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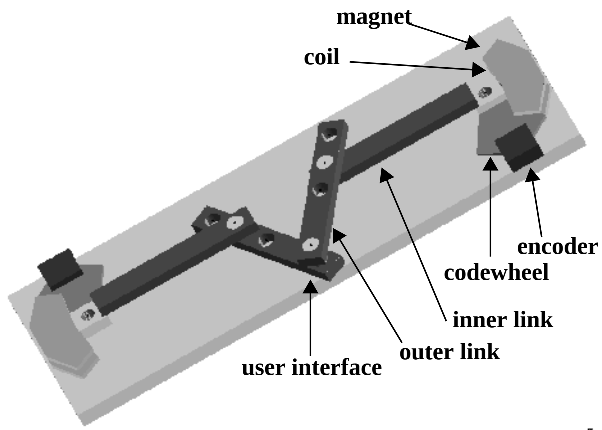
The PantoMouse

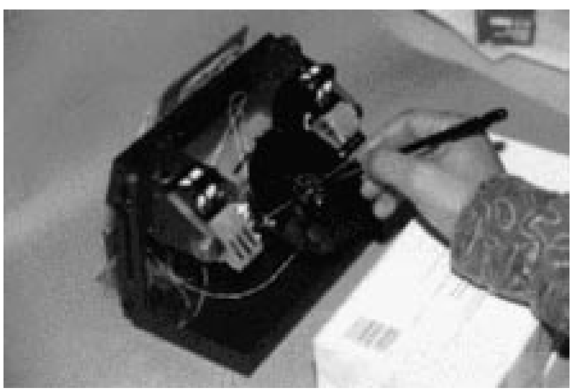


Technical Data

Degree-of-freedom	2
Workspace	$10cm^2$
Spatial resolution	0.01mm
Static Friction	less than 0.01 [N]
Force Output	continuous 0.4 [N]; peak up to 1.2 [N]
Inertia	20-30 [gr]
Mechanical Design	P.Buttolo, R.Oboe
Electronics and control	P.Buttolo, R.Oboe, S.Piovan

The Pen Based Force Display

3 DoF configuration

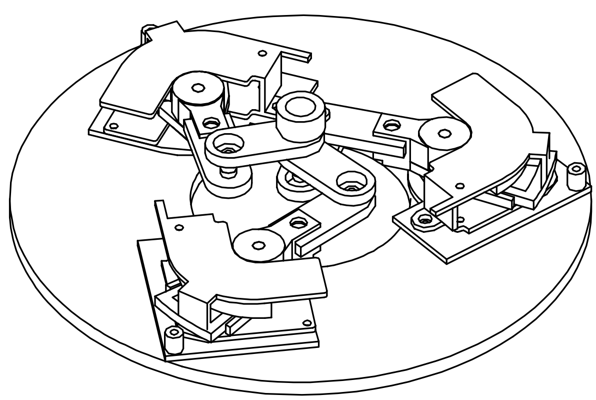


Technical Data

Degree-of-freedom	2 or 3
Workspace	$15\ mm^2 \times 15\ mm$
Spatial resolution	0.015mm
Static Friction	less than 0.01 [N]
Force Output	continuous 0.5 [N]; peak up to 2.0 [N]
Inertia	8-12 [gr]
Mechanical Design	P.Buttolo, B.Hannaford
Electronics and control	P.Buttolo, B.Hannaford

2 DoF configuration: Electronics and PC interface

2 DoF configuration: CAD drawing



We implemented an Adaptive-Dynamic-Bounder, to ensure that the “dynamics” of the simulation is compatible with the delay in the communication. To this purpose, each client estimates the round trip delay in between peers, and sends the data to the server. The server determines the maximum round trip delay, and sends back to all the clients what are the maximum allowed absolute speed and maximum change in speed, after a collision of the ball with a virtual racket.
These parameters are calculated so that, in the worst case, the ball will not travel more than a distance equal to the length of the squash-court in a time equal to the communication delay. This is necessary because the local estimated position of the ball is not necessarily the position of the ball of the AO. When the AO hits the ball, and passes the role of AO to the next player, the ball could already have been traveled out of the court. The longer the delay, the higher is this probability of such an occurrence.

A similar technique, not yet implemented, could be used to limit the maximum speed achievable by the user in moving the racket, introducing an active damping proportional to the maximum delay. In such a way, not only the dynamics of the ball could be limited, but also that of the players.

The protocol used for communication is an enhanced UDP built on top of the UDP/IP standard.
Standard UDP allows a faster round trip communication, but packet may not be received or received out of order.
Our enhanced UDP implementation manages a reliable flow for single event packets, such us connection and disconnection requests. In the case of continuous flow of information, such as the positions of the players, packets are sent unreliably, but packets out of order are discarded.
The enhanced UDP offers also other functions, such as

- check if the other peers are dead or alive, checking if any packet has been received in a certain period of time.
- send a packet every fixed amount of time, to signal that the peer is alive. This technique is known as heartbeat [Gossweiler et al., 1994].
- synchronize an event, such as the start of the game.

Force Feedback and Shared Simulations in Aerospace Applications

The design and production of large, complex systems such as airplanes requires a bewildering array of sophisticated and interrelated processes.
To insure overall efficiency and profitability of such an enterprise, process specialists must collaborate frequently and well, both within a given discipline and between disciplines. Haptic-enabled simulation has the potential to improve the speed, breadth and depth of such collaboration [McNeely, 1993].
For example, consider the scenario that a fuel pump must be relocated inside an engine strut.
Two design engineers collaborate to find a nominally suitable new location, using haptic based CAD with its efficient grab-and-move paradigm, and taking turns adjusting the pump’s position while discussing design criteria.
A manufacturing engineer observes that any of the contemplated pump locations will greatly complicate the strut’s assembly sequence, and addresses this problem by shifting a nearby bulkhead, which creates new possible pump locations, then moves the pump to one of those new locations.
A maintenance engineer notices that the bulkhead change prevents maintenance access to another, unrelated component, and responds by readjusting both bulkhead and pump.
All parties take turns manipulating objects, feeling collisions, masses, interferences, explaining their reasoning and discussing criteria until a good compromise solution is found.
In other scenarios, this type of collaboration could be extended to include many other specialists, including customer representatives.

The “one user at a time” architecture is seen to have broad applicability under this vision. Concurrent force feedback, despite its serious technical challenges, is inherently required to simulate certain scenarios, e.g., multi-person maintenance tasks. It would also incrementally improve the speed of collaboration in scenarios such as the one described above.

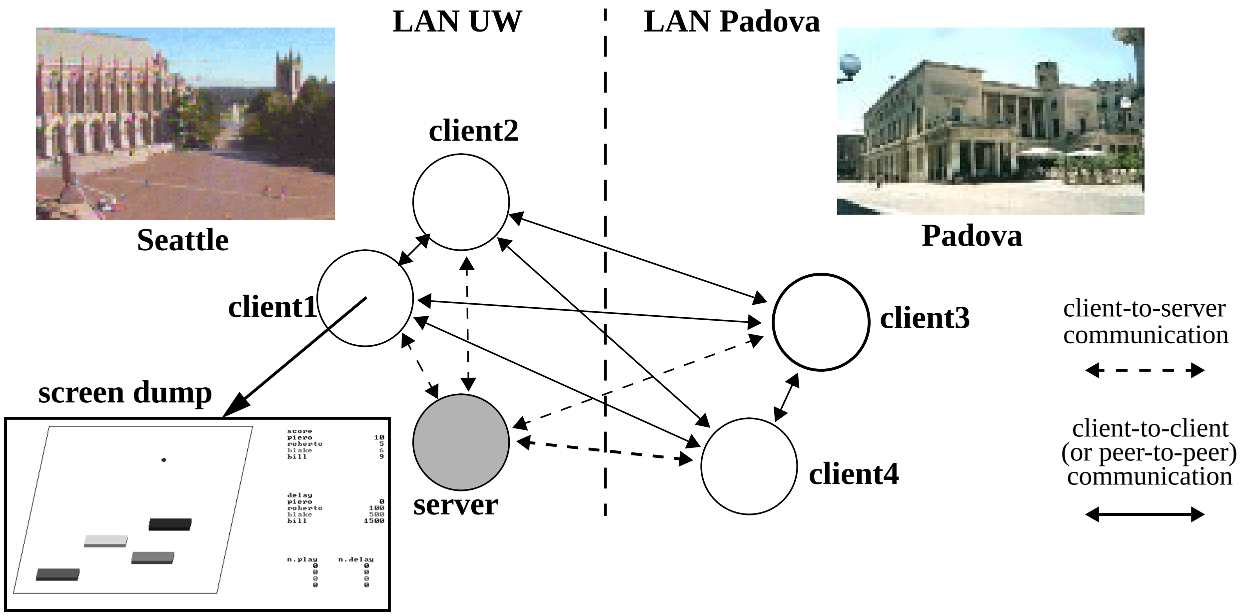


figure 1

A Server (grey box) is used to handle connection-disconnection requests to the game, to synchronize the start and end of the game, and to monitor the correct functioning of the system (dashed line). Each client (white boxes), contains the complete model of the system, which consists of the dimensions of the squash-court, the position of all players, and the position and the speed of the ball. All players periodically send their relative position, plus the position of the ball if they are the AO, to the others players and the server (continuous line). In figure is also the screen dump for client n.1

In the following paragraphs we will describe two practical applications.

- "Force Feedback Multi-player Squash". This game was implemented mainly to test the feasibility of the previously described architecture, and to observe the effects of random delay over trans-atlantic shared simulations.
- a hypothetical shared virtual environment for design of commercial airplanes.

Force Feedback Multi-player Squash

"Force Feedback Multi-player Squash" (FFMS) is a practical implementation of "one-user-at-a-time" architecture. A similar system, "multi-player handball" has been implemented at University of Alberta [Shaw, Green, 1993].

In real squash, two players alternate in hitting the ball. At a specific time, a player is the designated hitter, the others are waiting, trying to anticipate the next move.

In FFMS, more than two players can play together, but as in real squash, only the AO is allowed to touch the ball. Using a haptic device, as in real squash, players feel the collision with the ball. The speed of the ball after collision, and the intensity of the stroke reflected to the operator, is determined by applying the principle of conservation of energy to the system composed of ball and racket.

The system architecture is peer-to-peer like, in other words, information is not only sent to a central node (the server) but exchanged between all clients (see Figure).

The system consists of:

- a Server, that is used to handle connection-disconnection requests to the game, to synchronize the start and end of the game, and to monitor the correct functioning of the system;
- multiple Clients, one per player. Each Client contains the complete model of the system, that consists of the dimensions of the squash-court, the position of all players, and the position and the speed of the ball.

All players periodically (at a changeable frequency, set by default to 20Hz) send their relative position, plus the position of the ball if they are the AO, to the others players and the server. For a medium-large number of players, instead of actually sending the same packet to all the others players, a single packet could be sent using multicasting [Macedonia, Brutzman, 1994]

Non-AO update the position of the ball, in between reception of new packets, using a predictive model. Once a new packet arrives, the new data is used to adjust the estimated position. This technique is called dead-reckoning [Gossweiler et al., 1994].

sions in the virtual simulation or to constrain motion inside specific areas or along desired directions.

Humans can perceive frequencies up to 1500Hz, but can discriminate frequencies only up to 300Hz [Shimoga, 1993]. State of the art physical devices can reproduce force components up to 50Hz [Iwata, 1993], [Massie, Salisbury, 1994], [Ramstein, Hayward, 1994], [Buttolo, Hannaford, Mar95]. Using such haptic displays, operators can touch simulated objects with stiffness of 2000-4000Nm. These values have been experimentally found to be the minimum required to reproduce a realistic feeling of touch [Rosenberg, Adelstein, 1993].

The presence of vibrations, due to poor position sensing resolution or low mechanical natural frequency, could spoil the virtual experience. Mechanical or software simulated friction, stabilizes the devices during the interaction with stiff virtual surfaces. On the other hand, manipulation with a sticky device is slower, fatiguing and unrealistic. For similar reasons it is important that the inertia of the device is kept as low as possible. The mechanical design of the haptic devices is therefore essential.

Of equal importance is the design of the collision detection software (CDS) and the haptic device driver (HDD) [Buttolo et al., Oct1995]. Because force feedback is a bidirectional exchange of information-energy, latency and slow sampling rate may introduce instability in the VR system:

- To reflect force component up to 50Hz, the model must be updated for collision at least at 1kHz. This may be a serious computational burden, if the environment model is richly detailed.
- Preliminary studies by one of the authors have proven that even small time delay (latency) in the control loop, such as 5-10 msec, can cause instability.

Two Force Feedback Haptic Displays

Parallel, direct drive (or low gear ratio) manipulators are characterized by a very stiff mechanical structure, low moving inertia and limited friction. [Asada, Kanade, 1983], [Asada, Youcef-Toumi, 1987]. Taking advantage of these properties, we designed and built two parallel, direct drive, haptic displays (see appendix at the end):

- The “PantoMouse”, is a 2 Degrees of Freedom (DoF) planar, parallel, direct drive structure, designed and built at the Universita’ di Padova, 1992.
- The “Pen Based Force Display”, is a planar, parallel, direct drive, actuation redundant manipulator, that can be used either as a hand held 2 DoF mouse or can be connected to an additional couple of actuators that provide motion along the vertical axis. [Buttolo, Hannaford, Nov1995]. The system is entirely portable as carry on luggage.

These devices have been successfully used as master devices for remote manipulation systems (RMS) [Buttolo et al., Oct1995], [Hannaford et al., 1995], [Hwang, 1995], and as haptic devices for virtual environments (VE) [Buttolo, Hannaford, Mar1993], and shared virtual environments [Buttolo et al., Nov1995].

In the following paragraphs we will describe a Shared Virtual Environment architecture and two practical applications.

Force Feedback in Shared Virtual Environments: a “one user at a time” architecture

There are many examples of SVE for a small, medium and large number of participants [Broll, 1995], [Calvin et al., 1993], [Carlsson, Hagsand, 1993], [Codella et al., 1993], [Gossweiler et al., 1994], [Kazman, 1993], [Macedonia et al., 1995], [Maxfield, 1995], [Singh, 1995], [Stansfield, 1995], [Shaw et al., 1993], [Stytz et al., 1993], [Wang et al., 1995], [Zyda et al., 1993]. However, force feedback is provided to the users in only few systems [Ishii et al., 1994].

Integrating a force feedback interface in a shared virtual environment introduces some serious constraints. If multiple users are to manipulate the same portion of the SVE, demanding requirements have to be satisfied for latency and sampling rate, as we explained in the previous paragraphs. If minimum latency cannot be guaranteed, because of the characteristics of the communication media [Claffy, 1994], a compromise has to be accepted, otherwise the systems might be unstable, and therefore dangerous to the user.

One possible solution is a “one-user-at-a-time” architecture. Only one user at a time, the Active Operator (AO), is allowed to modify and feel force from the environment. The other users, non-AO, are allowed to watch the on going interaction through a visual display[1], move around in the SVE, but not touch or modify objects.

In such a way, a copy of the environment can be run on each local machine. Once the AO has completed his/her interaction, all the copies of the SVE are updated to match the AO’s copy. The AO then releases the role, that is assigned by the scheduler to a different operator. The system could be implemented with a sophisticated scheduler, that allows different AO in different area of the virtual object (as in a database, for different items), or in a more simple implementation, the operators could share the role of AO in a token ring fashion. The role of AO is passed from player to player, in a fixed order.

1. The up-date rate for the refresh of the visual display is not as critical as that of the Force Server.

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Force Feedback in Shared Virtual Simulations

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Abstract

Virtual reality is a powerful tool for training, simulation and computer aided design. Replacing the traditional mouse with a force feedback device might enhance the performance of such systems, permitting a more natural interaction. The software interface and the mechanical design of force-feedback devices is critical. The operative system must be real time and guarantee low latency and high sampling rate. Additional constraints are introduced if there is a need for sharing the simulation among multiple players. In this paper we will present two haptic devices, and a distributed architecture that allows operators to manipulate objects in a shared virtual environment. We will conclude with two examples, a multi-player squash game and a shared force-feedback CAD system for airplane manufacturing.

Keywords

Virtual Reality, Force Feedback, Haptic Displays, Shared Virtual Environments.

Introduction

Virtual Reality (VR) is a powerful tool for training, simulation, and computer aided design. The "state of the art" flight simulators are an example of the "realism" that can be achieved. The sensation of being in a "real" environment, while interacting with a VR simulation, is usually referred as "sense of presence" or "immersion".

In most of the current applications the focus is in providing a good visual feedback to the user, trying to improve the tracking-registration and the resolution-refresh rate of head mounted displays. However, the lack of proprioception, in other words, the impossibility of really "touching" the virtual objects, makes the interaction unreal and more difficult.

Hannaford [Hannaford et al., 1991] experimentally proved that, in a telemanipulation system, providing kinesthetic feedback to the operator significantly reduces the time required for the execution of some tasks, and the amount of energy (and therefore stress) spent by the operator. Because of the similarities between remote and virtual manipulation, it is reasonable to assume that similar results should hold true for virtual reality applications.

Force feedback is particularly important in safety critical VR simulations:

- In the more sophisticated flight simulators force feedback is used to enhance the feeling of immersion. The operator sits on a 6 DoF parallel manipulator that reproduces part of the flight dynamics, and holds an active stick, that provides the exact resistance to motion.
- VR systems offer the possibility of training surgeons without risking casualties and minimizing the cost. However, force feedback is indispensable, otherwise the perceptual experience in the virtual world will not correspond to the real one, making the training useless, if not dangerous.

In many applications, it is desirable to allow multiple users to interact in a Shared Virtual Environment (SVE). A platoon of soldiers, a plane crew, a surgical team can, in a SVE, train together. The level of interaction depends on the physical constraints of the communication media and on the available computational power. The architecture of the distributed simulation must fit the specific application.

In the following paragraphs we will list the issues in providing force feedback to users of VR systems, we will briefly describe two force feedback devices, and than we will introduce a shared virtual environment architecture.

Force Feedback

Force feedback enables the operator to manipulate the environment in a natural and effective way, enhances the sensation of "presence", and permits a faster rate of information (visual plus haptic).

The user interacts with a mechanical interface, called haptic device[1]. In a CAD system, this can be used:

- as a pointing device, like a multi Degree of Freedom (DoF) mouse;
- to reflect force back to the user, to simulate colli-

1. Haptic displays are also called force feedback mouse, master devices, or force displays.