# Haptic Interaction with Three-Dimensional Bitmapped Virtual Environments

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## Abstract

This paper briefly describes the design and implementation of a system integrating a force-reflecting haptic interface, the PHANToM, with a high-powered computer designed to efficiently compute cellular automata, the CAM-8. The goal was to build a system to allow users to interact with real-time three-dimensional bitmapped simulations running on the CAM. Such simulations are far more computationally complex than can currently be computed on the PHANToM host. This system can also provide an intuitive user interface for manipulating data within CAM simulations.

## Background

Computational systems exist that allow large-scale 3D cellular automata systems to be rapidly computed. In general, these systems are used to simulate physical environments with very limited user interaction. Using the PHANToM, we can develop methods to allow intuitive human interaction with these large-scale bitmapped simulations.

Most computer generated virtual environments are constructed from polygonal models of objects. This limits user interaction with such systems to rules that may not accurately model a physical system. With advances in technology it has become feasable to work with three-dimensional bitmapped environments, computed by cellular automata simulations. Systems exist that can iterate a set of rules over a large multi-dimensional space, primarily for examining physical simulations such as lattice-gas or hydrodynamic models. Interactive user interfaces for real-time manipulation of these existing systems have been lacking. Force-feedback *haptic* touch interfaces provide interesting possibilities.

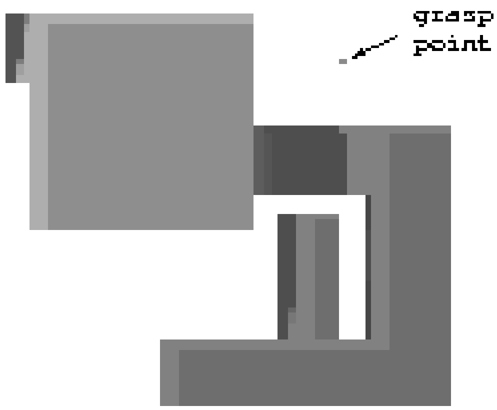
## Previous Work

A substantial amount of work has been done in the past on the technologies underlying this research. Physical modeling with discrete spatial-lattice *cellular automata* models has been studied[margolus-99]. Haptic interaction with polygon-based computer simulations has been extensively explored, however, haptic interaction with volumetric simulations has not been as well studied.

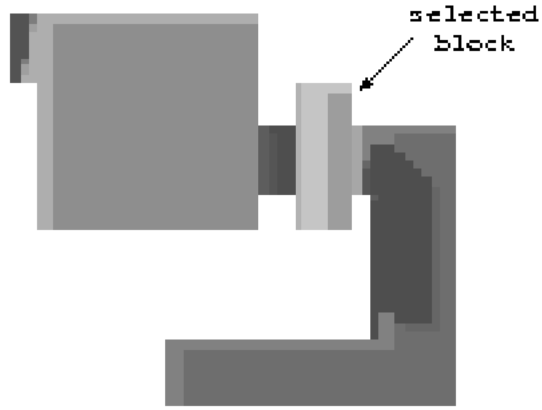
## Approach

Work in the past year has included the design and implementation of a basic system combining a PHANToM haptic interface[massie-94] and the CAM-8 cellular automata machine[margolus-96] to provide a three-dimensional haptic user interface for real-time simulations running on the CAM. This was a successful demonstration of what can be done with current technology. Given the high (1 kHz) response rate required for haptic interaction, there were initially problems due to the communication and computation delays inherent in the system. These were overcome with a novel method for coping with latency that in effect trades some degree of spatial accuracy of interaction for timely and sharp haptic responses[floyd-99].

This is an acceptable trade-off. If the haptic response is inaccurate, this is eminently noticeable to the user. Objects feel soft or unwieldy, and in the worst cases violent oscillations may occur. The result of




Static 3-D Pieces (with grasp point)




Static 3-D Pieces (with selected block)

spatial inaccuracy, however, is far less noticeable to the user of a haptic interface as long as other forms of feedback match the haptic feedback. As the user is operating the haptic interface in free space, they have very little in the way of a frame of spatial reference beyond their own proprioception. For small coordinate offsets, this effect is not easily perceptible to the user.

## Latency Issues

As the PHANToM and the CAM-8 connect to different host computers, the two machines need to exchange information for the system to work. I first examined the possibility of standard closed loop operation at a lower response rate. Given Ethernet communications and the speed of the CAM-8, a loop rate of 100 Hz would not be an unfeasable goal. To determine whether or not this was a viable direction to continue working towards, the simple "Hello, sphere" program was reimplemented to operate over the network.

Testing revealed serious problems with this model of operation. The environment presented to the user is of very low fidelity. The stiffness of items in the enviroment is determined by the stiffness of the haptic interface and the stiffness of the closed servo loop, of which the latter is the limiting factor with the PHANToM [massie-93]. Additionally, the large delays in force updates could often lead to violent instabilities in the system.

The same problems this system encountered with communication and computational latency have previously been seen when using force feedback devices for teleoperation. The computational delays are essentially no different from additional communication delays, so the whole system can be likened to time-delayed teleoperation in a virtual environment. Some existing systems have been designed to cope with delays at least as large as 1 s [niemeyer-96], which is far greater than the expected system latency. A number of different options were explored, but none of them were found to be suitable, as most made unacceptable assumptions such as a passive remote environment.

## Time vs. Space Tradeoff

To meet system design goals, it was necessary to formulate a new method for coping with latency in virtual teleoperation. For the kind of high-fidelity force response desired, it is clear that the closed haptic response loop should not extend beyond the haptic interface host, and should be designed to operate as quickly as possible based on a local model of the remote virtual environment. By relaxing environmental restrictions further, we are able to find an acceptable solution to the latency problem.

All of the conventional methods explored make a fundamental assumption about the nature of the system: There is a direct spatial correspondence between the local and remote environments. That is to say, if there is a wall five inches from the neutral starting position in the remote environment, then the user will perceive it five inches from the neutral starting position with the haptic interface. Fixed objects in the remote environment are also fixed in a frame of reference about the haptic interface.

This assumption is understandable when teleoperating in a remote real environment. The slave robot physically exists in that remote environment, and when it collides with an object it encounters natural restoring forces that should be communicated back to the master. This is not, however, the case when operating in a virtual environment. The slave robot exists only inside the computer, and does not necessarily encounter forces unless we choose to compute them, and these forces can be computed without affecting the state of the environment. It is free to penetrate solid objects and violate the physics of the virtual universe if we so desire. None of the other similar systems encountered took advantage of these properties.

This understanding allows us to make a simple trade-off of temporal versus spatial accuracy. We are able to provide a high-fidelity haptic response at the exact time the user penetrates an object in the virtual environment by relaxing the spatial correspondence between the haptic interface workspace and the virtual environment.

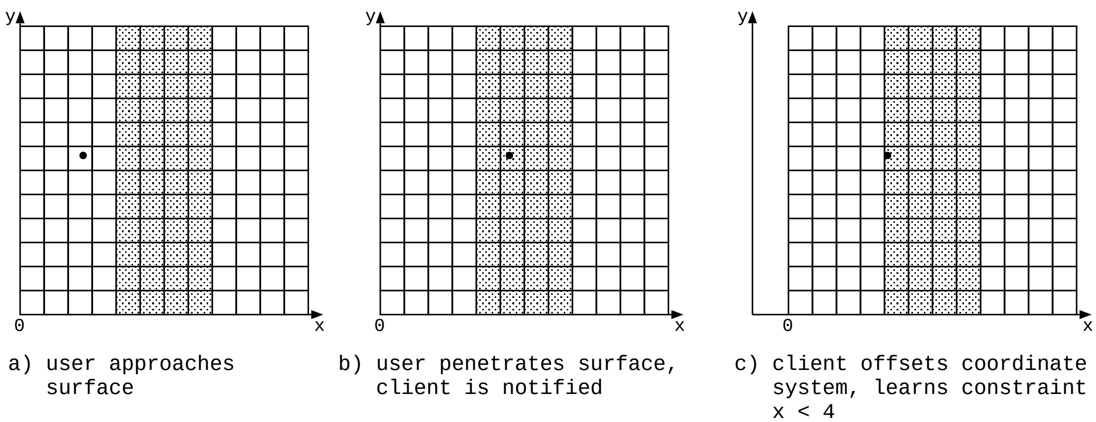



Figure 1: Time / Space Tradeoff

A simple example: Consider that the user is moving unimpeded through free space, and there exists a solid surface some distance in front of the user (Figure 1a). As the user moves towards the surface, at some point they will penetrate the surface given the current frame of reference of the haptic interface (Figure 1b). Some delay length later, the computation server will realize that the user has violated physical constraints of the environment. In a traditional teleoperation system, it would then compute a force to deliver to the user which by the time it was delivered would be incorrect, as the user may have moved significantly during the time it took to compute and communicate this force. Instead, the server tells the haptic client that the user has penetrated a surface in the environment, and where that collision occured. The client uses this information to offset the coordinate system the user is operating in so that instead of having significantly penetrated the surface the user is merely just within it, computes an appropriate force response, and caches the constraint implicit in the existance of that surface so that forces to impede further progress in that direction are computed on the client alone (Figure 1c).

In other words, when a user collides with an object in a remote virtual environment, instead of immediately encountering a restoring force they frictionlessly push the coordinate system (and all objects therein) away from them for the duration of one round-trip delay. After this delay, the haptic client has learned of the environmental constraints and can provide force feedback as appropriate.

## Conclusions

The currently available hardware puts this project just within the bounds of possibility, where a proof-of-concept system was feasible and more complex systems will be possible soon. Designing a general purpose interface to bitmapped simulation is not easy; due to the properties of different simulations it often seems necessary to tailor the haptic interface to the task at hand. Additionally, the current method for coping with the large latencies found in the implemented system significantly restrict the realm of simulations that can be easily interacted with via the haptic interface.

Parallel computers such as the CAM-8 are engines that allow real-time presentation and manipulation of large amounts of data, such as a three-dimensional bitmapped virtual environment, however they suffer from the fact that there are few effective ways for a user to directly interact with a simulation. This research begins to provide interfaces for automata-based simulations that are easily understood and consistent with the way a user would expect a simulation to behave, based on their real-life haptic experience.

Such interaction may be of use for controlling and analyzing scientific and engineering simulations, for interacting with 3D bitmapped medical data, and in general for many of the applications for which direct haptic interaction has been studied and proposed in connection with non-bitmapped virtual reality simulations.

## Future Work

There are a number of directions in which future work on this research could proceed. Currently implemented examples do not make particularly efficient use of the available computational power and should be expanded to explore more dynamic applications in a variety of fields. The power provided by a next-generation parallel computer would greatly expand the scope of simulations accessible to this research. Expanding the implemented system to include a user interface beyond single point haptic interaction, by the use of multiple PHANToMs or other more complex interfaces, would also be interesting. Further, some of the methods devised for coping with communication and computation delays should also be applicable to conventional force-reflecting teleoperation.

## Acknowledgements

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