Wind and Warmth in Virtual Reality – Requirements and Chances

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Abstract: Wind and warmth are often ignored in Virtual Reality systems – even though studies suggest that they are able to improve users' presence as well as task performance for certain challenges. In this work, requirements of a wind and warmth system are analyzed and the hardware setup used to create this kind of sensations is described. According to requirements identified, a system able to create wind and warmth in a CAVE environment is presented. Special challenges as a possible disruptive influence of specialized hardware on user tracking and their solutions are faced. Furthermore an approach of how to integrate wind and warmth in Virtual Reality applications is described and discussed.

Keywords: Virtual Reality, Multimodal Feedback, Wind Simulation, Warmth Simulation

1 Introduction

Enhancing immersion in Virtual Reality applications has been a focus for decades. Concerning the sensations such systems offer, realistic rendering has become very advanced – up to nearly photo-realistic. Also systems providing spatial sound are widely available. In the last years, more and more applications of tactile feedback even in systems designed for end customers are used. On the other hand, although Morton Heilig presented the Sensorama – a system capable of stereoscopic images, stereosound, wind and olfactory feedback [LH62] – already in 1962, not all kinds of these perceptions have been completely investigated. The focus in Virtual Reality research is often laid on graphics and interaction methods. Less research has been done for example on how to approximate other influences like wind and warmth and for making them available in Virtual Reality applications.

Therefore it seems appropriate to implement those parts already partially presented in the 1960s, but more or less ignored over the years: warmth and wind. Especially wind sensations proved to enhance the user's task performance if presented during certain tasks [DJ06] and could also be an interesting extension for VR games. As no standardized Virtual Reality hardware is available for creating those kinds of sensations, requirements must be analyzed and used for developing an appropriate setup. Furthermore a software model representing wind and warmth and performing a natural mapping on the hardware is desireable. In the following, a first glance on such an approach is given, challenges, the according solutions and emerging possibilities are presented.

We will start by giving an overview of related work dealing with wind and warmth in Virtual Reality. Then requirements to transfer the concepts of wind and warmth sensations to Virtual Reality are presented – concerning the hardware and software needs. Afterwards, a hardware implementation and an abstract software model are presented with respect to the identified requirements. The contribution finishes with a discussion of the findings and prospects concerning future work.

2 Related Work

In the following, existing approaches to face the challenges of wind and warmth in Virtual Reality environments are described.

2.1 Wind

In 2004, Moon and Kim presented the WindCube, a wind interface for Virtual Reality applications [MK04]. The system uses 20 fans arranged in three levels on the y-axis attached to a cube (1m x 2m x 1m). The user stands in the middle of the cube. No realtime wind calculation was realized: They developed an editor in which the user can design a wind field for a stationary scene. Afterwards the mapping of wind on fans was done as follows: (1) Determine the wind vector towards the user, (2) select fans which will be activated and set their blowing strength. To determine the wind's influence on the user's presence, the test participants are navigated through a city during a snow storm. They perceive only the visual feedback in the control condition without the possibility of influencing the scene. In a second condition, the setup was enriched with wind which lead to a significant improvement concerning the user's presence. In a pilot study, the authors also found that test subjects cannot distinguish between winds which come from neighbouring fans if the angle between both fans is less than 45 degrees.

For evaluating the influence of wind simulations on user performance, Deligiannidis and Jacob evaluated the "VR Scooter" [DJ06]: a system which is designed like a real world scooter on which the user wearing a HMD is placed. The scooter itself is used for navigation inside the VR and also for haptic feedback. A fan providing wind is placed in front of the user. During a study with 13 participants, the authors discovered that perceived wind improved both, task performance and the subjective user experience.

Except for globally mounted fans as described above, there exist also setups with wind devices directly attached to the user itself. Cadin et al. presented a system with 8 CPU fans arranged in a circle around the user's head [CTV07]. They evaluated the error of estimating the wind direction and the presence during a flight simulator application. Concerning the error, a standard deviation of 8.5 degrees from the correct value was measured. Furthermore, the system greatly improves the user's sense of presence.

2.2 Warmth

There is only small amout of research describing the role of warmth in Virtual Reality.

In 1996, Dionisio published an overview of how a system using warmth sensations could be modeled [Dio96]. He also provides a detailed overview of different types of hardware devices with advice for which kinds of application they could be used. The author presents an implementation using fans, infrared lamps and Peltier-elements. An evaluation showed that the changes in the stimuli intensity were perceived at least in 25 percent steps and the hardware devices' position was determined flawlessly by the subjects.

Rosenblum and Dionisio described a system for simulating warmth in detail [RD97]: They used three fans and three infrared lamps arranged around the user. For providing feedback on the user's skin, Peltier-elements were attached directly on the body. By the use of a virtual (thermal) cursor, the activation of the hardware devices was calculated. The presented implementation takes also the influence of heat sources on their environment e.g. walls and other objects into account. In the presented case, the fans were used only to simulate warmth differences – not real wind.

3 Requirements to simulate Wind and Warmth in Virtual Reality

The focus of a system providing wind and warmth sensations in context of Virtual Reality is laid on representing the sensations as real as possible. This raises requirements for a hardware as well as a software model.

3.1 Hardware Requirements

First of all, especially when using hardware which is able to create heat, it must be ensured that no user could be harmed or endangered by the system. This includes preventing direct contact between users and heat sources. If the heat sources are mounted on top of the rest of the hardware, it should be possible to adapt their position depending on the user's size. The overall heat created by the hardware must be controlled by sensors – also for not endangering the rest of the hardware setup. Furthermore, as one of the most important conditions for Virtual Reality applications, the whole system has to work in real time and the latency has to be as small as possible. We suggest that an adaptation of the wind direction to the user's position and orientation inside the scene is important: Otherwise there would be a gap between visual feedback and the sensations perceived. This must also be considered when developing the software model. It would be counterproductive if a system for wind and warmth sensations would disturb other parts, such as tracking or the user's possibilities of interacting with the scene. Such disruptive effects must be excluded by the hardware used. Finally, perceptions which are not consistent with expectations could decrease the sense of presence [JZ98]. Therefore there must be a balance between realism and computational costs.

See the following hardware affordances ordered by priority:

H1 Do not endanger the user or hardware due to the setup

H2 Provide real time, low latency

H3 Allow adaptation of sensation's direction

H4 Prevent disturbance of existing hardware and interaction possibilities

3.2 Software Requirements

After developing hardware requirements meeting the above mentioned criteria, we now come to the sofware requirements. Concerning the handling of sensations, virtual occlusions have an important role: If a user stands in a small virtual room between solid walls, it would be unaccustomed for him – and thus would distort immersion – to perceive wind which comes from the outside. As mentioned above, the adaptation of the sensation's direction in reference to the user position must also be considered. Concerning wind and warmth influences in the real world, it is evident that there cannot be only one source of a certain type: There could be for example a set of fans in a virtual room which all blow in different directions with different intensities. The interaction of many sources of one type must be considered. Even more, wind and warmth cannot be regarded as enclosed systems – both have an influence on the perceived temperature and temperature can also have an influence on wind. Arising from this argument, it seems likely that a distinction between certain types of wind and warmth must be made: On the one hand wind and warmth effects which are created by weather influences, and which are valid for nearly the whole scene, and on the other hand effects created by objects in the scene itself (e.g. a fire or a virtual fan). Those sources must also have an appropriate kind of attenuation function: Local heat sources for example (e.g. a fire) which influence large areas of the scene would destroy the realism.

Many different scales are used to quantify possible sensation intensities like the Beaufort Scale, or SI-Units ($\frac{m}{s}$) for wind and degrees Celsius/Fahrenheit for warmth. On the other hand, developers often prefer to describe units in intervals between zero and one. It appears to be helpful to allow a set of measurements and to map them on the hardware's level of activation.

If the software model meets those affordances it is of course necessary that it is correctly mapped on the hardware without losing too much information represented by the model. Additionally, the power of the hardware should be used as complete as possible.

The following list summarizes the software requirements which must be faced when developing a wind and warmth model:

S1 Provide real time, low latency and balance between realism and computational costs

S2 Adapt to user's position and orientation in the Virtual World

S3 Consider occlusion

S4 Use an attenuation function

S5 Provide a model for different types of wind and heat sources

S6 Provide convenient scales to describe the sensations' intensity

S7 Consider crossmodal influences (e.g. influence of wind on warmth perception)

S8 Use the full power of the hardware

4 Implementing Wind and Warmth in Virtual Reality

As shown in the last section, there is a set of requirements for enriching a Virtual World with wind and warmth. In the following, we describe how those requirements are tackled with respect to hardware constraints after presenting the previous setup on which this work is based.

4.1 Previous Technical Setup

Our Virtual Reality setup is based on a three-sided CAVE environment (front, floor, left). It is equipped with an ART tracking system (10 infrared based cameras). InstantReality (IR), developed by the Fraunhofer IGD is used as Virtual Reality framework. IR utilizes the X3D standard and allows to create VR applications with minimal effort. An extension of the framework enriches objects with information about their properties (e.g. their sound, their physical behaviour). Only the type of the object must be declared and the system determines its characteristics and informs the corresponding subsystems (cf. [FW12]). Besides those components, the setup also comprises sensations in the form of sound, tactile feedback and (basic) wind.

Wind is enabled by eight axial fans by ADDA with a diameter of 25.4 cm and a wind performance of 12.735 m^3/min. To reduce noise, they are driven by 115 Volt instead of 230 Volt. On full power, they have a sound intensity of 55.6 dB/A measured at a distance of one meter. Figure 1(a) shows a single ADDA fan as it is used for the wind simulation. Eight fans directed to the center of the CAVE are attached on the top of the projection walls. The angle between two neighbouring fans is exactly 45 degrees (cf. [MK04]). All fans are placed above the user, because preceding tests showed that the largest part of the wind (and also the warmth) is perceived at the head and the hands. To be able to control all fans continuously, they are connected to a MultiDim MKIII Dimmerpack by ShowTec and driven via the DMX-Protocol. Our previous system supports only one global wind source for a Virtual World. The direction can be adapted and the intensity is specified on the Beaufort Scale. No occlusion handling is performed.

(a) Axialfan AK25489 by ADDA

(b) Infrared lamp with color foils mounted on top of the CAVE

Figure 1: Fans and lamps used to extend the hardware setup.

4.2 Extending the Hardware Setup by Warmth Generators

The technical setup is extended with 6 heat sources. They are distributed in a way that existing hardware is not affected directly and still the user is able to move freely in the CAVE and to sense warmth (H4). The field of use of a system using e.g. only one source would be too constricted due to the fixed direction. Therefore multiple heat sources are used (H3). Heating Coils as they are used for heating small rooms like garages react to slowly (H2). The same applies to specialized air conditioners. Heaters which burn gas for creating heat are often used for firefighter simulations, but they are too dangerous for an indoor Virtual Reality setup (H1). Furthermore, hardware mounted directly on the user (like Peltier-elements or suits as presented in [Dio96]) cannot be used: It would be possible that such a system would prevent the user from interacting normally, because she feels intimidated by the hardware attached to her (H4). Therefore a warmth system should be attached to the CAVE similar as it is done for the wind. Accordingly, the use of infrared lamps seems to be the only feasible option: we use 6 infrared lamps as heat sources. They provide the shortest latency, they do not need to be attached directly on the user and they are comparatively save.

Each lamp has a power of 250 Watt and is able to heat the area directly in front of the lamp up to 100 degrees. They are mounted above the user and are directed towards the center of the CAVE (see figure 2). Due to the user's clothes, most of the created warmth can only be perceived at the head area and the hand. The lamps distance to the user can be changed according to his size for offering everyone comparable sensations. This also ensures preventing injuries if a user is too tall and would hit a lamp which would have a proper distance to a smaller user (H1). To prevent endangering the user or parts of the hardware by too much heat, the whole system is monitored by temperature sensors (H1). To prevent distraction by emitted visible light, heat-proof color foils are mounted in front of the lamps (see figure 1(b)). However as the tracking system used depends on infrared light reflections, the effect of the lamps on the tracking performance must be observed. See the next section for testing results. Altogether, the hardware setup presented here fulfills all detected requirements.

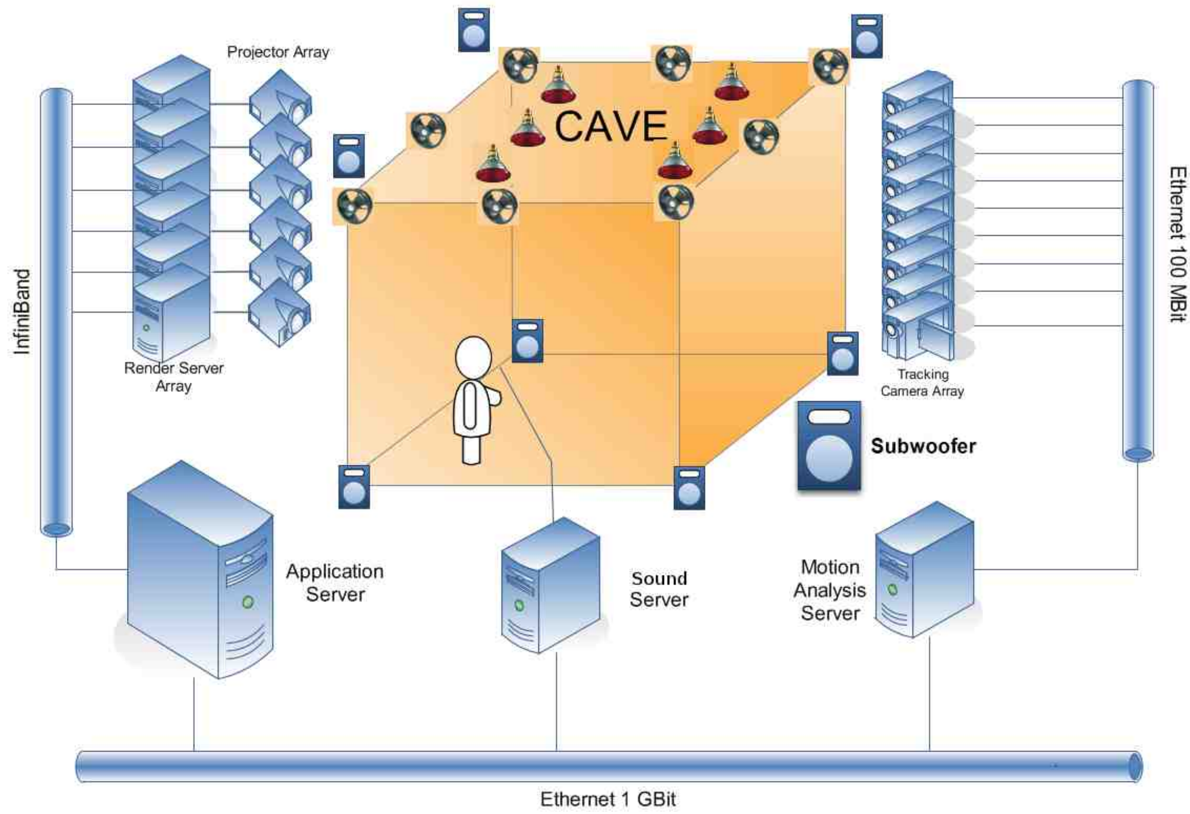

Figure 2: Technical Setup

Influence of the Infrared Lamps on Marker-Based Tracking

For estimating the influence of the infrared lamps on the tracking performance of the ART system, a tool which inspects the tracking coverage of the area inside the CAVE was developed. A tracking target is moved through the CAVE with the goal to touch nearly all possible positions. The whole CAVE area is divided into 20x20x20 blocks. The tool controls whether each block has been touched by the target. This is carried out as long as all blocks except from those in tracking gaps are touched.

A first recording was done without the use of the lamps to define a baseline. In a second run all lamps were activated. The results showed, that the coverage of the tracking was not influenced. However, some of the cameras have blind spots while the lamps are active. Because of the large number of cameras which exceeds the minimal number of cameras necessary for marker tracking, this does not have any significant influence. Further studies will be carried out to determine the minimum number of cameras necessary for marker tracking while using the infrared lamps.

4.3 A Model for Wind and Warmth in Virtual Reality

This section deals with the question of how to provide a model for representing wind and warmth sensations in Virtual Worlds using the above mentioned setup. A realistic physically modeled representation of wind and warmth sensations would be too complex to compute in realtime and with low latency. Thus this model delivers an approximation of their impact (S1). Wind and heat sources are represented as nodes in the scenegraph. They are sent to the wind and warmth engine which calculates the node's influence, for example the activation of the hardware depending on occlusion, user position et cetera (cf. figure 3).

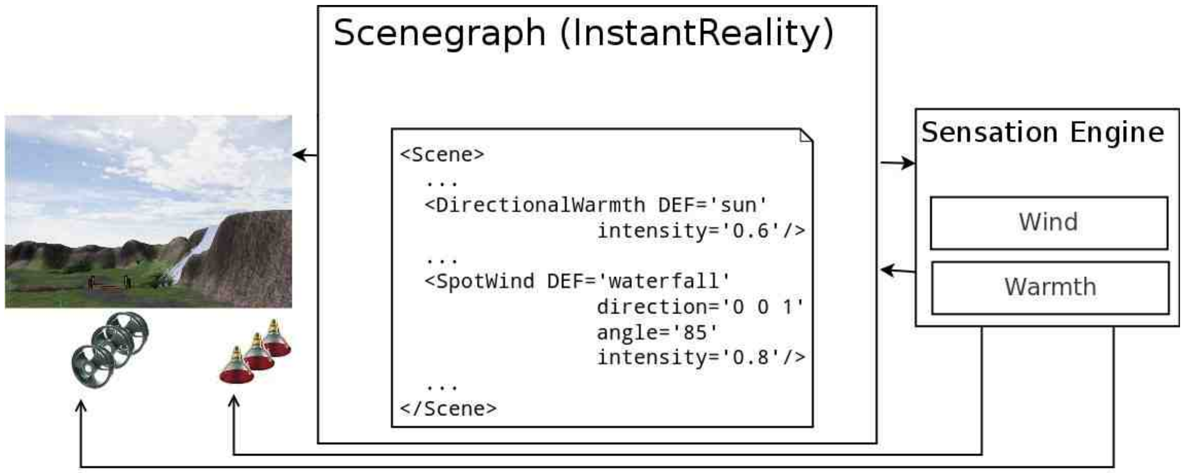

Figure 3: Short glance on the framework

The basic calculation of occlusions is performed on the InstantReality scenegraph (according to S3):

```
Data: shoot ray from object position and positions neighbouring the object in the
      opposite sensation node direction
Result: list D of distances to the hit points
isOccluded = false;
forall d in D do
    if d = infinity then
        return false;
    else
        if d > MAX_DISTANCE then
            return false;
        else
            isOccluded = true;
if isOccluded then
    return true;
```

Algorithm 1: Occlusion check

The constant $MAX\_DISTANCE$ ensures that objects like trees or small hills which are too far away from the user can be ignored for occlusion. The mapping of one single sensation node on the hardware is straight forward:

$force = attenuation(Intensity, DistanceToUser)$;
$\vec{d}$: normalized vector to sensation node for given user position;
adapt $\vec{d}$ to user rotation;
forall *HardwareDirection in HardwareComponents* **do**
  $angle = inner\_prod(\vec{d}, Hardware\vec{D}irection)$;
a: activation for component with smallest angle;
Activate the other hardwareComponents proportinal to their angle to the user;

Algorithm 2: Mapping of sensation nodes on the hardware components satisfying reqirement (S2) and (S8)

Here, $HardwareComponents$ stands for the fans and infrared lamps. $HardwareDirection$ is the direction of the mounted hardware component towards the user. Combining multiple sensation nodes is done by introducing a basic assumption: After preceding tests it is assumed that wind and warmth sensations which have an influence to each other accumulate additive. Using this information, the activation can be calculated nearly as easily as described above: The activation array for each hardware component has to be calculated for each sensation node, afterwards they are all summed up and normalized. Concerning warmth stimuli the concepts of radiation and conduction are ignored for simplicity and we concentrate on the convection of the heat sources.

The intensity of the stimulus can be specified in Beaufort Scale or meter per second (wind), degrees in Celsius/Fahrenheit (warmth) and in the interval [0,1] (S5). Each node has a certain direction. Wind nodes emit their wind only in the given direction, for warmth nodes the vector between user and node is taken as direction. Furthermore the nodes can be occluded for the user and for objects in the scene (cf. algorithm 1). As mentioned above, sensations created by weather influences are not the only sources which have to be considered: Fans, fires and other sources can have very different properties, therefore a distinction between the following kinds of wind and warmth are necessary (S5):

- Directional Wind/Warmth
- Spot Wind and Point Warmth

Their naming is an analogy to the Directional Light and Spot/Point Light in the X3D-standard. Both kinds of winds are described in the following.

`Directional Wind and Warmth` is created by weather influences and affects the whole scene. They are analogous to the ambient wind described in [FW13], but extend the concept by occlusion checks. Directional Wind and Warmth nodes only have a direction and no position, so they are valid for the whole scene. Concerning algorithm 2, the direction vector is used for the variable d.

`Spot Wind` is a local wind which could be created by a fan or events like a passing train. It has a position and affects only the area which lays in a cone directed into the wind direction (see figure 4). Lastly it is defined by position, intensity, angle (of the cone) and a direction, analogous to the InstantReality implementation of the X3D standard. The cone defines the area in which the wind is perceivable, outside the cone it's intensity is zero. The cone's height is given by a certain attenuation function which is also used to determine the force with which a spot wind affects the user and certain objects inside the scene (S4). Figure 4 shows the visualization of a Spot Wind produced by the splash of a waterfall.

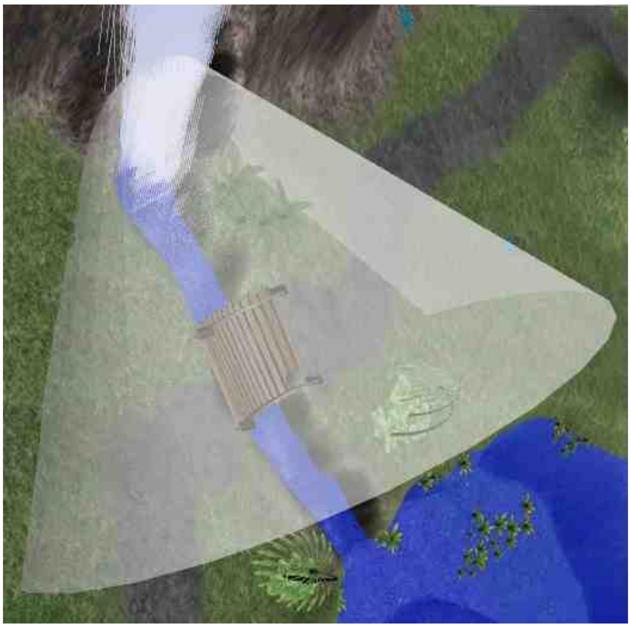

Figure 4: Visualization of a Spot Wind produced by the splash of a waterfall.

`Point Warmth` is analogous to Spot Wind. The only difference is the direction: Point Warmth nodes emit their warmth equally in all directions. Virtual heat sources could be for example a fire or a heater.

The occlusion for Spot Wind and Point Warmth nodes works similar to the one described in algorithm 1. It differs only in the $MAX\_DISTANCE$ constant which is not necessary in this case, because of the attenuation function.

4.4 A Glimpse on Performance

The whole framework in combination with the InstantReality system runs a standard scene (basic environment, directional wind and warmth nodes, SpotWind and PointWarmth nodes) at about 30fps. The hardware itself reacts much slower: A single infrared lamp needs about 1 second from switched off until the user can sense the full warmth. Switching off can be felt instantly. A single fan needs approximately 3 seconds for making the user feel its wind and approximately 1 second for switching off. Due to the design and the hardware model, this reaction time does only apply for wind and heat sources, the user approaches inside the scene. For sensations which already have an influence on the user, the perceived reaction time (e.g. to the user's rotations) is shorter: Fans and lamps neighbouring the most activated device are already active on a lower level, so that they are able to reach their full power in a much shorter time. Finally, the system fulfills at least partly requirements (H2) and (S1).

5 Discussion and Future Work

This work analyzed the requirements for hard- and software concerning the enrichment of Virtual Reality with wind and warmth. Based on those requirements, it was demonstrated how the generation of these sensations could be implemented. Pitfalls like disturbances of the overall system by new hardware components were faced and solved. An exemplary setup fully satisfying the hardware requirements was described. The influence on the tracking system was measured, so it is ensured that the tracking is not disturbed.

Furthermore a software framework that is capable of representing the most important wind and heat types as they can be used for Virtual Reality was presented. The sensation sources are represented in the scenegraph and their influences are calculated by an external engine. Most of the software requirements (S1 to S6 and S8) are fulfilled. To analyze crossmodal influences between wind and warmth generators (S7) and to extend the model according to those findings will be subject of future work. Also the geometry of the CAVE should be taken into account: How much do the sensations damp due to a user standing next to a wall and are there any turbulences when a fan blows onto a wall? The most important part concerning future work is the evaluation of the presented framework. This will be done by user studies testing single parts of the system, like the mapping of sensation nodes on hardware components, the attenuation functions et cetera. It must also be evaluated what the constraints of simulating wind and heat sources by this system are. Due to the location of the hardware, directional winds and the simulation of the sun as heat source which come from above or from the side are likely perceived realistic. But what about events like fans or fires which come from below? Difficulties in simulating those kinds of sources could lead to gaps between the visually perceived environment and the wind and warmth sensations. Here the possibilities, but also the boundaries of the technology must be analyzed as exact as possible. This will allow the developer of a Virtual World to avoid those conflicts when designing the application.

Finally, a large scale experiment for analyzing the influence of wind and warmth sensations on the user's presence will be performed. Here an experimental setup like the virtual pit first presented by Slater et al. [SUS95] seems to be appropriate. Another important question is in how far the presented setup can benefit from mobile setups like the one presented in [CTV07]. Especially an analysis concerning the comparability of the perceived presence would be important.

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