperative manipulator designed for microsurgical procedures. Figure 2(b) shows the da Vinci® Surgical System (Intuitive Surgical, Inc.) [12,13], an impedance-type telemanipulator designed for minimally invasive surgical procedures. The virtual fixtures created and studied in our lab are designed explicitly for systems such as these.

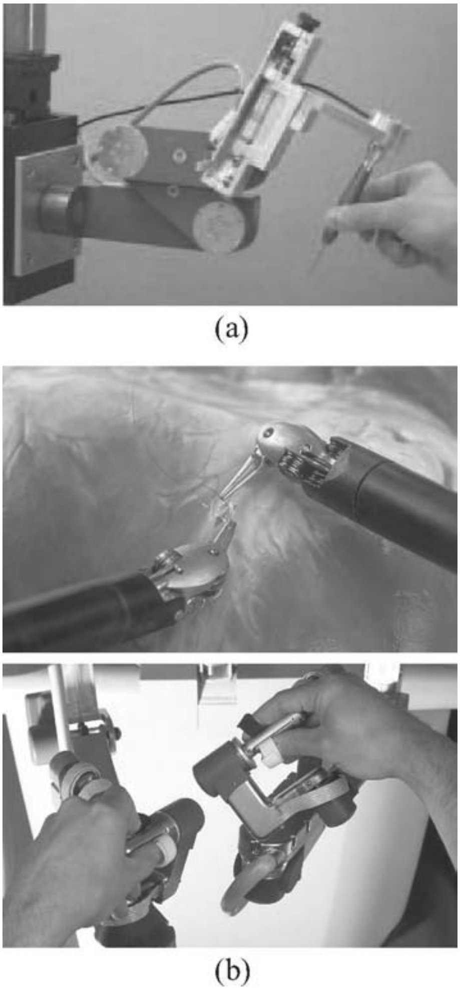

Fig. 2. (**a**) The Johns Hopkins University Steady-Hand Robot [33]. (**b**) The da Vinci® Surgical System [12, 13] (image used with the permission of Intuitive Surgical, Inc.).

2 Prior Work on Virtual Fixtures

"Virtual fixtures" [1,17,26–29] (also appearing under the name of "synthetic fixtures" [31], "virtual mechanisms" [15,24], "virtual tools" [14], "virtual paths and surfaces" [25], and "haptically augmented teleoperation" [34]) have been applied to robotic manipulators using a variety of methods, though they can generally be categorized as either *guidance virtual fixtures* or *forbidden-region*

Fig. 3. (**a**) Guidance virtual fixtures assist in guiding the robot along desired paths. (**b**) Forbidden-region virtual fixtures help keep the robot out of forbidden regions.

virtual fixtures. As their name implies, guidance virtual fixtures (GVFs) help keep the manipulator on desired paths or surfaces. Alternatively, forbidden-region virtual fixtures (FRVFs) [28] help keep the manipulator out of forbidden regions of the workspace. These virtual fixture types are illustrated in Fig. 3.

The majority of prior work on virtual fixtures has been applied to telemanipulation. Rosenberg [29] implemented FRVFs as impedance surfaces on the master device to assist in peg-in-hole tasks. Joly et al. [15] introduced a proxy-based [36] GVF method where the proxy is constrained to move on the virtual fixture, and the master and slave both servo to the proxy position and affect its movement along the virtual fixture. Micaelli et al. [24] extended this method to allow for multiple proxies, each on its own virtual fixture and with its own dynamics. Itoh et al. [14] developed a task-assistance tool that connects admittance-type robots to virtual fixtures with impedance control methods. Park et al. [26] implemented FRFVs on the remote slave by rejecting master commands into the forbidden region. In their method, the slave manipulator servos to a proxy, and the proxy follows the master when outside the FRVF, but will not follow the master into the forbidden region. Turro et al. [34] implemented GVFs on a system with an impedance-type master and admittance-type slave. The master is bound to a proxy, which is constrained to move on the virtual fixture, and the slave then tracks either the master or the proxy, depending on the desired level of user control. Payandeh and Stanisic [28] implemented virtual fixtures on both the master and slave manipulators, using a variety of geometries, to help guide the remote manipulator in a predetermined task. Kuang et al. [17] then applied this research to difficult assembly tasks. The virtual fixtures above were implemented with penalty-based or potential-field methods. These are impedance-type virtual fixtures that act in an active way, in that stored potential energy in the virtual fixture may potentially be released in an undesirable fashion.

Virtual fixtures have also been implemented on passive cooperative manipulation systems known as Cobots [25]. Park et al. [27] extended these methods to telemanipulation systems where the master device is a Cobot, for assistance in nuclear deactivation and decommissioning tasks. These virtual fixtures act in a passive way in the sense that the virtual fixtures are only able to restrict, and not generate, motion. These so-called passive virtual fixtures work much like methods developed for autonomous robots, such as "passive velocity field control" [21]. It is also possible to implement passive virtual fixtures using admittance-type systems. Since these nonbackdrivable robots move in a highly-controlled fashion, one can passively restrict movement in any given direction by simply not commanding any movement in that direction. This type of virtual fixture has been implemented on the Johns Hopkins University Steady-Hand Robot [33] by Bettini et al. [7] and Li et al. [18]. In [18], an optimization-based approach is used to construct motion constraints from known task geometries and instantaneous robot kinematics that can be applied independent of the manipulator type (cooperative manipulation or telemanipulation, admittance or impedance type). Research on this type of virtual fixture has also been recently been extended to admittance-type telemanipulators by Aarno et al. [1].

Prior work on virtual fixtures has been largely ad hoc, with significant reliance on particular applications. Thus, in this paper, we attempt to unify the past and present research in the field by considering the design, analysis, and application of virtual fixtures to various system types. In Sections 3 and 4, we discuss how guidance virtual fixtures and forbidden-region virtual fixtures, respectively, can be used for task assistance in both cooperative manipulation and telemanipulation. Then, in Section 5, we discuss in detail the issues involved with safe and functional implementation of virtual fixtures. Finally, in Section 6, we present a set of interesting topics for future work in this field of research.

3 Guidance Virtual Fixtures

Guidance virtual fixtures (GVFs) assist the user in moving the robot manipulator along desired paths or surfaces in the workspace. GVFs can be of either the impedance or admittance type [6]. Impedance-type GVFs act as potential fields, actively influencing the movement of the robotic manipulator. These impedance methods can lead to unexpected and undesirable movements of the manipulator, so we have chosen to focus on GVFs of the admittance type.

Admittance control typically takes the form $\mathbf{v} = K_a\mathbf{f}$, where $\mathbf{f}$ is the user's applied force vector, K_a is an admittance gain matrix, and $\mathbf{v}$ is the output velocity vector. This control scheme is sometimes referred to as proportional-velocity control. Admittance control has the desirable property that the velocity of the manipulator is proportional to the applied force, so the manipulator does not move if the user does not apply a force. In addition, slow robot movement is achieved with a soft touch. Admittance-type GVFs are very natural with admittance-type cooperative systems, but can also be implemented on impedance-type telemanipulation systems with a novel Pseudo-admittance control law [2,4].

3.1 GVFs for Cooperative Manipulation

In an admittance-type cooperative manipulation system, the robot motion is proportional to the user's applied force, which is measured by a force sensor.

To create GVFs, an instantaneous preferred direction is defined based on the position of the robot relative to the desired path or surface. The applied force is then decomposed into components in the preferred direction and in other, non-preferred directions. By eliminating the commanded motion due to the applied force in the non-preferred directions, we create a passive guidance along the preferred direction. Implementing GVFs in this fashion essentially makes the admittance gain matrix K_a both state and input dependent. Details of this GVF method can be found in [7].

Varying the response to the non-preferred force component creates different levels of guidance. *Hard* guidance refers to GVFs where none or almost none of the non-preferred force component is permitted, leaving the user with no or little freedom to deviate from the preferred path. Alternatively, *soft* GVFs give the user the freedom to move away from the path by allowing some motion in the non-preferred directions. We conducted an experiment with the JHU Steady-Hand Robot to evaluate the effect of GVF admittance on user performance, including accuracy and execution time [23]. Three tasks (Path Following, Off-path Targeting, and Avoidance) were selected to represent a broader class of motions that can occur in a real task execution. GVFs were used with varying admittance to keep the user on the preferred path, in this case a sine curve on a horizontal plane.

Figure 4 shows the robot trajectories during the Off-path Targeting and Avoidance tasks, with three levels of guidance. In the Targeting task, the users were instructed to reach the target located on the perimeter of the circle outlined in gray. In the Avoidance task, the users avoided the area by trying to follow along the circle perimeter. Robot trajectories in the Path Following task were similar to the portions seen outside the circular area in the two off-path tasks shown in Fig. 4. In the Path Following task, the users performed

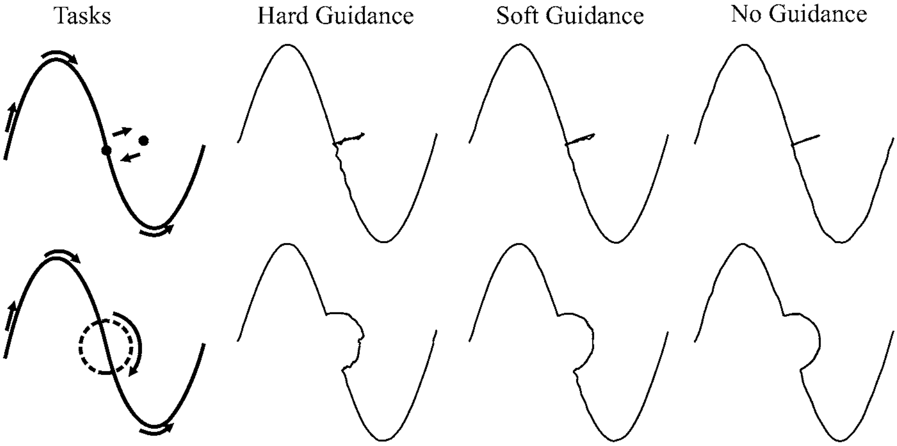

Fig. 4. Robot trajectories in the Targeting task (**top**) and the Avoidance task (**bottom**) with JHU Steady-Hand Robot.

the task more accurately (with statistical significance) with GVFs, though not significantly faster. In the off-path tasks, the users had to fight against the GVF guidance to complete the desired motion. This represents situations where the virtual fixture is incorrectly placed and the user wishes to override the guidance. As expected, users take significantly longer to perform off-path tasks with increased guidance. Error also increases slightly. The experiment shows that GVFs can improve both time and accuracy simultaneously, while still allowing some independent user motion. More detailed descriptions of the experiment and the results can be found in [23]. GVF implementation for tasks in 3-D were also explored in Dewan et al. [9], where the tool was guided along a user-defined desired surface. In this experiment, stereo cameras were used to reconstruct the workspace and track the tool position and orientation.

3.2 GVFs for Telemanipulation

In telemanipulation, good position correspondence between the master and slave robots is desirable to create a sense of telepresence for the user. However, it is actually the slave manipulator that we wish to guide using GVFs, and master movements in its corresponding workspace are somewhat less important.

The GVFs developed for admittance-type cooperative manipulators could trivially be extended to telemanipulation systems where both the master and slave are of the admittance type. However, unlike cooperative manipulation systems, telemanipulation systems are typically designed as impedance-type systems (that is, the master is an impedance-type haptic device, while the slave manipulator can be of either the impedance or admittance type). For these systems, we do not control the velocity of the system directly (due to force-source actuation), so we cannot implement admittance control directly. We have developed a novel telemanipulation control algorithm called Pseudo-admittance control [2, 4] that mimics admittance control on impedance-type telemanipulators, and extends the GVFs described in Section 3.1 and [7] to telemanipulation. Pseudo-admittance makes use of a proxy [36], which exists only in software, that can be commanded to move under admittance control.

Under Pseudo-admittance control, the master servos to the slave position, while the slave servos to the proxy position, as illustrated in Fig. 5. The proxy moves under admittance control, using the force of the master's servo controller as its input force. GVFs are then implemented by attenuating the commanded velocity in non-preferred directions, as described in Section 3.1. Figure 5 shows the experimental results from two PHANToM® robots [32] configured for Pseudo-admittance control. Using different levels of guidance (i.e., modifying the calculation of the preferred direction and the attenuation of velocities in the non-preferred directions), the slave is guided to a preferred plane in the workspace, but the user retains ultimate control to move the slave anywhere in the workspace.

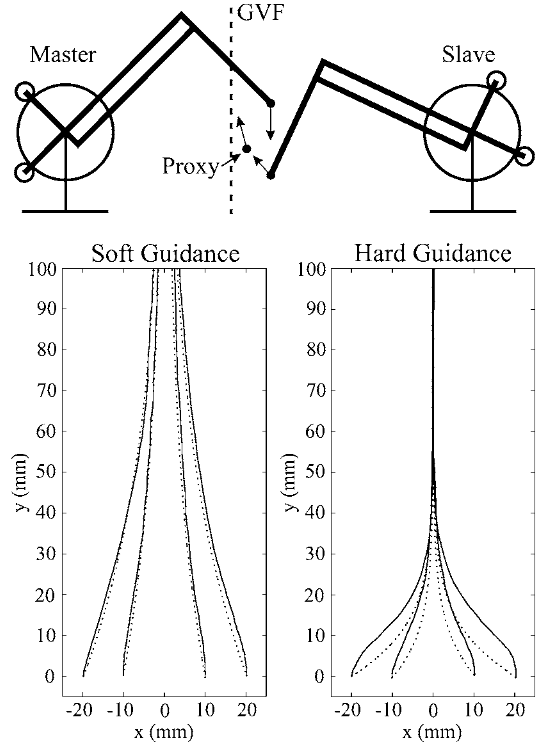

Fig. 5. Guidance virtual fixtures implemented on two PHANToM® robots (**top**) configured for Pseudo-admittance Bilateral Telemanipulation [2, 4]. The robots are shown superimposed on the same workspace to aid in visualization. Experimental data (**bottom**), with master (—) and proxy (···) trajectories, are shown for two levels of guidance. The slave servos to the proxy. The GVF is on the plane $x = 0$. The user applies a force approximately in the positive y direction, and the manipulator is guided by the GVF.

4 Forbidden-Region Virtual Fixtures

Forbidden-region virtual fixtures (FRVFs) prevent the robot manipulator from entering into forbidden regions of the workspace. They have an on/off nature, such that they have no effect on the robot when it is outside of the forbidden region. As with GVFs, FRVFs can be of either the impedance or admittance type. Impedance-type FRVFs take the form of "virtual walls," which are commonly employed and studied for haptic virtual environments, and are typically implemented as simple spring-damper surfaces. These are penalty-based methods, so the force generated by the FRVF is proportional to the manipulator's penetration of the FRVF (i.e., some penetration is necessary to engage the FRVF). Admittance-type FRVFs are simply implemented by not commanding any manipulator motion into the forbidden region.

4.1 FRVFs for Cooperative Manipulation

FRVFs can be viewed as a subclass of GVF for an admittance-controlled cooperative manipulator. The FRVFs are trivial to implement, by simply eliminating any commanded motion into the forbidden region. Inherently, the forbidden region is the non-preferred direction defined in the GVFs.

Examples of FRVFs in cooperative systems are highlighted in [9] and [20]. In Dewan et al. [9], the virtual fixtures constrained the user to move along the shortest path between the current tool position and a predefined target on the surface. The robot admittance gain was turned to zero once the target was reached. Li and Taylor [20] combined both GVFs and FRVFs in creating anatomy-based motion constraints for a path-following task in a constrained workspace. The algorithm uses the robot kinematics, the user's force input, and a 3-D geometric model of the workspace to generate virtual fixtures and an optimal set of joint displacements to guide the tool tip along a path while preventing the tool shaft from entering into forbidden regions.

The user may want the option to intentionally move past the FRVF if it is deemed necessary. The GVFs implemented in Section 3.1 left the user with ultimate control to move the manipulator away from the desired path, but it is not clear if it makes sense to create admittance-type FRVFs that allow some motion into the forbidden region. In one sense, an admittance-type FRVF that acts in this way is not a FRVF at all. It may be possible though, through state-and-input-dependent adaptation of the admittance-gain matrix, to implement FRVFs that allow some penetration into the forbidden region while retaining their functional purpose.

4.2 FRVFs for Telemanipulation

As with the GVFs of Section 3.2, in telemanipulation we are only really concerned with penetration of the slave manipulator into the forbidden region. Penetration of the master device into the corresponding region of its workspace is somewhat inconsequential.

Impedance-type FRVFs can be implemented on telemanipulators by overlaying a penalty-based virtual wall on the existing telemanipulation controller. It is possible to implement the virtual wall on either the master or the slave side (or both simultaneously). Both have the effect of reducing movement of the slave into the forbidden region. However, each presents a different haptic experience for the user, depending on the underlying telemanipulation controller, and each provides different levels of disturbance rejection, depending on the location of the disturbance. In [2], we found that slave-side FRVFs are most effective at rejecting disturbances on the slave, while maintaining a sense of telepresence for the user (i.e., minimizing position error between the master and the slave). However, we found that master-side FRVFs are most effective at rejecting (un)intentional user commands into the forbidden region, while maintaining a sense of telepresence. The choice of FRVF architecture is likely to be task dependent.

It is also possible to implement admittance-type FRVFs through the use of a proxy. If the slave manipulator servos to a proxy, rather than directly servoing to the master, then we can influence slave movement in forbidden regions by adapting the dynamic properties of the proxy. When the master is not interacting with the FRVF, the proxy is made to follow the master exactly.

When the master moves beyond the FRVF, we attenuate the movement of the proxy past the FRVF (including removing the penetration completely).

Both types of FRVF act by attenuating slave movement into the forbidden region, while allowing the user to move the slave into the forbidden region if desired. The amount of attenuation, and consequently user control, is governed by system gains. Admittance-type FRVFs implemented on admittance-type slaves can be made to be infinitely stiff. The stiffness of an admittance-type FRVF with an impedance-type slave is limited by the stability of the virtual coupling between the slave and the proxy [6]; however, this FRVF can still be made to appear infinitely stiff to the user commands. The performance of an impedance-type FRVF is also ultimately limited by stability constraints. The stability of impedance-type FRVFs, under stability and passivity considerations, is explored in detail in [2].

5 Virtual Fixture Design Considerations

Prior work in virtual fixtures has focused primarily on application-specific virtual-fixture geometries and user performance of specific tasks. This section highlights a number of additional design considerations that are important for progress in this field; researchers have only recently begun to examine these issues.

One fundamental design problem is to determine the best type of underlying system for a virtual-fixture application. Cooperative manipulation systems are intuitive to use, due to the natural hand-eye coordination that comes from directly manipulating the tool. The sense of telepresence felt with a telemanipulator is limited by the position error in the system, as well as the quality of the visual and haptic feedback provided to the user. Admittance-type cooperative systems also have desirable "steady-hand" properties; the user's hand is literally steadied by holding onto the rigid, slow-moving robot. This behavior must be mimicked on an impedance-type telemanipulator; the slave manipulator can be controlled to move slowly, but a backdrivable master device is not as capable of steadying the hand of the user. However, telemanipulators provide not only the ability to manipulate distant environments, but also the ability to provide scaling in both position and force. Force scaling is also possible with cooperative manipulation [30], although an additional force sensor or accurate environmental model is needed to obtain the contact force. It is important, in general, to consider whether force sensing is necessary and practical in terms of size, cost, and environment compatibility.

System performance also depends on the accuracy of the task geometry definition. For example, a computer vision system can be used to reconstruct the workspace and define the geometry of the virtual fixtures. The accuracy of the virtual fixtures defined depends on the resolution of the vision system, calibrations, and the accuracy of the tracking algorithm, which can be sensitive to changing light conditions and occlusions. The designer of a virtual fixture

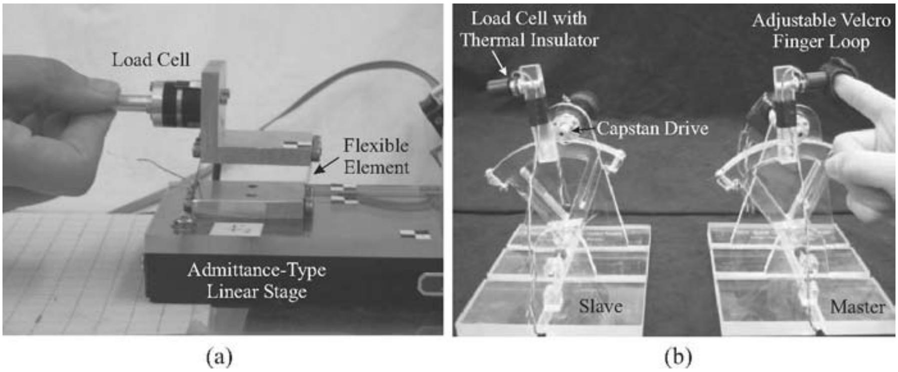

Fig. 6. 1-DOF experimental systems. (**a**) Admittance-type cooperative manipulator for the study of the effect of link compliance on virtual-fixture performance. (**b**) Impedance-type telemanipulator for the study of FRVF stability.

must be able to predict the sensitivity of system performance to inaccuracies in virtual-fixture geometry definition and develop mechanisms to correct for errors. It may be necessary to build in enough user control to compensate for inaccuracies in the virtual-fixture geometry, as was discussed in Section 3.1.

In cooperative systems, unmodeled robot dynamics, such as joint and link compliance, can introduce significant tool positioning error, especially for micro-scale tasks. Joint and link flexibility add unactuated degrees of freedom to the robot. A human actively and directly manipulating the tool exacerbates the difficulty of error correction. A hand dynamic model could be added to better predict the system response near a virtual fixture, and adjust the controller appropriately to compensate for the error. This issue is being investigated on a 1-DOF admittance-type system (Fig. 6(a)) where the FRVF was implemented as a virtual wall. Joint compliance was simulated with a physical spring added between the tool and the stage. Two methods were proposed to create a dynamic virtual fixture, with its location determined based on the system dynamics, that prevents the user from entering the true forbidden region. The experimental results shown in Fig. 7 indicate that accounting for both the dynamic properties of the hand and the effects of robot momentum are effective in preventing FRVF penetration. The description of the methods and the complete experimental results can be found in [22].

Another major concern in the design of virtual fixtures for impedance-type telemanipulators is stability. Because of their backdrivable force-source actuators, these systems are prone to instability if the control-system gains are too high. This makes stable and effective virtual fixtures conflicting goals. We have investigated the stability of FRVFs, considering effects of friction, sampling, and quantization, using both equilibrium stability analysis [2, 5] and passivity analysis [3]. We used a 1-DOF system, shown in Fig. 6(b), for this purpose. It is possible to design a FRVF to be passive, with the

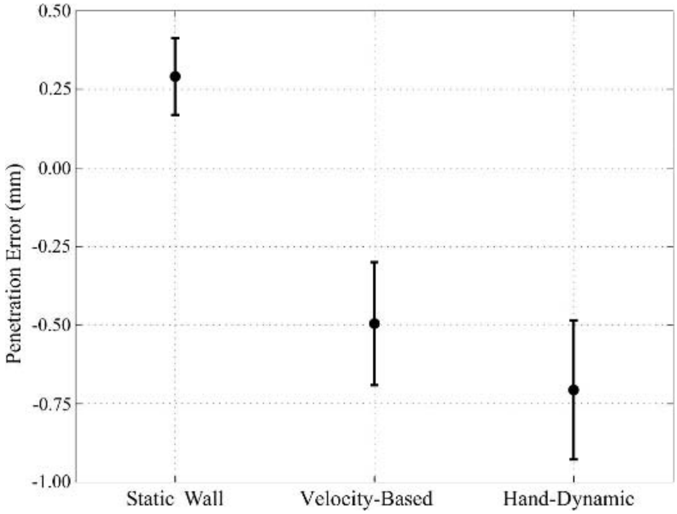

Fig. 7. Experimental results indicating that the effects of robot compliance on FRVF functionality can be mitigated through dynamic modeling of the robot and the human hand [22]. Mean values of the penetration into the forbidden region and standard deviation bars collected from eight users are shown. Negative error indicates no penetration into the forbidden region.

additional assumption of human passivity being sufficient for system stability. However, as shown in Fig. 8, we found that including an explicit model of potential human users can lead to stability predictions that are significantly less conservative than simply requiring passivity of the FRVF. The description of the methods and the complete experimental results can be found in [2,5].

It is tempting to model the human user as an exogenous input to the system, for the purpose of stability analysis, but in general, the dynamics of the human user are part of the closed-loop feedback system. However, it is also reasonable to assume that for certain slow-moving systems, the human user is essentially unaffected by the movement of the system. An initial study in our lab shows that, for an admittance-type cooperative manipulator, it is the velocity of the robot, and not the admittance gain, that directly affects human force control precision [35]. Thus, by restricting the velocity of the manipulator, it may be possible to consider the human user as an exogenous input, greatly simplifying system stability analysis. More research is needed to better understand the role of the human user in the total system response.

As illustrated above, it is not always obvious when dynamic modeling of the human user is necessary or desirable in virtual-fixture design and analysis. Most of the prior work on virtual fixtures has excluded modeling of the human user. In addition to mechanical modeling, experimental results of GVFs in cooperative systems suggest that human intent and psychophysics may also affect GVF performance. Selecting an appropriate level of guidance

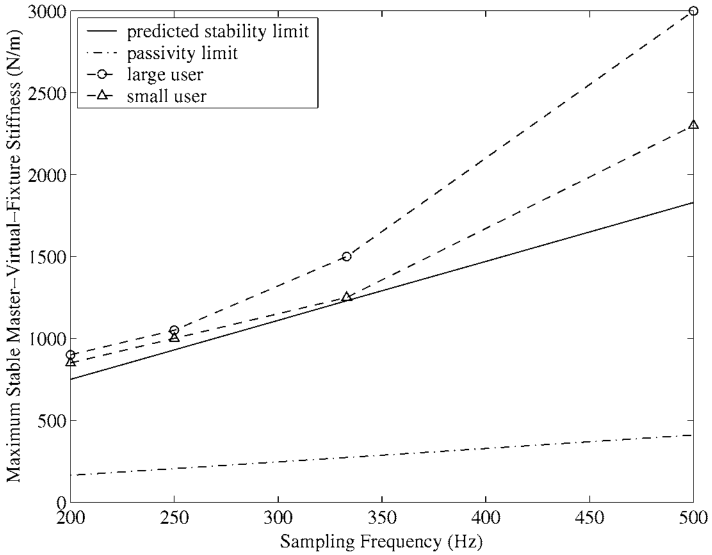

Fig. 8. Experimental stability limits on master FRVF stiffness on a unilateral telemanipulator, for large- and small-handed malicious users, compared to predicted stability limits based on models of the "worst-case" user [2, 5]. Passivity of the FRVF based on [8] is also shown. For each data point, the users found the stiffest virtual fixture for which instability could not be experimentally generated.

is required for optimal performance, and the selection is task dependent. Having a high level of guidance increases error and time for tasks that require off-path motions, though it significantly improves both time and error during path-following. An optimal GVF selection was explored in [23]. Artificial intelligence can also be added to adjust the GVF based on the user's intent. For example, Li and Okamura [19] and used Hidden Markov Models to recognize user motions and provide appropriate GVF assistance in a combined curve-following and object-avoidance task in cooperative manipulation. Aarno et al. [1] took a similar approach with telemanipulation. Kragic et al. [16] broke a complex microsurgical task into subtasks, each of which benefited from different types of virtual-fixture assistance.

6 Summary and Future Work

This paper described methods for design and implementation of haptic virtual fixtures on a number of different underlying platforms. Through analysis and experiments, we show that virtual fixtures can improve human-machine performance, while allowing the user to maintain ultimate control over the task execution.

There are a number of critical questions that provide important topics for future research in this field. For example, what is the best virtual-fixture geometry for a given task? How does the human user interpret the combination of haptic cues coming from the manipulated environment and the virtual fixture? Does this lead to haptic confusion, affecting the user's sense of immersion in the task? If the virtual-fixture geometry and/or gains vary in time, not only could it lead to confusion on the part of the user, but it also complicates stability analysis. Can virtual fixtures be used as training devices for complicated tasks, and then eventually be removed, much like training wheels on a bicycle [10, 11]? To what extent does the human need to be included in the analysis of these systems? It is desirable to say as much as possible about the robotic system itself, without needing to consider human dynamics. Is it possible to apply what we have learned thus far to the design of force virtual fixtures, which assist the user in applying the proper force to the manipulated environment?

It is important that we generalize the research in this field across systems and tasks, so that knowledge gained in individual research efforts can advance the field as a whole. Virtual fixtures will no doubt facilitate robot-assisted tasks that were previously impossible, but this nascent field is still rich with interesting research topics that must be explored before human-machine systems can capitalize on the full benefit of virtual fixtures.

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