ANYONE FOR TENNIS?

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Abstract

In this paper we present a Virtual Tennis Game. We describe the creation and modeling of the virtual humans and body deformations, also showing the real time animation and rendering aspects of the avatars. We focus on the virtual tennis ball animation and the behavior of the Synthetic Autonomous Referee, who judges the tennis games. The networked collaborative virtual environment system is described with special reference to its interfaces to driver programs. We also mention the VR devices used to merge the interactive players into the virtual tennis environment, together with the equipment and technologies employed for this exciting experience. We conclude with remarks on personal experiences during the game and future research topics to improve parts of the presented system.

1. Introduction

At the opening and closing session of Telecom Interactive'97 in Geneva, Switzerland, we presented in real time a virtual, networked, interactive tennis game simulation. The videotapes were demonstrated in the opening ceremony of Virtual Humans'97 Conference at Los Angeles, at the Virtual Technologies booth of SIGGRAPH'97 exhibition, as well as various conferences. This demonstration was a big challenge because, for the first time, we had to put together several different computer related technologies and corresponding software. This had to work in real time at a specific moment on the exhibition site with non-permanent installations. In this demonstration the interactive players were merged into the virtual environment by head-mounted displays, magnetic sensors and data gloves. The University of Geneva player was "live" on stage at the opening session and the other player in the Computer Graphics Lab of EPFL at Lausanne, separated by a distance of approximately 60 km. For managing and controlling the shared networked virtual environment we used our Virtual Life Network, which is a general purpose client/server network system using realistic virtual humans (avatars) for user representation. These avatars support body deformation during motion. The virtual humans also represent autonomous virtual actors such as the synthetic referee, who is part of the tennis game simulation. A special tennis ball driver animated the virtual ball by detecting and treating collisions between the tennis ball, the virtual rackets, the court and the net.

The paper is organized as follows: section 4 gives an overview of the networked virtual environment system used as software basis for integration. The autonomous referee and game automaton controlling the ball animation are detailed in section 5. Before the experiments and conclusions sections, we discuss the particular motion capture and VR feedback approaches built for the virtual tennis application. Let us first present the virtual human modeling stages and the real time skin deformation process, both important steps in the success of this project.

2. Creation of the virtual players

Modeling and deformation of virtual humans is an exhaustive task (Badler et al., 1993). Since we can use scanning devices for creation of the human shape, the modeling of the avatars seems to be obvious. However, with these methods we have no more information than the shape of the virtual human in default posture which is not sufficient for computing deformations during the animation (motion of the bodies, animation of faces). We use two different modeling tools in the production of the virtual players. These tools are linked with the animation we need to realize on each part of the body. One is a surface-based sculpting program used for modeling of heads (LeBlanc et al., 1991). The other is our software *BodyBuilder* (Shen et al., 1996), dedicated to the creation of human bodies using metaballs attached on a skeleton. Using texture-mapping and texture-fitting methodology enhances the final realism.

2.1. Sculpting the player's face, hands and feet

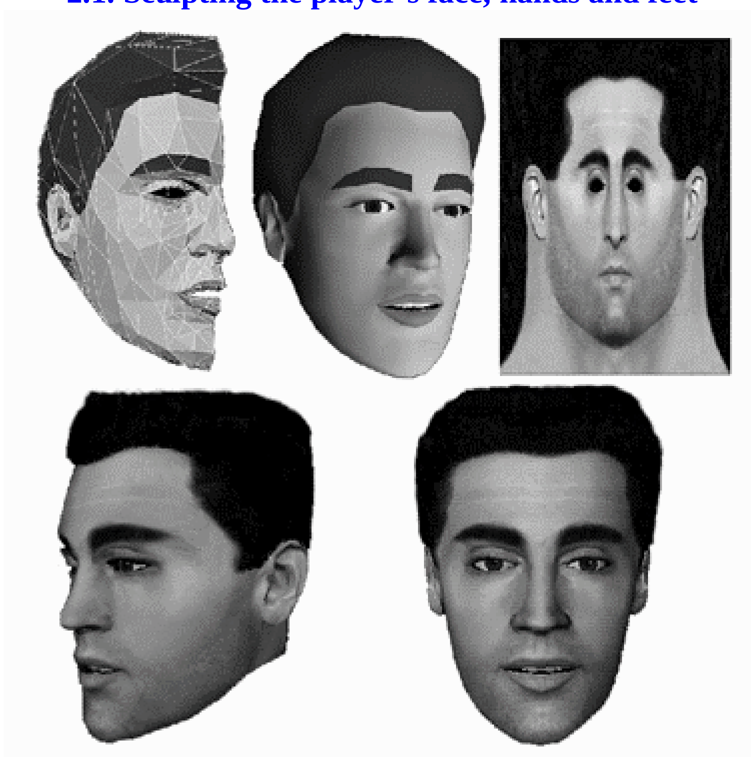


Figure 1 . Description of images from left to right, top to bottom: (1) One half of the head is created, (2) the other half, the eyes, and the teeth are added, (3) the texture is designed, (4 & 5) the texture is adjusted to the 3D model.

The method we use is similar to traditional sculpting with clay or wax. The designer starts from an irregular triangle mesh, modifying it with simple tools like adding, deleting, modifying, assembling and splitting primitives of the surface. The use of local and global deformations on the 3D head provides the designer with a sense of real sculpting, by being able to transform the object gradually. This kind of modeling suits our needs in facial animation, because the user creates the heads knowing the animation requirements. Thus they are able to create more detailed regions on the animated parts of the head, (lips, eyelids...) and less detail on the other non-animated parts (hair, forehead...) (Figure 1). For the tennis players, we constructed the heads from an already existing head that is precisely defined in terms of the complexity of the deformable regions. The idea is to deform the template to get the head we want to design. It is obvious that the best solution is to start with a template as close as possible to the target face. For hands and feet, the same approach is used.

2.2. Body creation of a tennis man and a tennis woman

BodyBuilder is a software that is dedicated to human body modeling by the creation of a human envelope. The human form is obtained by attaching metaballs into the joint articulations of a skeleton entity (created/animated by the user). A spline surface is computed using a ray-casting method on the body envelope. The surface is then triangulated and assembled with the head, hands and feet (Figure 2). The user can easily deform, scale, rotate and translate the metaballs to model the global shape of the body.

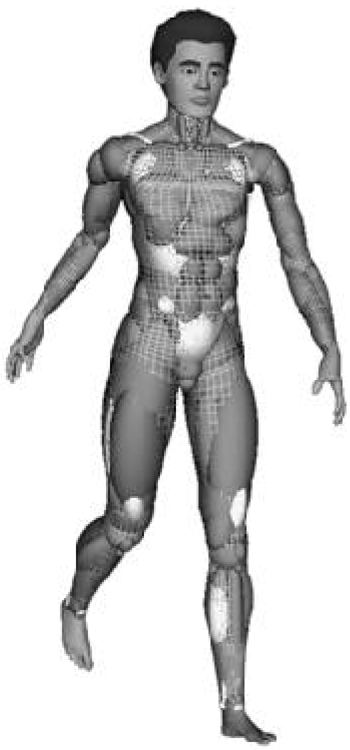


Figure 2. Creation of the body

Figure 3 . Body surface with textures

Creation of human bodies is a difficult task, which needs anatomical knowledge and experience in muscular deformations because metaballs act almost like the muscles under the skin envelope. Thus creating a nice shape of a human body in a specific posture requires knowledge of the muscle shapes in that posture (Figure 3). There is also a need to keep the exact proportions of the body because the human eye can easily detect the slightest defect. Once a body is created (male or female), we can create another one by using it as a template for the body creation. Although BodyBuilder generates high quality deformation, its computations are too heavy for real time applications. Therefore real time deformations are made using another technique (presented in section 3) based on the skin mesh provided by BodyBuilder.

2.3. Texturing

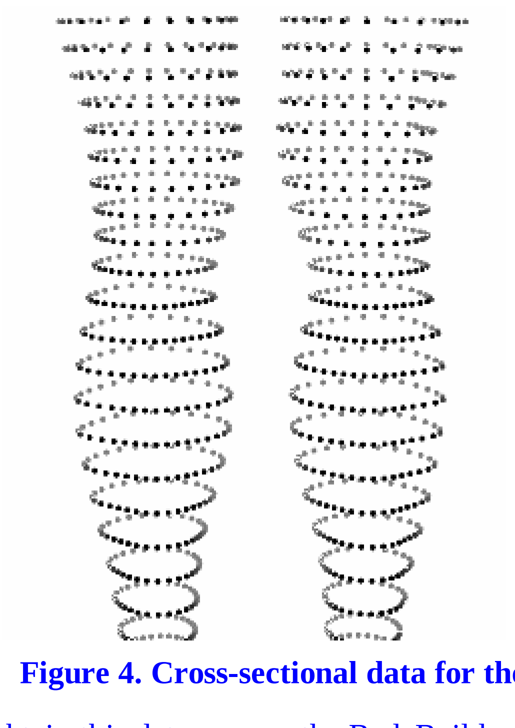
As we use a modeling method for creation of the avatars, we cannot just texture the head and the body using simple projections. If there are features on the texture (nose, eyes, hair,) we want them to match the corresponding details on the 3D object (Figure 3). This is a difficult operation when the images and the 3D objects are slightly different. We created an interactive texture-fitting software (Sannier et al., 1997) for realizing this kind of precise texturing (Litwinowicz et al., 1994). The idea is to allow the designers to correlate the main features, of the texture, directly with the 3D object. These features are projected on the 2D image where the designer can adjust the position of these features; the texture is then applied to the object using these points as references. The user is able to warp the texture locally and directly onto the 3D object, which provides more flexibility.

3. Body Deformations

There have been many attempts to produce fairly realistic virtual humans, but few of them have been oriented towards real-time animation. As a result, most examples of real-time animated humans often lack realism in the sense they rarely show human characters whose skin is properly deformed. In this section we shall describe an efficient method we have been using to render and animate realistic tennis players in real-time. By relying on cross-sectional data and deforming skin contours we succeed in representing a player in a most accurate fashion while preserving a consistent frame rate. This approach only deals with the body itself, which means the hands, head and feet are not taken into consideration in the following.

3.1. The Model Data

The surface model for the virtual players is conceptually simple, containing a skeleton and an outer skin layer. The envelope is basically a set of points. The underlying skeleton is a hierarchical model comprising a total of thirty-two joints corresponding to seventy-four DOF's (Boulic et al., 1995). Because human limbs and trunk exhibit a cylindrical topology, a natural centric axis comes out in each body part. If we consider for example a human leg, the natural axis runs vertically. Now if we scan this leg along its axis (in a top-bottom fashion for instance) and look at cross-sections of this limb at regular times, the outermost points of each cross-section would form a drawing similar to Figure 4. Essentially, these very points make up our model's envelope.



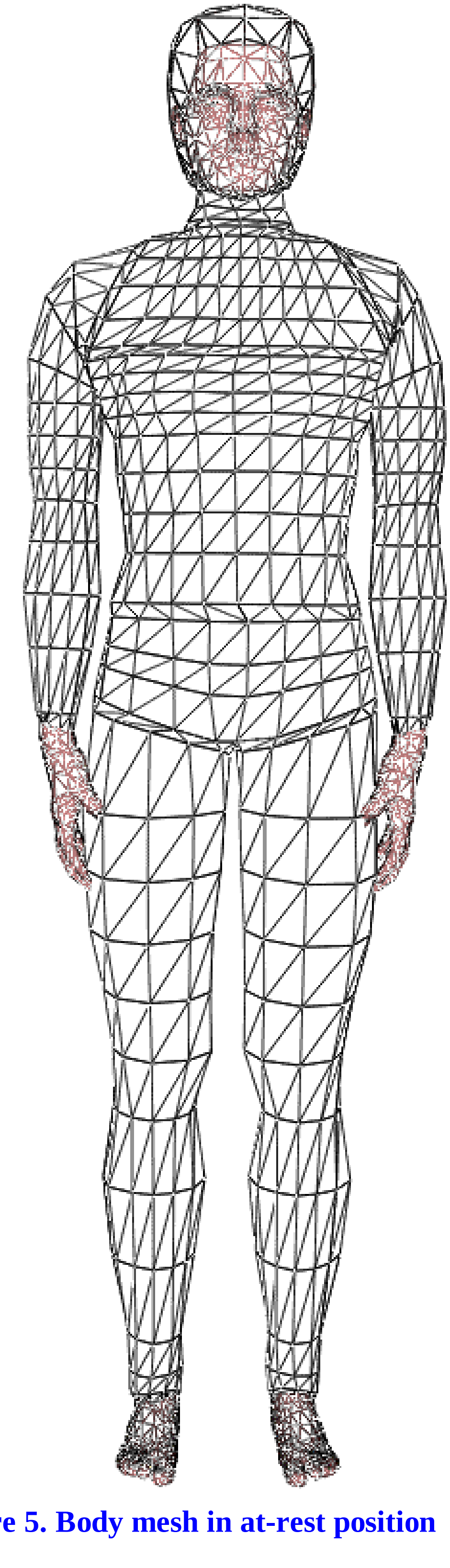


Figure 4. Cross-sectional data for the legs Figure 5. Body mesh in at-rest position

To obtain this data, we use the BodyBuilder software, described in Section Two. This tool allows the construction of highly realistic human models from implicit surfaces. Once a model is rendered it is possible to sample its skin surface and then output cross-sectional data (Shen et al., 1996). BodyBuilder divides a human body into eleven logical parts, namely: neck, torso, shoulders, forearms, waist, pelvis, thighs and calves. We are also provided with skin contours for eleven body parts. For the sake of clarity, when speaking in the following of a (cross-sectional) contour, we will mean the set of outermost, coplanar points (vertices) of a given cross-section. Each body part is then composed of a certain number of cross-sectional contours, which in turn are made up of a fixed number of vertices. However, a contour belongs to only one body part and contours belonging to the same part have an equal number of points. Therefore a triangle strip can be constructed from two adjacent cross-sections by simply connecting their points. Thus, it is possible to construct an entire triangle mesh for each body part directly from the contours' points. Figure 5 below shows the resulting mesh, when assembling all the body parts. The connections between distinct parts can clearly be seen in some regions (e.g. the shoulder area).

3.2. Animation by deforming the contours

During the tennis game, joint angles are updated permanently in the virtual skeleton. We associate every joint with a cross-section and make sure every joint lies in the cross-section plane to which it is mapped. This particular mapping helps us deform the cross-sectional contours that lie between two successive joints. The basic idea behind contour deformation is to use the angle between two connected segments in the skeleton to drive the position and orientation of the cross-section planes in-between. In Figure 6(a), which could illustrate the case of the leg for instance, $\mathbf{L}_1$ is the direction of the upper segment, possibly the thigh and $\mathbf{L}_2$ is the lower one, possibly the calf's axis. Let $\mathbf{N}_L$ and $\mathbf{N}_U$ be the normal vectors of the cross-section planes at the segments' ends. We set the orientation of the cross-section plane that passes through the joint to be the bisection plane of the two links. Let this bisection plane normal be $\mathbf{N}_0$. Suppose now that O_i and $\mathbf{N}_i$ are the center and normal respectively of the *i*-th cross-section plane along the upper segment. $\mathbf{N}_i$ can then be computed by direct interpolation of two end normals $\mathbf{N}_0$, $\mathbf{N}_L$. Knowing the normal vector $\mathbf{N}_i$, it becomes straightforward to compute the new local coordinates of each vertex $\mathbf{V}_j$ belonging to the *i*-th contour (Figure 6(b)). It often makes little sense to interpolate the normal vector of every cross-section plane along a skeleton's segment. As an example, let us consider a walking human. In this case, most of the deformations are obviously concentrated in small areas surrounding the joints, such as the knees, ankles or elbows. Therefore, it is preferable to apply our deformation system only on the contours that reside in the vicinity of a joint, so as to gain as much rendering time as possible. Practically, we determined the number of contours to be deformed in a heuristic fashion. However, there exist some cases for which it would be more realistic to use a fully deformed model, when twisting one's arm for example.

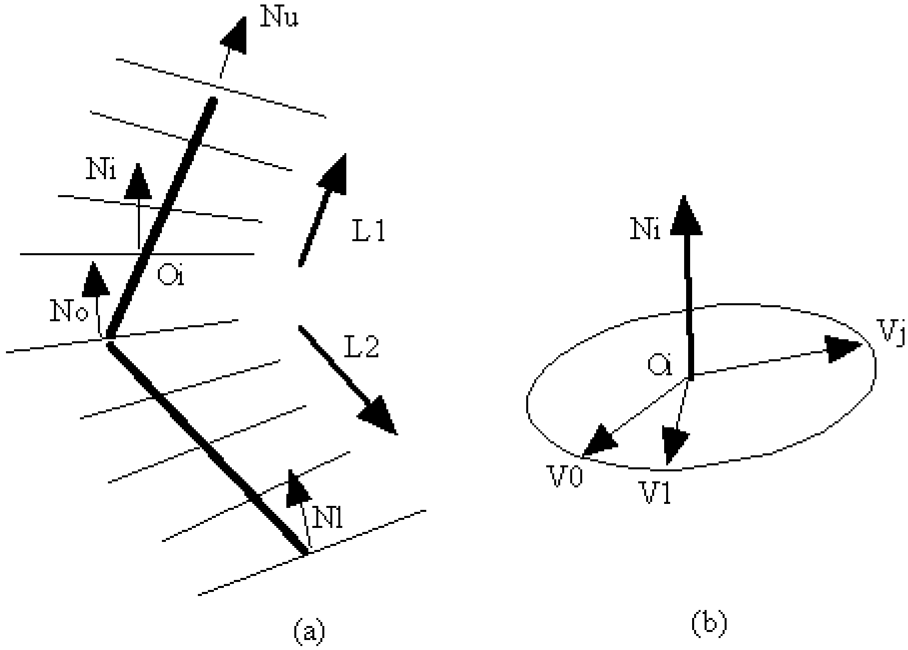


Figure 6. Cross-sectional plane orientation

3.3. Implementation

We rely on the Performer library to have an efficient implementation. This real-time graphics toolkit lets applications achieve maximum graphics performance from all Silicon Graphics workstations. With this library, it is easy to create a 3D scene with many objects coming from different modelers. Yet, except morphing, no deformation capabilities are available in Performer. Consequently, we define our own structure to be compatible with the Performer data arrangement (linear). By using an index array to define triangle meshes, we avoid duplicating vertices and achieve an efficient memory management. It is also easy with Performer to apply a texture onto a 3D surface. In our model configuration, we are able to apply different textures on each body part. Thanks to dedicated hardware, texture mapping turns out to be a good way to increase visual realism at quite a low cost in computational terms. A single-CPU Octane workstation computes the deformations of all body parts for a model containing about 14,000 vertices in 11 milliseconds. Thus, we manage to run a walking sequence (all body parts involved) of a body model composed of 13,500 textured triangles at 36 frames per second.

Finally, because the computational cost of our deformation method is directly proportional to the number of vertices/contours, it is particularly well suited for level of detail.

4. Integration and Networking

There is an increasing interest in Networked Virtual Environments (NVE); various successful systems have been developed (Carlsson et al., 1993; Macedonia et al., 1994). Virtual Life Network (VLNET) is a general-purpose client/server NVE system using highly realistic virtual humans for user representation (Capin et al, 1997). VLNET achieves great versatility through its open architecture with a set of interfaces allowing external applications to control the system functionality.

Figure 7 presents a simplified overview of the architecture of a VLNET client. The VLNET core performs all the basic system tasks: networking, rendering, visual data base management, user management including body movement and facial expressions. The previously described body deformation module is integrated in the client core. When actors are animated, each client updates the skin shapes of all visible virtual actors within the client's field of view. A set of simple shared memory interfaces is provided through which external applications can control VLNET. The VLNET drivers also use these interfaces. The drivers are small service applications provided as part of VLNET system that can be used to solve some standard tasks, e.g. generate walking motion, support navigation devices like mouse, SpaceBall, etc. The connection of drivers and external applications to VLNET is established dynamically at runtime based on the VLNET command line.

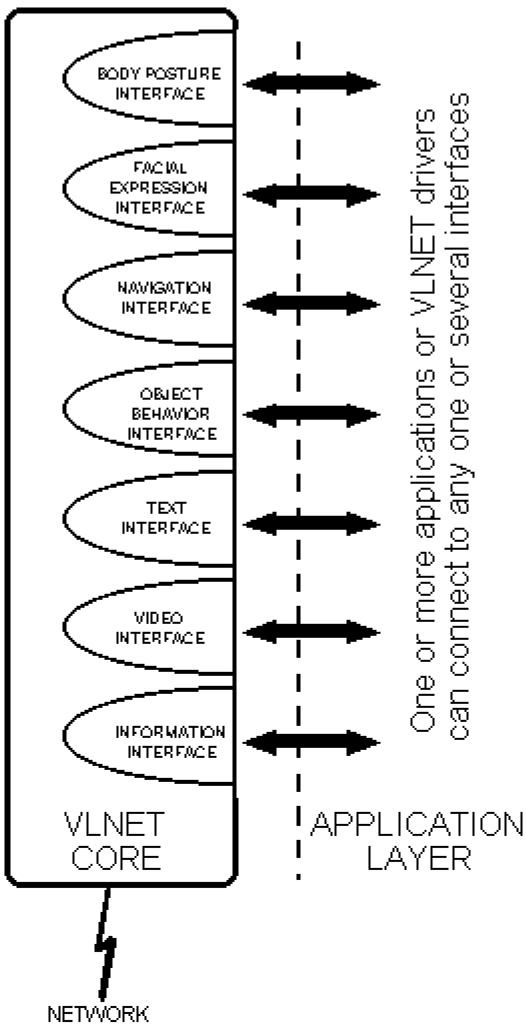


Figure 7. Simplified view of VLNET client architecture

The *Facial Expression Interface* is used to control expressions of the user's face. The expressions are defined using the Minimal Perceptible Actions (MPAs) (Kalra et al., 1992). The MPAs provide a complete set of basic facial actions. By using them it is possible to define any facial expression.

The *Body Posture Interface* controls the motion of the user's body. The postures are defined using a set of joint angles corresponding to 72 degrees of freedom of the skeleton model (Boulic et al., 1995) used in VLNET.

The *Navigation Interface* is used for navigation, hand and head movement, basic object manipulation and basic system control. All movements are expressed using matrices. The basic manipulation includes picking objects up, carrying them and letting them go, as well as grouping and ungrouping of objects. The system control provides access to some system functions that are usually accessed by keystrokes, e.g. changing drawing modes, toggling texturing, displaying statistics. The *Object Behavior Interface* is used to control the behavior of objects. Currently it is limited to the controlling of motion and scaling, defined by matrices passed to the interface. It is also used to handle the sound objects; i.e. objects that have prerecorded sounds attached to them. The Object Behavior Interface can be used to trigger these sounds. The *Video Interface* is used to stream video texture (as well as static textures) onto any object in the environment. The Alpha channel can be used for blending and achieving effects of mixing real and virtual objects/persons. The interface accepts requests containing the image (bitmap) and the ID of an object on which the image is to be mapped. The image is distributed and mapped on the requested object at all sites.

The *Text Interface* is used to send and receive text messages to and from other users. An inquiry can be made through the text interface to check if there are any messages, and the messages can be read. The interface gives the ID of the sender for each received message. A message sent through the text interface is passed to all other users in a VLNET session. The *Information Interface* is used by external applications to gather information about the environment from VLNET. It provides high-level information while isolating the external application from the VLNET implementation details. It also allows two ways of obtaining information, namely the request-and-reply mechanism and the event mechanism.

We have given a brief description of VLNET that allows us to show how external programs can be interfaced to the VLNET system. The focus of this presentation was on VLNET interfaces. For more details on VLNET the reader is directed to references (Capin et al., 1997; Pandzic et al., 1997).

4.1. Integration of game simulation in VLNET.

Figure 8 shows the VLNET server - client - driver configuration for the networked interactive tennis game simulation. The autonomous agents are controlled by a ball/referee driver (detailed in the following section), which accesses the shared virtual environment through shared memory interfaces of a VLNET client process (see Figure 9). Through the object behavior interface of this client, the driver program is periodically updated with the actual positions of the players' rackets.

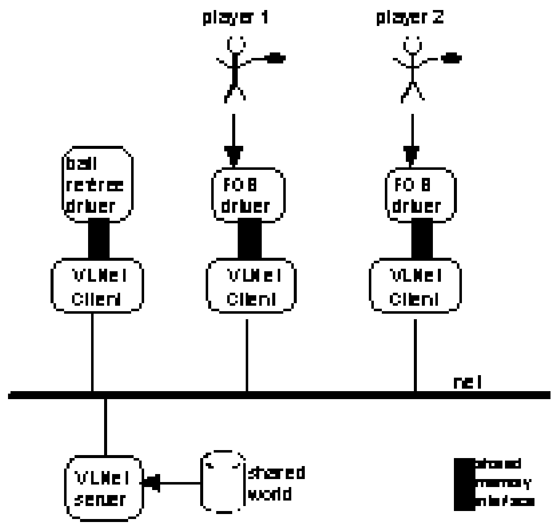


Figure 8. The VLNET server - client - driver configuration

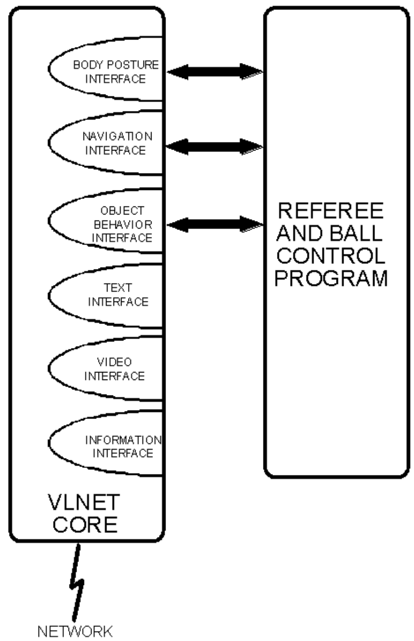


Figure 9. The VLNET interfaces used for the autonomous Referee and the ball driver

The sound events and ball position are broadcast through the same interface, for each frame. Through the body posture interface, the body data of the Referee is broadcast to the other VLNET clients. The body data or joint angles are created by using the AGENTlib software (Boulic et al., 1997) developed for motion control for virtual humans. The navigation interface can be used to map the camera of the VLNET client to the eyes of the autonomous Referee in order to watch the shared virtual world from the Referee's point of view.

The network bandwidth requirement is 20 kb/s per virtual human (without facial animation): 20 kb/s for the body parameters (joint angles) communication and 10 kb/s to transfer the navigation matrices. Each animated object (rackets, ball, ball's shadow) needs approximately 10 kb/s. In this application, all these information are delivered uncompressed to save computation power for other tasks.

5. The game

We already described a networked tennis game facility in (Noser et al., 1996) where a user with a Spaceball could play against an autonomous actor. The game was judged by a synthetic sensor based referee. The ball was animated by a force field based particle system driven by a numerical differential equation solver. A disadvantage of that system was the need of a relatively high frame rate to allow a reliable collision detection and response treatment that slowed down the simulation speed of the whole game. In this paper, we address the modeling of a tennis game with a synthetic humanoid referee which is especially developed for a networked virtual tennis game simulation with interactive players merged into VR by two sets of magnetic sensors, described in more details in section 6. The real time constraints, the network and user interface delays, and the need for several player levels led us to a multilevel game design for beginners and experienced players.

The tennis court, net and the two rackets are all relevant to the Tennis Ball animation. All these elements have to be defined in a VLNET file describing the shared virtual environment which is downloaded by each VLNET client at the beginning of a networked tennis game session (Figure 10).

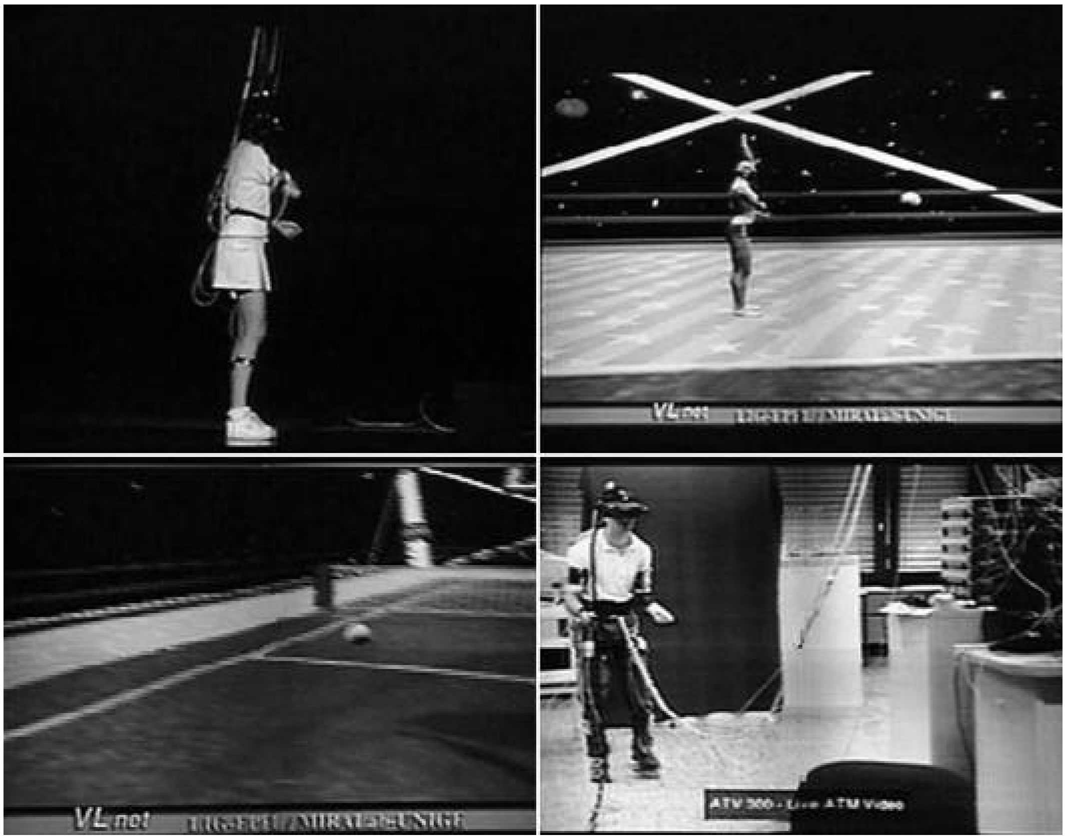


Figure 10. Ball simulation in the network game

We implemented the physics of ball animation in a straightforward manner, based on simplified physical laws for particle-like balls. In order to compensate certain network induced problems and to allow several game levels, we used several methods for the ball - racket collision response. These methods range from user friendly "missile like" balls, that fly automatically to the partner's racket, to physically based collision response with ball spin effects for advanced players on fast networks and computers. In particular, we implemented the following collision response methods:

a) racket determined: determined only by racket velocity
b) friendly ball: missile like, flying to the partner's racket
c) mixed response: mix of methods a) and b) with user defined weights
d) physical response: approximation based on physical laws.

The synthetic referee is designed for an optimal judging of real time, interactive and networked tennis games. This referee is not any more based on synthetic sensors as described in (Noser et al., 1996), but it accesses directly information available in the animation process for speed optimization. Moreover, it uses extensively the interface of VLNET as described earlier.

Figure 11. The autonomous Referee (synthetic referee)

The high level behavior of the referee and the game itself are modeled with finite state automata similar to those described in (Noser et al., 1997). To create the movements of the referee at motor level we use the AGENTlib software package (Boulic et al., 1997). The resulting body postures are mapped through the body posture interface onto the avatar in the shared environment of VLNET.

The synthetic referee represents a very useful feature of the tennis game model as it frees the players from updating themselves the current game. Visually, it is represented by the humanoid illustrated in Figure 11. Furthermore, it is able to walk around in the virtual environment, and it can execute prerecorded motion tracks. For game result announcements it plays back prerecorded sounds. To judge the game the referee only needs information from the sound events produced by the ball. Therefore, it does not matter whether it judges autonomous humanoids or interactive users, or both of them.

Figure 12. Referee automaton

The high level behavior of the referee is illustrated in Figure 12. We suppose that the referee is already positioned correctly that is next to the court where it judges the game. The corresponding humanoid stands next to the net or sits on a chair. During a match, the referee only moves its head in order to look at the players or to track the ball. At the beginning of a game or after a game fault, it looks first at the receiver and at the server. Then, it throws the ball into the game. The server and receiver have to be at their corresponding start position.

The ball is thrown into the game about one meter above the actual position of the server's racket with a certain vertical upward velocity. During the game the referee tracks the ball with its head (eyes) and captures the ball-floor and ball-racket sound events which permit it to detect game errors. If it detects an error, it announces the type of error, updates the game, and announces the new game score if it has changed. Finally, if the match has not finished, it announces the player who has to serve, and the whole scenario is repeated until the end of the match. A tennis game can be described by a set of states and transitions as illustrated in Table 1, Figure 13, and Figure 14.

Table 1: Tennis game states

States	Description
start	at the beginning of a game the players have to be at their initial play positions
service	the server has hit the ball with his racket
serviceBounced	the ball has bounced once after the service
receiver	the receiver has hit the ball
receiverBounced	the ball has bounced once after the hit of the receiver
server	the server has hit the ball
serverBounced	the ball has bounced once after the hit of the server
update	a game fault occurred and the referee updates the game and announces the score of the game

The game is always in one of these states. The transitions between states are triggered only by ball-floor or ball-racket collision events. To control these transitions, the referee needs to know the identity of the actor involved for each racket-ball collision. For each floor-ball collision, the referee needs the position where it happens. With this information the referee can manage the game automaton and recognize game errors. Figure 13 and Figure 14 summarize the transition rules for bounce events and ball-racket collision events. At the begin of an arrow, there is the ancestor state, or the state of the game before the corresponding bounce event or the ball-racket collision event happens. The label of an arrow indicates some condition that must be fulfilled in order to trigger the transition.

According to Figure 14, for example, a ball-racket collision triggers the following transitions if the ancestor state is "service", i.e. the server has already hit the ball. If the receiver hits the ball, he commits an error, as the ball must first bounce on the court. Therefore, the referee interrupts the game and updates it. If the server hits again the ball, and if he has already committed a fault indicated by the Boolean variable let == true, its a fault of the server as he has hit twice the ball. In this case he can't any more repeat the service. In this case the referee stops and updates the game. However, if it's his first error at the service (condition == not let AND server), he has a second attempt (let = true), and the service is repeated. Figure 13, for example, describes the transitions triggered by ball-floor collision events or bounce events. If we consider again the "service" state as ancestor state, we see that if the ball bounces inside the service allowed court area (condition: in), then the game state goes into the state "serviceBounced", and the game continuous normally. If the ball is out of the allowed court area and if it is the first error (condition: out AND not let), the server gets a second chance to do a correct service. If, however, it is the second error (condition: out AND let), it's a fault for the server and the game has to be updated by the referee.

Regular transitions describe tennis playing without faults. At the beginning of a game the server has to hit the ball, that has to bounce first in the corresponding court area before the receiver can hit it back. Then, alternatively, the server and the receiver can play directly or let the ball bounce before returning it. Of course, each bounce has to happen inside the corresponding court area.

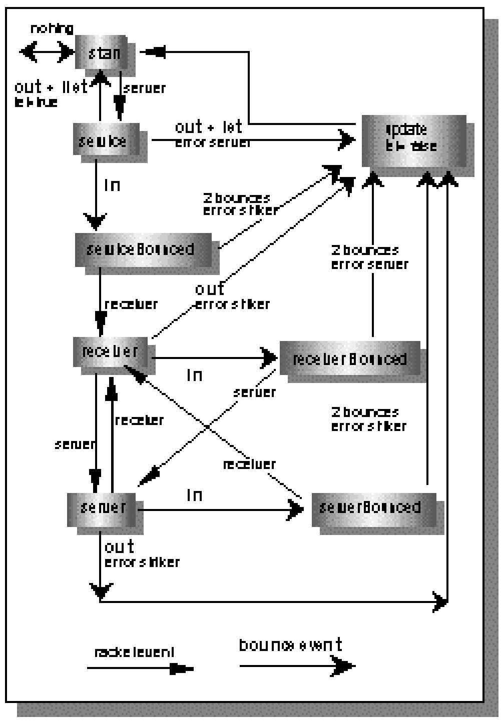


Figure 13. Game automaton with regular events and bounce events that are faults

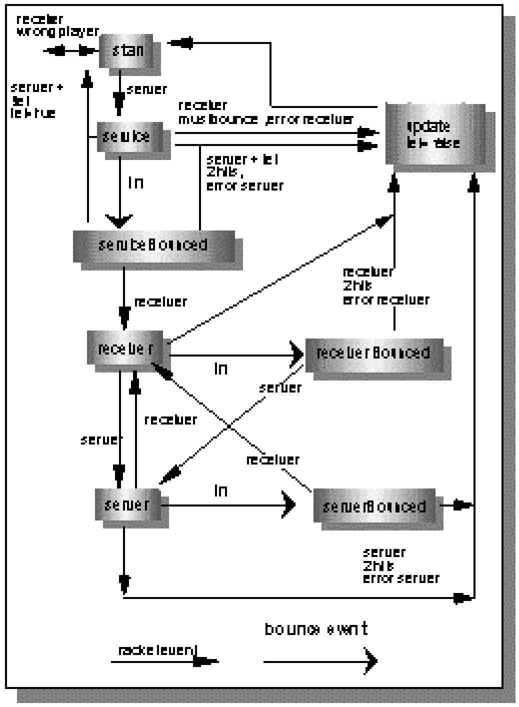


Figure 14. Game automaton with regular events and racket events that are faults

The referee judges the game according to international tennis rules, but with some modifications taking into account the given constraints and simplifying the implementation. The placement of the actors and the first service are decided at the beginning of a match by a script. During the game there are no change of ends as currently, the players can't move from one courtside to the other. At the service, the referee does not control the server position. After the service the ball has to bounce first on the opponents side, but not necessarily in the diagonally opposite service square as demanded by the international rules. Additionally, collisions between the body of the actors and the ball or the net are ignored. A player wins a set if he has won at least six games and two games more than his partner has. He wins the match if he has won two sets. The tie break procedure is not implemented.

6. Immersive Technologies

6.1. Magnetic motion capture

The player movements are controlled using the human motion capture (MC) technique (Molet et al., 1996) based on magnetic sensors. Other methods for real time human MC are proposed by (Bers, 1996; Hirose et al., 1996; Semwal et al., 1998). We just had to make a specific VLNET external driver, later called fobnet, to control the virtual players in the shared virtual tennis scene (Figure 15). The fobnet driver uses three VLNET interfaces: the body posture interface, the navigation interface, and the object interface. The captured posture of the player is sent to VLNET through both body posture and navigation interfaces. The posture provides the player's view parameters and his/her global position. Similarly, the object interface is used to set and update the position and orientation of the player's racket according to the current player's hand location. The Referee client uses this information to detect ball/racket collision by querying its own VLNET client.

Due to the magnetic sensing technology constraints, we face the following problem: the tracking of the players' positions is restricted to a smaller range than the real tennis court dimension. We experimented with two solutions to overcome this difficulty.

First we tried to scale the measured displacement of the global location of the players in the frontal and lateral directions. However, we found that the position amplification should remain within, at most, a factor four in both directions to allow a proper control of the players. With amplification values greater than four, players can hardly adjust their position to hit adequately the ball because little movements produce great location change and thus their stability is lost. This maximum experimental value is not enough however for reaching all locations of one side of the court.

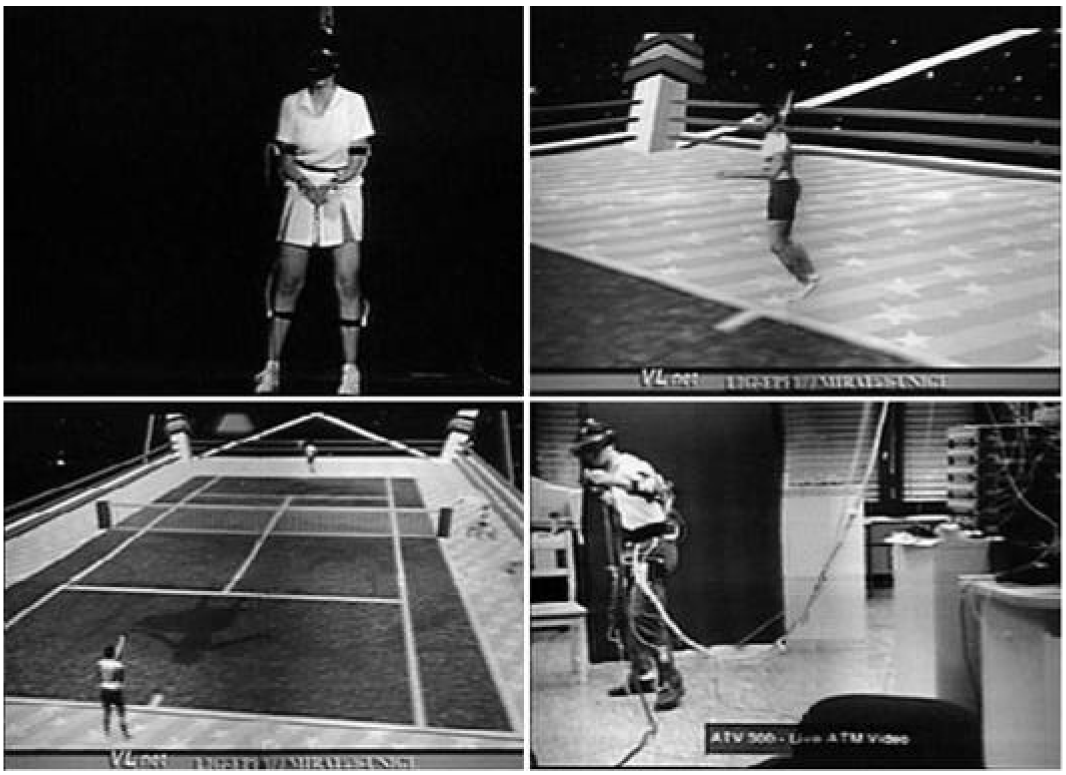


Figure 15. Real time tennis game using MC

The second solution, allowing one player displacement to cover their side of the court, is to use an indirect navigation procedure. This procedure is defined as follows: the global position tracking remains active to control the player's position (with or without reasonable motion amplification) in a restricted zone around the calibration position of the player (Figure 16). When the measured actor position goes outside this perimeter, as illustrated by actor 2 in Figure 16, we activate another navigation paradigm. The global position of the virtual perimeter associated with the MC restricted zone starts to move with respects to the direction indicated by the current player position (Figure 16).

When the player has reached the desired place, he/she just re-enters the MC restricted zone to stop the additional navigation motor. In the latest version, we have used this navigation paradigm with amplification values set to two in both lateral and frontal directions. Thus the virtual perimeter associated with the MC restricted zone is twice as large as the real perimeter.

The limitation of this procedure comes from the need to enter back inside the MC restricted perimeter to stop the indirect navigation. However, this non-intuitive stop-command is quickly learned by players and allows them to reach the net, giving more interest to the game.

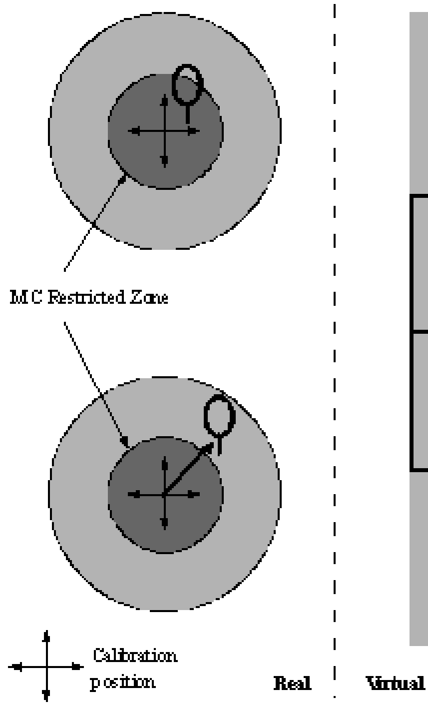


Figure 16. Player 1 is in the MC restricted zone and his avatar moves with reasonable motion amplification; Player 2 is outside the MC first perimeter: the virtual perimeter's global position moves.

6.2. Visual and tactile feedback

The Head Mounted Display (HMD) viewing control is easily retrieved from the current posture of the virtual human head. However, we have locked the rolling (rotation around the frontal axis) degree of freedom of the camera used to render the scene because our HMD has a restricted field of view and no peripheral information is displayed. It is well known that in the absence of motions in the peripheral field of the human vision system, the head/camera rolling is perceived as a floor rotation rather than the real head rolling. This phenomenon is even strengthened by the lag between the real head motion and the rendered visual feedback. During all the experiments, only few people reported some light motion sickness symptoms (Hettinger et al., 1993) such as general or visual tiredness and headache.

Our HMD has a relatively low resolution (247x230, 57600 triads) compared to NTSC and it is quite difficult to distinguish small objects from a certain distance. Therefore to help the player to track the ball, we have slightly increased the virtual ball size compared to the normal tennis ball. We used several other simple yet effective methods to provide better game feedback to the player. The visual tracking of the ball is improved with the help of the ball shadow. This shadow is rendered using a dark, flat object that simultaneously follows the ball path but vertically projected on the ground. For depth perception and court visibility, the designers built scenes comprising textured spherical sky, transparent net and racket while keeping the total amount of texture under the maximum resources available to prevent a fall of performances. In such an immersive environment, the collision between the ball and the racket can hardly be perceived visually by players but the collision feedback is greatly improved by using sound event (real collision sound) and glove vibration using the Cybertouch glove option at the impact time.

Special data glove gesture commands help to remotely trigger operations in a similar way as that described in (Molet et al., 1997) and without the requirement of any intermediate user. We used four basic remote commands: magnetic sensor calibration (Molet et al., 1996), service launching, changing the game level and resetting the game. All these functions are activated by distinct hand postures.

7. Experiments and results

7.1. Equipment and configuration

A game session consists basically of three VLNET clients, two player clients associated with fobnet (motion capture controller) and one client for the referee and ball driver. In addition, we usually launch a fourth client without human representation. This last client is responsible for the virtual video camera management. This allows the rendering of the game from various points of view for non-immersed spectators (or else only the players would enjoy/see the game). The frame rate at the player and referee levels should be, at least, eight frames per second (visual feedback) and postures per second (motion feedback) for proper "playability". Otherwise the ball and the players motion are hardly perceived by participants. Similarly, the ball controller included in the referee driver needs sufficient racket position updates to be able to compute effectively the ball-racket collision detection and response. In the virtual tennis demonstration between Geneva Telecom Interactive'97 and the Computer Graphics Lab in Lausanne, we employed the following hardware (see Figure 17): • At the Geneva site, two Silicon Graphics Onyx 2 for the first player client and the Virtual Video Camera client, both hosts were connected to one Impact over local Ethernet. The Impact contained one ATM card and was used as a router for fast communication with Lausanne.

The VR devices comprised a MotionStar from Ascension with fourteen sensors, one Virtual Research's VR4 HMD, two Cybergloves from Virtual Technologies and one Spaceball (from Spaceball Technologies Inc.) used to drive the virtual video camera.

• At the Lausanne site, one Onyx was used for the second player client and two Impacts were responsible for the Referee client and for the VLNET server. These three machines were using ATM cards for communicating with the server. The VR devices were identical to those used at Geneva except for the magnetic sensors: a set of sixteen Flock of Birds from Ascension Technology (only fourteen were used in the motion capture process).

During the exhibition, the audience could watch simultaneously four different displays on large screens (Figure 10, Figure 15) while hearing the sound emitted by the Geneva player client. Two screens contained the video images of both players filmed with (real) video cameras. The video stream of the Lausanne player was transmitted to Geneva over a dedicated ATM line. The third screen showed a copy of the subjective view of the Geneva player (bottom right image in Figure

10) and the last display was devoted to the output of the virtual video camera conducted by one animator (top left images in Figure 10 and Figure 15). The animator was directing the shooting of the game, in a TV like manner (e.g. close-up view of the players and Referee, general views, smooth camera motion, etc).

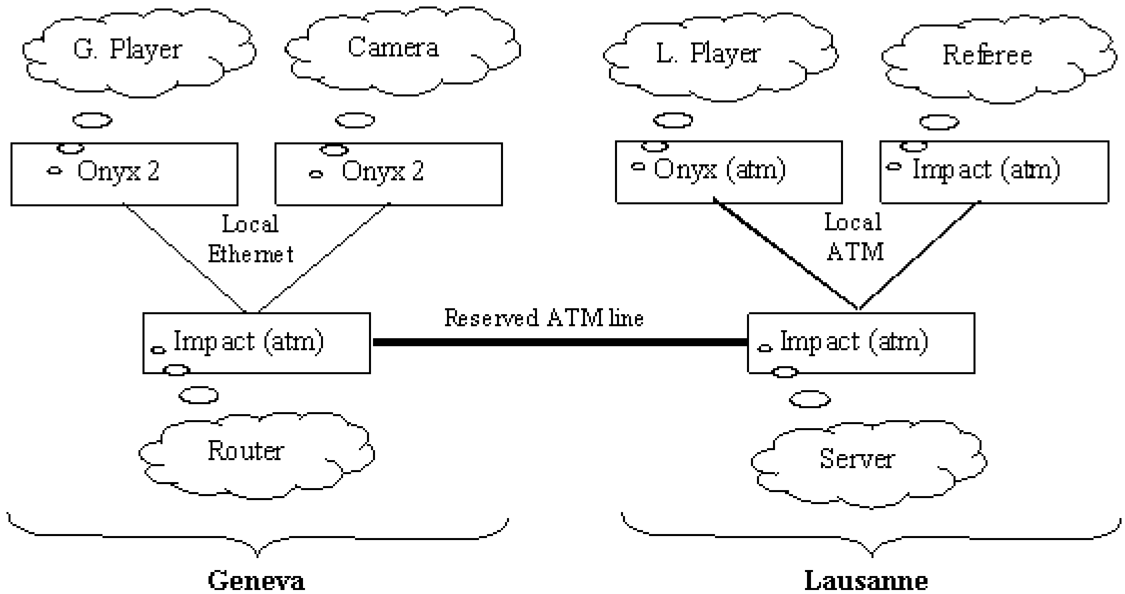


Figure 17. Telecom Interactive'97 configuration.

7.2. Results

For this project, a motion capture program, a tennis ball simulation program, a virtual camera control program, and an autonomous referee program, each written by different persons, in different cities, needed to be integrated within the same environment. Furthermore, new versions of software were developed simultaneously; therefore it was difficult to integrate software within one application. Additionally, the time to develop the whole application was only 4 months. VLNET architecture allowed each developer to work independently, and make tests every week for half a day with new versions of other programs. The system could satisfy the requirements of this demonstration within the time constraints, and the resulting NVE simulation speed was sufficient for the high interactivity requirements of the game.

The choice of the ATM network was mainly made because of its reserved and constant flow. Over the Internet, though the bandwidth is (usually) sufficient, message packing first delays the updates and as a result, updates are sometimes all made at the same time thus producing an unpredictable animation of the ball. Naturally, other network technology, with similar functionality, can replace ATM without any change at the application level.

From the player's point of view, the different game levels corresponding to different response to ball/racket collision (section 5) were ranged from too easy for the "missile" ball behaviour, to impossible for the physically-based response. We used extensively the "missile" ball technique during development and earlier experiments of the game because it allowed us to play in single player mode by just placing a second standalone racket in the opposite side of the virtual court. During the exhibition, we mostly used the mixed response mode. This mode modifies the "missile" behavior by taking into account the velocity of the racket at the impact time. We only activated the racket-determined method when no fault occurred during more than ten consecutive hits. Only trained players could reach this state. No immersed player ever succeeded in hitting the ball using the physical response technique; the ball would always fly far away from the desired place. Obviously there are many limitations in the system compared to the real tennis: the lack of visual information in the peripheral field, the MC matching between the real player and his/her avatar, the visual feedback frame rate and lag, and the discrete nature of the collision detection are all involved in the final result. Nevertheless, we could investigate and enjoy new game situations that would be impossible to produce in real life like the missile ball behavior. Furthermore, one achievement of this prototype system is that it showed VR technologies are mature enough to build entertaining applications and are no more reserved to VR specialists. After a few hours of training, Melanie Thalmann who had never experienced VR immersion before, managed to play "live" virtual tennis in Geneva.

8. Conclusions and Future Research

We have presented a virtual tennis game based on the VLNET framework. The game brings together different computer technologies and software including network, motion capture, virtual reality, shared environment, controlled and autonomous virtual humans.

In future research, we want to improve the real-time deformation module in the spine region of the humanoids. This will permit us to activate the multi-joint control of the spine (Molet et al., 1997) in the motion capture process without sacrificing the look of the virtual human surface. We already tested its use at the player level and we found that the spine, hand and head motions were greatly improved. This motion capture accuracy reflects strongly on the subjective views rendered for the HMD because the captured position and orientation of the head induces the viewing parameters. We especially noticed the enhancement in the service phase when the ball is high above the virtual shoulder, as it is much easier to see and hit. Moreover as the precision of the hand's spatial position increases, controlling the racket becomes more natural to players. Using sound localization techniques could bring another improvement for better ball localization. It might however be too expensive in our situation where the frame rate is a critical issue.

The main reproach about this virtual tennis come up with that it attempts to achieve two antagonist goals at the same time. One goal is to demonstrate that current VR technology allows the creation of immersive 3D games where participants share the same virtual world and can act/interact using their real body movements. The other goal is to present a showcase application for many aspects of the virtual human simulation. The showcase focus diverges from the computer game logic in the sense that it requires huge resources to display the best possible virtual human as opposed to what would be sufficient to embody a virtual adversary located at the other side of the court at the current HMD screen resolution. One of the main concerns in the game context is to ensure the best possible frame rate whereas a close-up of a low-resolution virtual human would not score high viewership ratings. A nice solution would be to use level of details for virtual humans with separate control at each VLNET client according to their own viewpoint locations. This way the divergent goals would be unified without compromise.

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Figure 1. Description of images from left to right, top to bottom: (1) One half of the head is created, (2) the other half, the eyes, and the teeth are added, (3) the texture is designed, (4 & 5) the texture is adjusted to the 3D model.; 4
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