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Physics-based Approach to Haptic Display

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Abstract

This paper addresses the implementation of complex multiple degree of freedom virtual environments for haptic display. We suggest that a physics-based approach to rigid body simulation is appropriate for hand tool simulation, but that currently available simulation techniques are not sufficient to guarantee successful implementation. We discuss the desirable features of a VE simulation, specifically highlighting the importance of stability guarantees.

1. Introduction

A haptic display (or force reflecting interface) is a device which lets the user touch, feel and manipulate virtual environments, rather than just seeing them. As an example, the haptic display of a linear spring must enforce a specific relationship between force and position. Thus if the user grasps the display and applies a certain force, a predictable displacement will result. Many such devices have been developed in recent years, including but not limited to [1, 3, 4, 5, 8, 9, 12, 14, 15, 18, 19].

One promising area for the application of haptic display is tool use, both in terms of the design process and the training of new users. For example, designers could reduce prototyping time and costs by implementing new ideas in a virtual environment, rather than in a machine shop. Conventional VR can be and has been used in this way (see [21] for one example). However, for many tools, appearance doesn't allow a designer to understand how the tool will perform. For this class, functionality is demonstrated by the physical interactions the tool allows between a user and an environment. To explore this functionality, we need the ability to construct and physically interact with virtual environments.

Recently, virtual reality has been used to train Space Shuttle support personnel at Johnson Space Center in procedures that require the use of highly specialized hand tools. While some of these tools are quite ordinary, others have unusual shapes and functions (see Figure 1 for example).

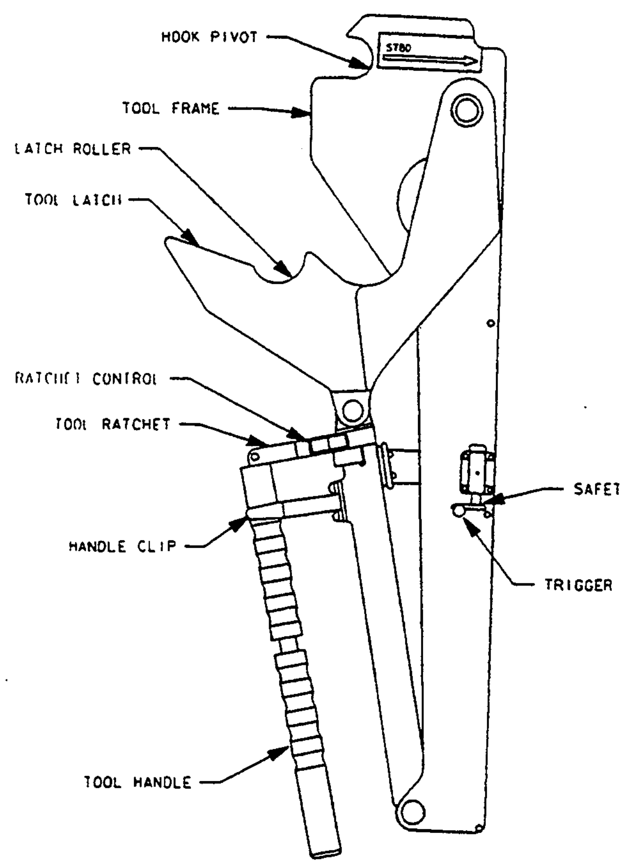

Figure 1. Example of complicated hand tool

However, in the current training environment, tools are not represented at all, since that would require simulation of the interactions between virtual objects. For example, one merely points to a bolt that needs to be loosened, and it loosens itself. Clearly, this is useful for learning a complicated *procedure*, but not a physical *skill* . For simple tools, this is not a problem, but for more complicated ones, the physical skill is a challenging part of the task. To provide astronauts and support personnel with a proper environment for mastering these physical skills, NASA has resorted to using a full-scale mockup of the Shuttle. An alternative to this rather expensive process is to include the hand tools in the VR simulation. Like in the tool design example given above, some tools' functionality cannot be demonstrated with visual information alone. For these tools, haptic interaction is a necessary component of training.

Both of these examples call for an extremely flexible device, capable of being programmed to feel like a wide variety of objects. The flexibility we seek is not just in the device, but in the VE software itself. We would like to be able to adjust parameters quickly and easily, without having to "recompile" the virtual environment.

In a strict sense, the VE software is a real-time simulation of a physical system. It is important that this simulation behave in a physically reasonable manner, because it interacts with two systems (the human user and the handle that he/she grasps) which are, in fact, physical. There are many ways to approach this kind of physics-based simulation, and a vast literature from which to draw knowledge. The next section will review aspects of this literature, specifically addressing the needs of hand tool simulation and haptic display.

2. Rigid body simulation review

Before reviewing simulation techniques, we need to consider the class of physical systems with which we are concerned. We will therefore limit our scope to *rigid body simulation*, which is often appropriate in the context of tool use. However, we need to pay particular attention to each simulation method's ability to deal with *unilateral constraints*, which are ubiquitous in tool use. A unilateral constraint is the type of constraint that typically occurs when two rigid bodies come into contact. It may also be viewed as a bilateral constraint (e.g. a revolute or prismatic joint) that is removed whenever the constraint force becomes negative. Unilateral constraints are challenging to implement because they require a dynamically changing topology (i.e. there is more than one set of motion equations, and which set is enforced depends on the state of the system). With this in mind, there are three major classes of rigid body simulation that we will consider here: constraint stabilization, coordinate partitioning / velocity transformation, and recursive constraint propagation. All three classes assemble a set of motion equations, solve them for accelerations, and integrate to obtain position and velocity.

For constraint stabilization [2, 16, 24], the starting point is the unconstrained equations of motion. Lagrange multipliers are added for each constraint, and the extra equations needed to solve for these multipliers are obtained from the second derivative of the constraint equations. Unfortunately, this technique doesn't precisely enforce the constraints, but rather their second derivatives. Since numerical integration results in finite errors at each time step, the constraint will be violated after just a short period of time. To fix this problem, position and velocity dependent terms can be appended to the constraints' second derivatives, tending to preserve and stabilize the constraint. The difficulty is that picking these position and velocity dependent terms for high accuracy makes the differential equations stiff, mandating smaller time steps to solve accurately. The advantages to constraint stabilization are flexibility and ease of implementation of unilateral constraints. The primary disadvantage is computational cost, so this technique is rarely if ever suitable for simulating complex systems in real time.

Another approach is to identify the constrained degrees of freedom and integrate the remaining equations. The difficulty, of course, lies in identifying those degrees which are constrained and which are free to move. The constraint doesn't even have to be on one of the state variables - it could simply enforce a specific relationship between two of them. A clever approach to this kind of problem is "generalized coordinate partitioning", which automatically extracts the integrable coordinates from the constraints [17, 23]. These coordinates represent non-stiff equations, which can then be integrated easily by any number of techniques. This technique is promising, as it has been used for real-time simulations, and can handle unilateral constraints in a straight forward manner. A drawback of generalized coordinate partitioning is that it expects independent constraints, so the situation shown in Figure 1 could not be allowed without additional logic.

Figure 1. Example of dependent constraints.

Finally, there are recursive techniques, which can provide greater efficiency for certain complicated systems [10, 11, 13, 22]. However, they require topological preprocessing, meaning the connectivity of the bodies must be assessed and a computational hierarchy established beforehand. This type of preprocessing eliminates the possibility of a dynamically changing topology, so extra provisions must be made to govern collisions between bodies.

While one of these approaches to rigid body simulation may provide a suitable starting point for a VE hand tool simulator, it must be appreciated that haptic display introduces certain additional considerations. Specifically, haptic display differs in three key ways : real-time processing (as already mentioned), high update rates and stability guarantees.

Due to its interactive nature, haptic display requires real-time processing, a problem it shares with conventional virtual reality. Conventional VR, however, is not typically physics-based, so this requirement, while posing a problem in terms of video update, isn't too difficult for the simulation itself to handle. For physics-based simulation, the need for real-time processing eliminates constraint stabilization as a likely choice, since it requires solution of stiff differential equations, a difficult process in real time.

Haptic display has the additional requirement of high update rates because of the bandwidth of human tactile senses (upwards of 1 KHz). This problem is not shared by conventional VR, since the bandwidth of human optical senses is around 70 Hz. This is not to say that visual VR is easier than haptic VR, it just has a different set of challenges to overcome.

A primary goal of VR, whether haptic or visual, is to try to achieve "presence" in a virtual environment [20]. If the state of that environment becomes computationally unstable, the sense of presence will be damaged, if not completely destroyed (imagine if a wrench began oscillating uncontrollably against a nut). Thus, physics based VR, whether haptic or visual, needs to provide a stability guarantee. None of the methods described above can provide this guarantee. Our experience has shown that for haptic display, stability guarantees are the most challenging aspect of virtual environment implementation.

Our long-term goal is to design a haptics programming language which allows complex VEs to be rapidly assembled and modified, while providing stable, realistic interaction. Since all three of the above approaches have problems, we have begun investigating techniques which utilize parallel processing to achieve this goal. In the remainder of this paper, however, we discuss the problem of providing stability guarantees, rapidly becoming recognized as the sine qua non of haptic display.

3. Providing a stability guarantee

We believe two components are necessary for the haptic display of complex multiple degree of freedom tool simulations :

- The ability to display a set of haptic primitives. This set includes, but is not limited to, springs, viscous drag, inertia, friction and hard non-linearities.
- The ability to connect these primitives arbitrarily and still guarantee stability of interaction. Particularly important is the ability to implement unilateral and bilateral constraints.

Complex environments can be broken down into smaller simpler components called "primitives". A haptic primitive may be described as a mechanical impedance, a relationship, possibly history-dependent, between motion and force. Unfortunately, reliable display of such a primitive involves issues of safety as well as accuracy of display. Because the user, manipulandum, actuators and virtual environment form a dynamic system, stability of this system becomes an issue. We need an intellectual framework to predict the behavior of this system.

To ensure robust interactive behavior, as in the example of the wrench and the bolt, the physical world relies heavily upon the property of *passivity*. The wrench and bolt are obvious examples of passive systems, neither being able to provide energy to the other. It is well-known that the coupling of passive systems is guaranteed to be stable. Furthermore, humans are adept at manipulating passive objects in a safe and efficient manner. In our studies of virtual walls, we have found that passivity provides an extremely useful intellectual framework for understanding the stability problem.

In order to investigate the passivity of haptic virtual environments more closely, we built a one degree of freedom manipulandum [6], shown in Figure 2.

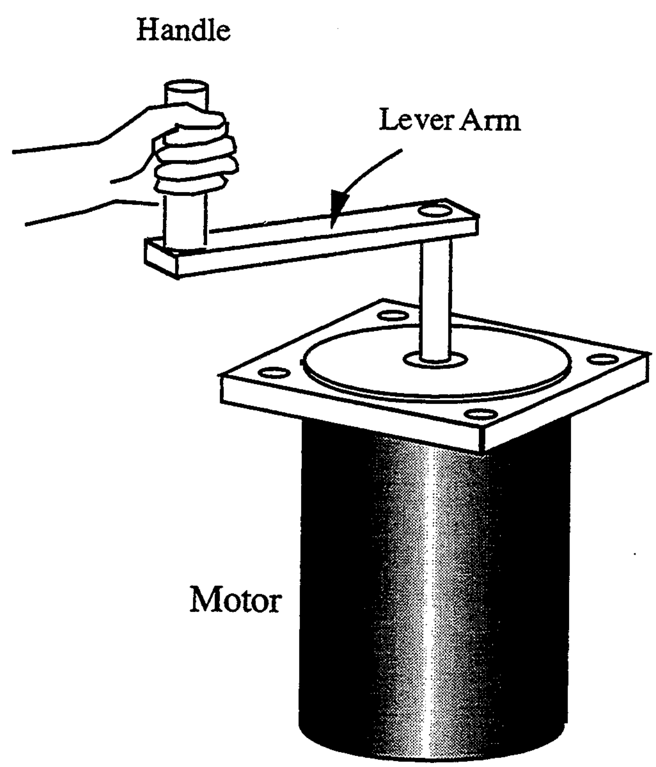

Figure 2. 1 DOF haptic display

The manipulandum is powered by a PWM-driven DC brushless motor. Position sensing is provided by optical encoders on the motor shaft. Controlled only by a 486 50-MHz PC, the system is capable of updating simple haptic virtual environments at up to 10 KHz. Graphic representation of the virtual environment is displayed on a 15-inch color monitor. A model of the system dynamics is shown in Figure 3.

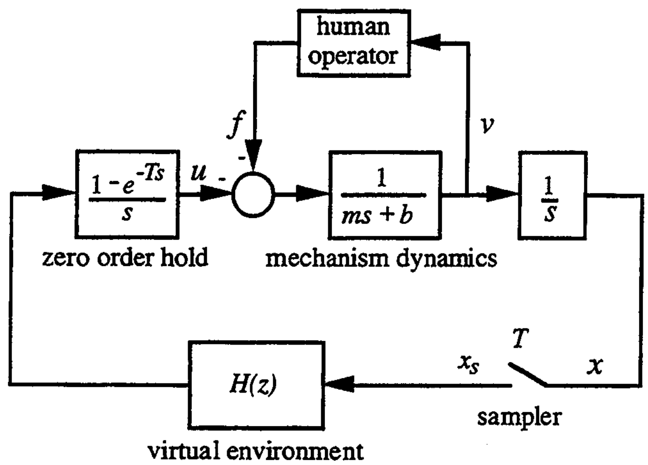

Figure 3. Model of a one degree-of-freedom haptic interface. m is the inherent mass of the display, b is inherent damping, H(z) is the virtual environment transfer function, v is velocity, x is position, x_s is the sampled position, T is the sampling rate, u is the control effort, and f is the force applied by the operator.

The difficulty in any traditional stability analysis of this system is the unmodeled dynamics of the human operator. Even though the virtual environment itself might be stable, interaction with a human operator via a haptic interface may *cause* instability. In our studies of virtual environments, we have had many experiences with human operators adjusting their own behavior until oscillations resulted. However, if the display is truly passive, then human operators should not be able to destabilize the system. If this approach is taken with the model presented in Figure 3, the following theorem, proven in [7], results :

Theorem — A necessary and sufficient condition for passivity of the haptic interface model in Figure 2 is:

$$b > \frac{T}{2} \frac{1}{1 - \cos \omega T} \operatorname{Re}\left\{ (1 - e^{-j\omega T})\, H(e^{j\omega T}) \right\}$$

$$\text{for} \quad 0 \le \omega \le \omega_N \qquad (1)$$

Here, b is the inherent damping of the display, T is the sampling rate, $H(z)$ a pulse transfer function representing the virtual environment, and $\omega_N = \pi/T$. This theorem shows that inherent physical damping is required to make a haptic display passive. This result goes against the conventional wisdom of haptic display design that a device have minimal inherent friction and damping.

Virtual Walls

It is important to note that a haptic display may be called upon to exhibit a wide variety of impedances, including those which are highly nonlinear. As a specific but enlightening example, we consider the virtual wall. The virtual wall can be modeled with three haptic primitives, a stiff spring, a damper and a hard non-linearity, implemented in parallel (see Figure 4).

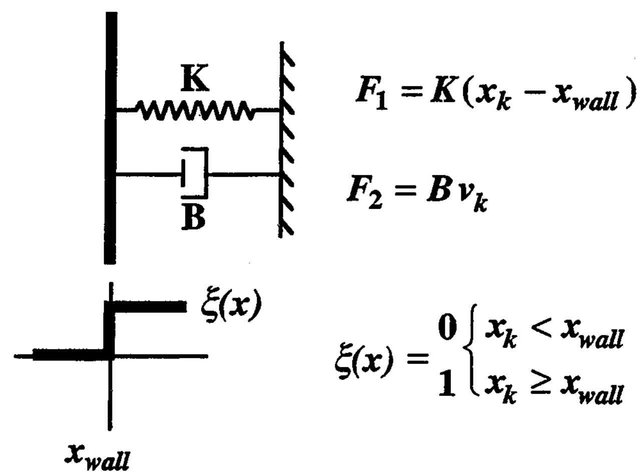

Figure 4. Model of a virtual wall as a spring and damper in parallel. K defines the virtual stiffness, B the virtual damping, and x_{wall} the location of the wall.

such that the total force experienced by the operator is given by :

$$F = \xi(F_1 + F_2) \qquad (2)$$

The virtual wall is extremely challenging to implement since it includes the extremes of impedance, along with rapid transitions between them. Outside the wall, the operator should be able to move the device freely (low impedance), but inside the wall, the operator should be unilaterally constrained (high impedance). The device needs to be able to implement both of these extremes and be able to switch between them almost instantaneously. We feel that if a system can successfully simulate contact with hard surfaces, it possesses the *dynamic range* to display the results of many useful virtual environments. Substituting the specific equations for a virtual wall, (1) reduces to :

$$b > \frac{KT}{2} + |B| \qquad (3)$$

where b is the inherent physical damping of the device, K and B are the virtual stiffness and damping, and T is the sampling rate. Based on (3), it is easy to see that inherent damping and sampling rate have significant effects on the passivity of virtual walls. Another more subtle factor that doesn't show up in this analysis is the effect of sensor resolution on system performance. The effect of these factors on stability was quantitatively assessed in [6]. The results are summarized as follows :

- Inherent physical damping of the haptic display improves passivity
- High update rates increase achievable stiffnesses of virtual walls
- If encoders are used to estimate velocity, they should have extremely high resolution
- Digital filtering of the velocity signal can help achieve high values of virtual damping

4. Conclusions

Based on these guidelines (obtained with a 1 DOF device), we have equipped a 4 DOF manipulandum [14] with dampers, allowing us to construct multi-DOF virtual environments with convincing unilateral constraints. However, no method of guaranteeing system stability has yet been found. As mentioned above, our current research is focused on the development of a haptics programming language which will utilize parallel processing. This language will allow complex VEs to be rapidly assembled and modified, while providing stable, realistic interaction with the human operator.

5. Acknowledgments

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