Haptic Battle Pong: High-Degree-of-Freedom Haptics in a Multiplayer Gaming Environment

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Abstract

Recent advances in both haptic rendering techniques and CPU power have made haptic feedback increasingly accessible on consumer hardware. With the recent success of simple haptic feedback devices in console and PC game systems, more sophisticated haptic rendering is poised to enter the mass entertainment market in the near future. With this in mind, we describe "Haptic Battle Pong", a competitive networked game that makes extensive use of three-degree-of-freedom force-feedback and six-degree-of-freedom input. This is among the first games to fully utilize the capabilities of high-fidelity haptic devices, and we use this environment to explore the applicability of high-degree-of-freedom haptics to games.

We discuss our approaches to physical simulation, force-rendering, and networked haptic interaction. We also discuss several techniques we used to enhance the entertainment value of a traditional video game using the capabilities of a haptic display. Finally, we review the subjective responses of initial users and several lessons we learned that may be applied to future haptic games.

1. Introduction

Recent years have seen tremendous growth in the capabilities of high-performance, multi-degree-of-freedom commercial haptic devices, such as the SensAble Phantom [Massie and Salisbury 1994) and the Force Dimension Delta [Grange et al 2001]. Although these devices have been largely restricted to research users and specialty customers, high-end haptic systems have found applications in a variety of disciplines, including medicine [Agus et al 2003, Mendoza and Laugier 2003], assistive technology [Morris and Joshi 2003, Sjöström 2001], and product design [Nahvi et al 1998, Zhang et al 2003].

The past few years have also seen an explosion in the popularity of computer gaming, an industry that totaled over ten billion dollars in US sales alone in 2002 [Rocsearch, 2003]. With the advent of powerful CPUs on home computers and game consoles, the video game industry has begun to expand into multimodal interfaces. Consumer haptic devices – from "rumble feedback" devices to more sophisticated two-degree-of-freedom joysticks – have gained significant popularity, and are supported by numerous games and development APIs (e.g. DirectX).

Given the growing flexibility of high-performance haptics, the magnitude of recent growth in the video game industry, and the game industry's initial successes with haptic feedback, it seems almost inevitable that sophisticated haptics will find a key niche in electronic gaming.

However, there are still significant engineering and human interface challenges associated with haptics that have not been explored by existing video games. This paper describes "Haptic Battle Pong", a demonstration of the potential for haptics in video games. The project leverages the familiarity of classic Pong, but also addresses some of the key challenges presented by haptic gaming. In the context of the game and its development framework, we address three primary topics:

- *Tight, closed-loop integration of haptic feedback and simulation physics.* This has not been possible with the simple haptic devices used in current mass-market games; commercial games currently use haptics only to transmit information to the player.

- *Networked competition between players.* Networked haptic feedback presents numerous challenges associated with the high update rates required for haptic interfaces and the high latencies associated with network transmission.

- *Entertainment value of haptics.* It remains to be proven that high-degree-of-freedom haptics can enhance a player's video game experience; we present some novel techniques for enhancing traditional gaming environments and initial responses from users.

2. Game Description

Haptic Battle Pong (HBP) is a two-player networked game; each player is seated at a computer with a Phantom haptic interface (SensAble, inc.). We have successfully tested HBP with the Desktop, 1.0, 1.5, and Omni Phantom models. Our typical configuration uses a Desktop Phantom and a 1.5GHz Pentium 4. Graphics are rendered using OpenGL; a stereo display (using OpenGL's support for stereo rendering) is optional.

The core gameplay is consistent with the traditional "Pong" game; each player's primary objective is to make contact with a moving ball using a virtual paddle. The playing area is enclosed by walls on all sides. Each player is represented by an on-screen avatar, who can be moved in two dimensions using the keyboard. This

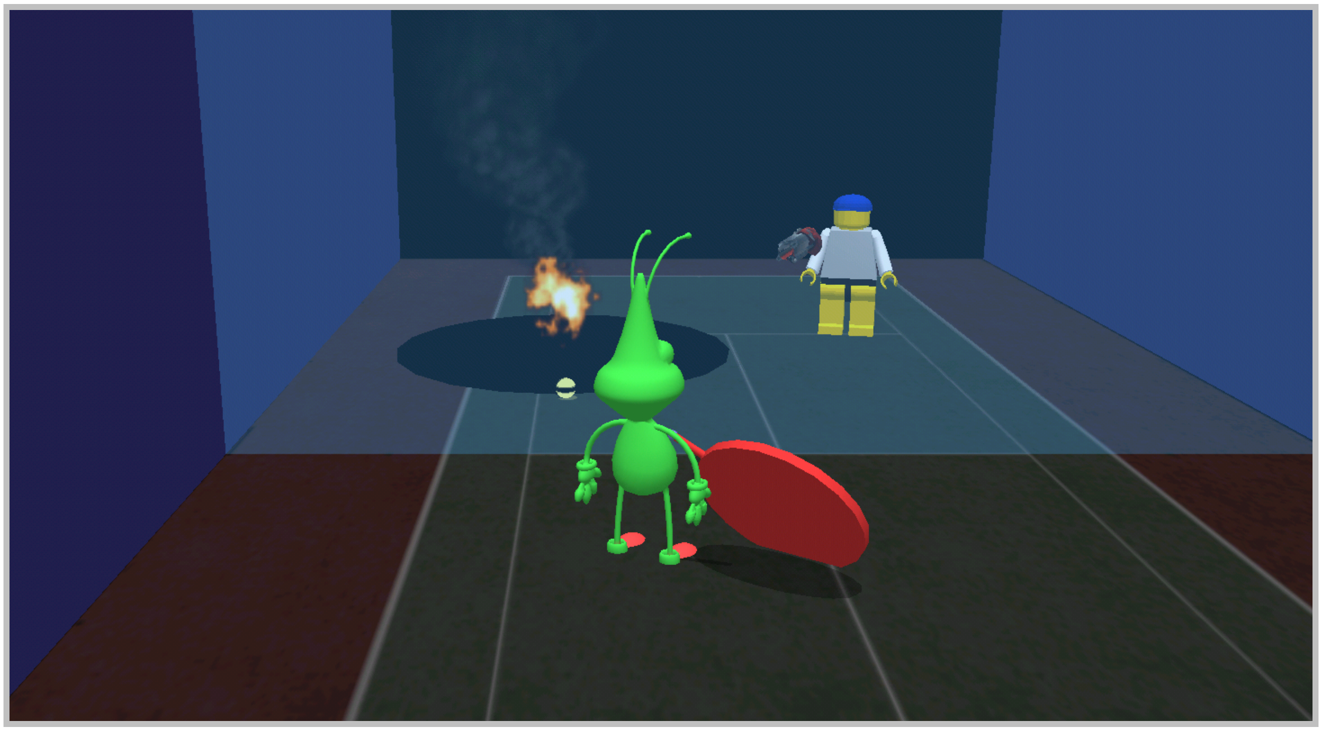

FIGURE 1: A screen shot captured from Haptic Battle Pong. Each avatar represents the center of a player's haptic workspace; players control tools in six degrees of freedom within that workspace.

avatar represents the center of the player's workspace; movement and rotation of the paddle within this workspace are performed using the Phantom. FIGURE 1 displays a screenshot of HBP, including the playing area and the player and opponent avatars.

In the competitive, networked mode of HBP, a player's "territory" includes half of the "court"; a player can only manipulate the ball within his or her territory. This simplification – which we refer to as the "private haptic space assumption" – greatly reduces the complexity of the networking (since haptic interaction is never precisely simultaneous), and is consistent with the gaming model of "pong"-type games and most existing sports-based video games. As we discuss later, this does not eliminate the sense of physical interaction among players.

A player's objective is to keep the ball in the opponent's territory; a player loses "health points" each time the ball bounces within his or her territory. Players also interact via a series of "haptic mines"; a player can enter his opponent's territory to place a mine on the court. If a player steps on his opponent's mine, he loses health points and is subject to one of several haptic effects, which make use of the Phantom's sophisticated force-rendering capabilities and enhance the level of interaction between players.

3. Physics and Force-Feedback

The most critical aspects of HBP's use of the haptic device involve the interaction between a player's paddle and the ball. Typical games that make use of the force-feedback effects available on consumer force-feedback devices simply render forces to inform the player about certain game events. In contrast, HBP defines a tight, closed-loop integration between the physics of the game and the force-rendering performed using the Phantom.

The interaction between the ball and the paddle is modeled as a sphere penetrating a solid disc with a fixed spring constant. The force exerted on the ball is always perpendicular to the plane of the paddle and is proportional to the ball's penetration through the plane of the paddle. This leads to a fairly intuitive model of contact from the player's perspective, and provides the basic physical properties that are expected from a ball-paddle collision. For example, the velocity with which the ball leaves the paddle is proportional both to the initial velocity of the ball and the initial velocity of the paddle (i.e., "swinging harder" makes the ball move faster).

The haptic display is used to render the force resulting from contact between the ball and the paddle. Initially, we set the force rendered on the Phantom to be proportional to the force exerted on the ball at all times, in the interest of physical realism and conservation of virtual energy. Initial results showed that this was not intuitive from a player's perspective, and generally led to very brief contacts that were difficult to control. We experimented with a variety of force models, and ultimately decided that the simplest contact model – a constant force that is not dependent on the velocity of the ball or the penetration distance of the ball – was an effective approach. The perceived effect was similar to the brief contact established between a tennis ball and a tennis racquet. The "force" of the impact was still perceived to vary with the force exerted on the ball, since longer contact times resulted in more net force being applied to the Phantom.

The only problem with this approach, initially, was that the Phantom tended to vibrate when a player tried to 'pick up' a stationary ball, due to the rapid and repeated initiation and release of contact with the ball. So at very low penetration distances (which occur only briefly in typical collisions), we apply a force to the Phantom that is proportional to the force applied to the ball.

to summarize, the force rendered on the Phantom can be represented as:

$$F_{haptic} = \begin{array}{ll} k_p\,(P_p - P_b) & (\text{for } |P_p - P_b| <= d) \\ c & (\text{for } |P_p - P_b| > d) \end{array}$$

...where F_{haptic} is the force applied to the haptic device, k_p is the gain used when rendering a linear spring force, P_b is the xyz position of the ball, P_p is the xyz position of the ball's projection onto the plane of the paddle, d is the maximum penetration distance at which linear spring forces are rendered, and c is the constant force applied when the penetration distance is greater than d.

We also model the ball's rotational acceleration resulting from motion of the paddle within the plane of the paddle surface during contact with the ball. The induced rotational acceleration is not tied to the induced linear acceleration; rotational acceleration is proportional to the tangential motion of the paddle, computed as:

$$d\boldsymbol{\omega} = dt((k_r((\boldsymbol{p}_{ball} - \boldsymbol{a}) \times \boldsymbol{v}_p)) - k_{rf}\boldsymbol{\omega})$$

...where ω is the rotational velocity of the ball, dt is the time elapsed between physics computation iterations, k_r is a constant linking paddle velocity to rotational acceleration, p_{ball} is the position of the ball, a is the projection of the ball onto the plane of the paddle surface, v_p is the linear velocity of the paddle, and k_{rf} is a constant governing angular deceleration due to contact friction. The first term on the right side of this equation induces an angular acceleration according to the tangential velocity of the paddle, and the second term introduces an angular deceleration due to contact friction.

Subsequent contacts between the ball and other objects (walls or paddles) result in a change in the ball's linear velocity due to the rotational momentum of the ball and friction between the ball and the contact surface. The perceived effect is similar in magnitude to the spin applied to a ping-pong ball, which causes visible deviations in the path of the ball upon surface contacts.

When contact between the ball and a user's paddle occurs, any rotational velocity accumulated by the ball induces forces on the Phantom that are parallel to the plane of the paddle. This increases the sense of competitive interaction between players, since one player's "spinning" motion can induce a force on the opponent's paddle that complicates his interaction with the ball. The acceleration of a player's paddle due to contact with a spinning ball is computed as:

$$f_{hr} = k_{hr}((\boldsymbol{R}_p\boldsymbol{\omega}) \times (\boldsymbol{p}_{ball} - \boldsymbol{a}))$$

...where f_{hr} is the force applied to the haptic device due to spin, k_{hr} is a constant linking tangential force applied to the paddle to haptic force, R_p is the rotation matrix defining the rotation of the paddle face, ω is the world-space rotational velocity of the ball, and p_{ball} and a are defined above. Note that conceptually a torque should additionally be applied to rotate the paddle around the ball, but most commercially-available haptic devices are unable to render torque, so we apply only the linear component of induced forces.

We also found it necessary to apply a non-linear air friction to both the linear and rotational velocities of the ball. Due to the wide range of swinging forces and velocities applied by players, the ball could reach extremely high velocities in some cases, which resulted in a loss of ball control by the players. We experimented with simply increasing the virtual mass of the ball and maintaining the linear acceleration model, but in this case small motions of the Phantom – which were typical among novice players – failed to adequately accelerate the ball. Therefore, we found that gameplay was enhanced significantly by placing an absolute upper threshold on ball velocity and applying air friction, which was modeled as a constant decrease in the magnitude of linear and angular velocities of the ball when it was not in contact with an object.

A player can also use his paddle to launch projectile bullets at his opponent (see FIGURE 1). This allowed us not only to add variety to the gameplay, but also to explore the application of 6-dof input and 3-dof haptic feedback to another popular class of video games. The "gun" is controlled like the paddle; the Phantom moves and rotates the gun within the workspace centered around the avatar. A keyboard button fires a bullet from the gun, which initiates a transient, constant force response along the axis of the gun, away from the bullet's path (simulating the recoil of the gun). Similarly, contact between a bullet and a player's avatar initiates a transient, constant force in the direction in which the bullet was moving.

The final application of haptic feedback in HBP was perhaps the most exciting for players who had not had extensive experience using the haptic devices. Each player is given four "haptic mines", which can be placed in the opponent's territory. When a player steps on a mine left by his opponent, he experiences a rumbling effect, similar to that provided by a standard force-feedback game pad. However, he also experiences a temporary haptic effect that is specific to the mine he encountered. The effects are:

- "Slow paddle" : The player's paddle is subject to a viscous force, equal to a constant (negative) multiple of the paddle's velocity.

- "Heavy paddle" : The player's paddle is subject to a gravitational force.

- "Remote operation paddle" : The Phantom held by the player who encountered the mine is connected by a virtual spring to the Phantom of the player who placed the mine, a simple form of tele-operation. I.e. if player 2 is subject to this effect, the force applied to his haptic device is computed as:

  $f_{p2} = (p'_{p1} - p_{p2})k_f$

  ...here f_{p2} is the force applied to player 2's haptic device, p_{p2} is the position of player 2's haptic device within its workspace, and p'_{p1} is the position of player 1's haptic device within its workspace, mirrored around the plane that divides the left and right halves of the workspace. This mirroring allows player 1 to more intuitively influence the movements of player 2's haptic device, which we found enhanced the entertainment value of the "remote operation paddle" interaction.

The fourth mine is not associated with a haptic effect; it causes only health damage and a rumbling force.

4. Networking

In order to avoid the latency-dependence experienced by many networked haptic environments, we make a "private haptic space" assumption: only one player can be in physical contact with the ball at one time, and players never directly come into haptic contact with each other. The ball is always within the territory of one player; this player is considered the "master", and his computer's physical simulation determines the "actual" position of the ball.

We propose that these assumptions will generalize to a wide variety of games, including most sports-based and shooting-based games. Note that it does not require that these zones be fixed over time, only that a single simulation master can be defined at all points in space at any given time.

These assumptions would not necessarily hold for general-purpose simulation environments, such as those used in surgical simulation research, or for games *based on* concurrent physical interaction, e.g. fencing or boxing.

Given these assumptions, the networking protocol aims to allow each computer to run its own physical simulation when the ball is in contact with the local player, to allow high haptic update rates during this critical period.

In fact, the networking protocol always allows physical simulation to run concurrently on both computers. Each simulation "owns" the territory that is occupied by the local player. When a simulation finds that the ball is in its territory, it is temporarily the "simulation master". In this state, HBP will transmit periodic simulation updates (position and velocity of the ball) to the remote machine. The remote machine will update its simulation, and continue with local physics computation until it receives another update. When the master determines that the ball has passed into the remote player's territory, it sends a final simulation update to indicate this status change, and the remote machine becomes the "simulation master". At all times, each computer periodically transmits the position and orientation of the local player and his paddle.

This approach allows each computer to maintain a highly accurate local physics model when the ball is in contact with the local player. When the ball is in contact with the remote player, the periodic updates are more than adequate for keeping up with the graphic frame rate (~100Hz), even when the local player is separated from the remote player by transcontinental distances. Dropped or delayed packets rarely cause visible glitches, since the physical simulation is updated on both machines at all times.

5. Results and User Reponses

We have successfully conducted games of Haptic Battle Pong both locally and across remote sites (including transcontinental games from Rhode Island to California). The networking strategy allows seamless transfer of physical simulation control, and thus smooth haptic interaction at all times.

Initial responses from players indicate that the haptic aspects of the game are intriguing and effective, enhancing the sense of interaction with an opposing player relative to a standard video game.

However, players – particularly players who had limited experience using the Phantom – initially found the six-degree-of-freedom input difficult to control. After discussions with players, we made several changes to the game.

One of the most challenging aspects of making contact with the ball was the need for very accurate depth perception. To this end, we added a shadow on the ball – which significantly improved position perception – and the ability to use stereo glasses with HBP when running in full-screen mode.

Initial responses to these changes are positive, although there is still a significant learning curve for novice users, during which players often fail to make contact with the ball. To ease this learning process, we added a "beginner mode" to the game, in which there is no gravity; the ball moves only in a plane parallel to the ground. In this mode, the objective of the game is to hit a target that appears behind the opposing player; this game is more like "Haptic Battle Air Hockey". The reduction in the necessary movement complexity greatly simplified the game for initial users. This provided an appropriate starting point for novices.

Similarly, because we found that the "spin" effect complicates gameplay, this feature is now optional and modal: the player has to hit a key to enable the "spin paddle", which is represented by a change in the paddle's color.

Another issue addressed by our initial experiments was the tendency of players to make movements that can potentially damage the (expensive) haptic devices. Because HBP is somewhat immersive and has the general feel of a video game, players tended to stop treating the device with the normal care generally used around haptic feedback equipment. The primary danger was rapid motion through the singularity in the Desktop Phantom's workspace, which could potentially break the last link of the device. Therefore, we found it critical to instruct players to use a particular grip (similar to a traditional table tennis grip) when playing HBP (see FIGURE 2). This was a bit counter-intuitive, since players preferred holding the Phantom as they would hold a tennis racquet. This inconvenience has potential implications for the design of haptic devices intended to be used for video games. Future work should also explore the impact of device structure and player grip on ergonomics; high-force and high-frequency applications may have harmful side effects, particularly for wrist-intensive applications.


(a) (b)

FIGURE 2: The grip used by the player significantly affects the structural impact that gameplay has on the haptic device. (a) correct grip, (b) incorrect grip, shown at this device's singularity

Overall, players felt that HBP provided them with a novel gaming experience, which required significant skills that had not been developed through experience with other video games.

6. Conclusion and Future Work

We have developed a game that makes extensive use of the Phantom's capabilities, both 6-dof input and 3-dof force feedback. The game can successfully be played across an intranet or internet, and players are left with a sense of *physical* interaction with both the gaming environment and the opposing player.

This success depended on a critical assumption, namely the "private haptic space" assumption described in SECTION 4. We propose that this assumption will generalize well to a broad variety of video games, and will be critical to allowing mass-market haptic devices to be used successfully over general-purpose networks. Our first priority in future work in this area is to apply the HBP simulation environment to other game types, to support this hypothesis.

Additionally, we plan to extend the game to more than two players; the assumptions we made allow a natural generalization to an arbitrary number of players.

More sophisticated graphical rendering – particularly more extensive use of stereo rendering – may help novice players adjust to the complex physical input system.

Finally, we plan to incorporate support for other haptic devices in the near future, particularly the ForceDimension Delta and the Phantom 6-dof. The latter will allow true torque feedback; we hope to explore the impact this has on the realism of ball contact.

Additionally, as high-degree-of-freedom haptics gains popularity, additional work will be necessary to evaluate the ergonomic impact of high-frequency, complex force-feedback. A future study will be necessary to evaluate this more formally; this may impact the ability for haptic devices to break into the consumer market.

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