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WAVE FIELD SYNTHESIS FOR VIRTUAL PROTOTYPING IN VR SYSTEMS

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ABSTRACT

Acoustical properties (noise and sound) play often a major role in product design not only in the consumer and automobile industry, but also in other industries sectors. For this purpose more and more digital product models replace physical prototypes in order to reduce time and design costs. Using digital product models during the virtual prototyping the acoustical product behavior can be simulated and optimized also in the early design phases. A key component of the virtual prototyping is the virtual reality with its immersive and real-time features. In worldwide audiovisual virtual reality (VR) systems only few ones combine the stereoscopic projection with the state of the art audio reproduction method called Wave-Field-Synthesis (WFS). This new technology uses a closed circle of several loudspeakers surrounding the listening area enabling a realistic sound impression as well as a precise localization of sound sources. For this a VR-scene description is needed which provides the sound reproduction (empiric measured or simulated) synchronously with the visual animation of machines, cars and other products. The paper describes the application of Wave-Field-Synthesis in VR systems to support the verification of design solutions. Furthermore guidelines and limitations for the use of WFS in VR-Systems are discussed. Finally some research tasks to reduce or avoid existing WFS-limitations are presented.

Keywords: Virtual Reality, Virtual Prototyping, Acoustics, Wave-Field-Synthesis, Design optimization

1 MOTIVATION

Today product development dominates manufacturing time and costs, which could be contradictory to high standards of quality. The use of computer based tools enables the representation of product properties and their optimization before first physical prototypes have to be build. One possibility for the representation of product properties is the use of the virtual reality (VR) technology. Therewith it is possible to create virtual objects and to simulate their behavior in a virtual environment which leads to faster and so cost effective virtual prototyping. Common VR systems are often limited by only providing visual information to the user. Therefore the transferable amount of perceptible information and so the simulation of properties of virtual objects is limited. To overcome such limitations using spatial sound systems in combinations with virtual environments has been a research topic from the early days on. The main drawback of most of spatial sound reproduction methods commonly used in VR systems is that they are based on audio effects rather than on synthesis of wave fields. The spatial acoustic simulation and reproduction can therefore only be done correctly for one listener. With the today's existing computer processing capability for handling high amount of data, wave fields of virtual sources can be synthesized in real-time. This leads to new methods in simulating and reproducing the acoustic behavior of virtual objects, and so to new possibilities in the early design process.

Taking the acoustic behavior of technical systems in the early design process into account allows for example limitation of noise level of a machine, which is already legally prescribed from ergonomic point of view. Beside the noise level an efficient analysis of the directional sound radiation must be considered for acoustic product evaluation.

Other example of the importance of acoustics in the early design process is in the area of the consumer goods industry - the so-called sound design - used to optimize the acoustic behavior of products. This is done mostly empirically and dependable statements are only possible after the manufacturing of first prototypes.

In all these cases the innovative sound reproduction method **Wave Field Synthesis** can be used in VR systems to auralize simulated sound fields of virtual objects in the early phases of design process.

2 VIRTUAL PROTOTYPING IN EARLY DESIGN STAGES

2.1 Virtual Prototyping

Figure 1 shows the well known design process and the application of software tools for the virtual prototyping. Due to the coordinate application of the suitable software tools in each design phase virtual prototyping can be successful applied for the development of new machines and high technology products [7]. VR is one of the key technologies that integrates the possibilities of virtual prototyping.

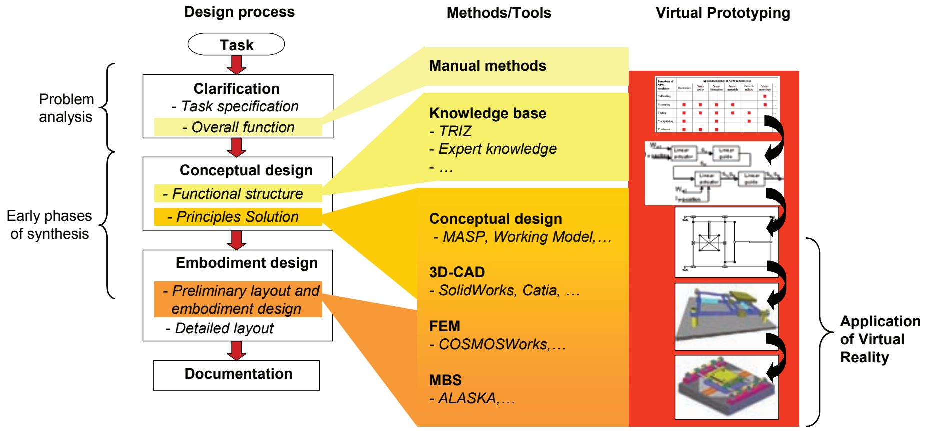

Figure 1. The main steps of the design process and tools for virtual prototyping

In general the virtual prototyping starts during the conceptual design. Based on the functional structure possible solution principles can be computer-based developed by using e.g. configuration matrix, effect catalogues or known conceptual design solutions. The function elements of the solution principles are often described with simplified geometric representations or symbolic elements. Series of calculations of the behaviors are possible on this level of abstraction (e.g. working space analysis, error and tolerance analysis, kinematic as well as static analysis). The predominant question is the analysis, simulation and optimization of motion concepts to find preliminary layouts. The use of special software tools (like Matlab, SAM, WorkingModel, Watt) supports this process. The using of VR in this early design stage can merge the results of different calculations to find a good solution principle to support the determination of basic embodiment design parameters, which are necessary for the model transfer into a CAD system, for finite elements analysis as well as multi-body simulation. In the phase of embodiment design the using of VR is state of the art in order to clarify e.g. working space or collision problems [1, 5, 7, 8].

2.2 The method of Wave Field Synthesis (WFS) in Virtual Prototyping

In the virtual prototyping process CAD systems are used to model virtual products. As a base for the physical calculations a 3D model of a product will be generated. Taking the mathematical description of the surface it is possible to simulate the sound radiation of the object, by knowing other parameters like material properties, connection to other objects and temperature. Our idea at that design step is to use WFS to auralize the directional wave field of the virtual prototype. Having a description of the sound field, radiated by the virtual object design engineers can turn the object and evaluate the sound field of the virtual product synthesized by WFS.

3 AUDIOVISUAL VR SYSTEM FOR VIRTUAL PROTOTYPING

3.1 The audiovisual VR system called FASP

In 2006 an innovative VR system was build in the Virtual Reality Competence Centre at the Technical University of Ilmenau in Germany (Fig. 2) [8]. This VR system called FASP combines stereoscopic projection and sound reproduction by means of the Wave-Field-Synthesis method. The stereoscopic projection setup has three flexible projection walls, while two are movable. Immersion grade, degree of freedom as well as size of the FASP installation can be adapted depending on the application and number of persons inside the VR system. Figure 3 shows the three possible installation setups of FASP. The condition for the reproduction of the sound field using the Wave-Field-Synthesis method is to have a closed circle of loudspeakers surrounding the listener area. The FASP installation has 208 loudspeakers.

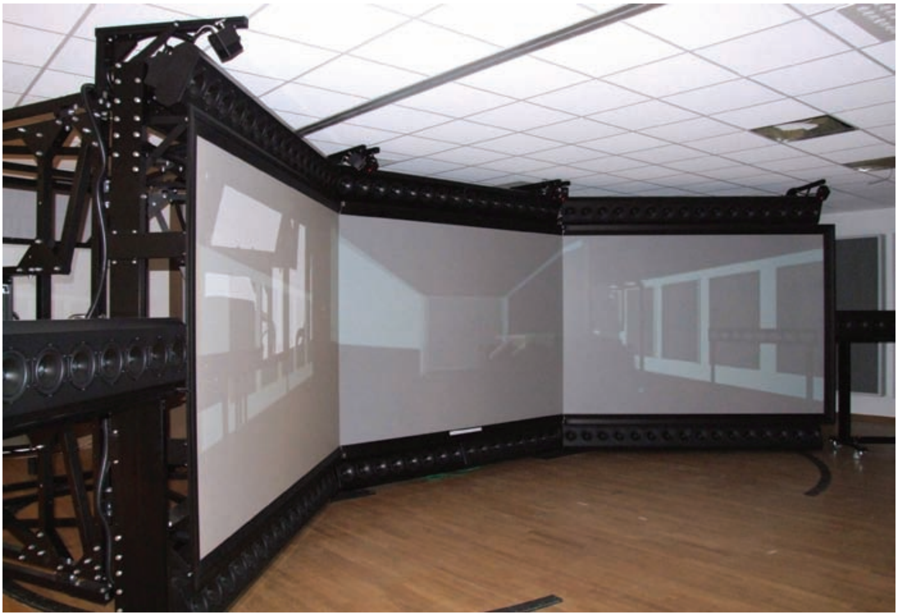

Figure 2. Audiovisual VR System "FASP" at the Virtual Reality Competence Centre in Ilmenau, Germany

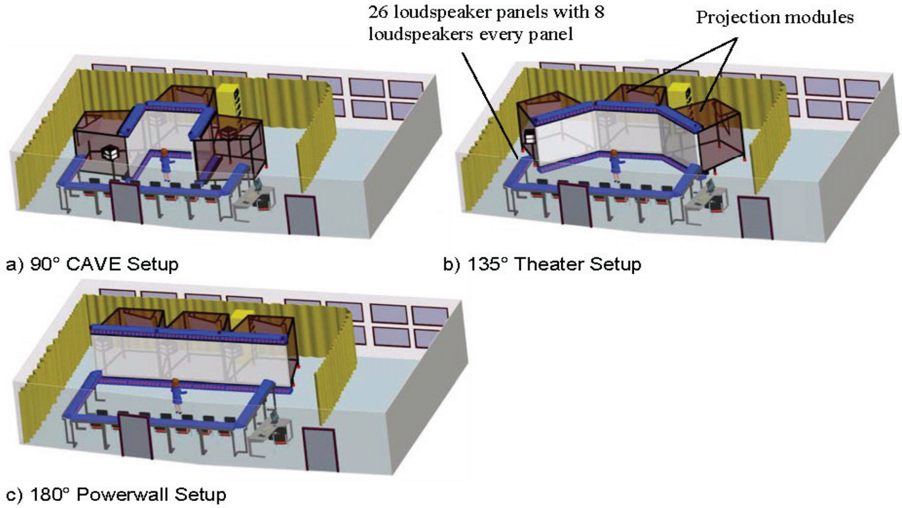

Figure 3. Possible setups of the audiovisual VR system

3.2 Acoustic Reproduction by Wave-Field Synthesis

Over time different methods for the reproduction of spatial sound have been developed. In general they can be grouped into discrete multi-channel loudspeaker set-ups, binaural reproduction and multi-object audio reproduction. The advantages and disadvantages of those methods are described in [4].
The multichannel loudspeaker reproduction is based on discrete multichannel loudspeaker set-ups, like the well-known standard 5.1 surround format, which uses three front, two rear speakers and the low frequency effect channel. Its main drawbacks are the restriction for the listener to stay at an optimum fixed seat. This means, a good spatial impression and immersion is restricted to a very small region of the listening area, the so called 'sweet spot'. In addition the optimum performance can only be achieved if there is sufficient room for 5 to 6 loudspeakers to be placed at a predefined position and if the reproduction room meets some acoustical requirements. The problem that the sweet spot is limited to a small fraction of the reproduction room limits the sound quality, when a number of people are supposed to listen simultaneously. Therefore an authentic, natural-sounding 3D-display is not feasible with this technique. Most efforts to improve multi-channel audio by introducing a larger number of loudspeakers are still limited to a fixed configuration of loudspeakers and limited in their performance.
A technique called Wave-Field-Synthesis (WFS), pioneered by Delft Technical University and developed by Fraunhofer IDMT for many market applications, can overcome the limitations of today's multi-channel (loudspeaker) reproduction and binaural (headphone) reproduction [2]. WFS permits the reproduction of a sound field, which nearly fills the whole reproduction room with correct localization and spatial impression [3, 6, 14]. The result is the possibility to move while listening in a similar way as to watch a hologram while changing the position. WFS is based on the wave theory concept of Huygens: All points on a wave front serve as individual point sources of spherical secondary wave fronts. This principle is applied in acoustics by using a large number of small and closely spaced loudspeakers (loudspeaker arrays) (Fig. 4). Each loudspeaker in the array is fed with corresponding driving signal calculated by means of algorithms based on the Kirchhoff-Helmholtz integrals and Rayleigh's representation theorems.

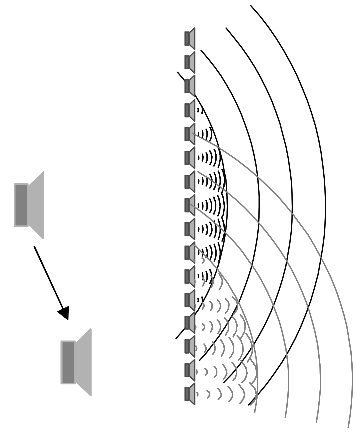

Figure 4: Wave-Field-Synthesis based on the wave theory [4]

For WFS these 3D-integrals are approximated for a finite number of identical loudspeakers placed in one plane. Without additional influence of the reproduction room the superposition of the sound fields generated by each loudspeaker composes the wave field in this plane perfectly up to the aliasing frequency. The aliasing frequency is given by the distance between loudspeakers. WFS enables an accurate representation of the original wave field with its natural temporal and spatial properties in the entire listening space only limited by the near-field properties of the loudspeakers used.
Virtual sound sources (point sources) can be placed anywhere in the room, both behind the loudspeaker arrays as well as inside the room (focus sources). The acoustical properties of the reproduced sound scene can either be the properties of the recording room, the properties of a prerecorded different venue or obtained from artificial room models. These properties can also be reproduced using plane waves (Fig. 5).

This new technology enables a realistic sound impression independent from the listener position. Due to the fact that a wave field is synthesized by this reproduction method, WFS is a strong tool for the auralization of machine acoustics and sound design. If the user is rotating or moving the VR scene sound source movements can be heard in real-time, because the WFS algorithms render the acoustical scene in real-time.

Currently studies investigate how WFS can be used as reproduction method for machine acoustics modeling, simulation as well as sound design.

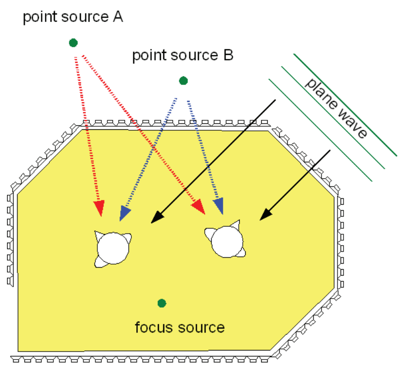

Figure 5: Reproduction of sound sources and plane waves [4]

3.3 Guidelines and limitations of WFS for VR systems

Wave Field Synthesis offers in comparison with all common multi-channel systems a large listening area of high quality sound reproduction independent from the listener's position. In VR systems where multi-user scenarios are common applications WFS is able to provide high quality spatial sound to multiple users without the need for headphones or user tracking [13]. Several users are able to localize the virtual sound sources at their correct positions at the same time.

As described in the last section, the theory of Wave Field Synthesis is based on simplifications of Rayleigh's integrals. This simplification restricts the synthesis of the wave field using WFS. While the reconstructed wave fronts are correct in terms of phase for the whole listening area, the synthesis of the amplitude can only be done right for a line through the auditorium. This line is called reference line [14]. If the listener leaves this line, the decay of the virtual source is not correct at his position. In common WFS systems where listener positions are unknown, the reference line will be placed according to the position of the virtual sound source to minimize the overall error in the receiver area [11].

If WFS will be used in VR applications, like in the FASP, user positions are known to provide perspectively correct stereoscopic images to the user. This information can also be used to optimize the reproduction of WFS by continuously moving the reference line according to the position of the listener [9].

In common WFS systems an auditorium enclosed loudspeaker array will be used to provide the listener with high quality spatial sound. For such systems a secondary source selection has to be done for each primary sound source position to prevent the listener from wrong localization. While synthesizing the sound field of a focused sound source, which is placed in the auditorium, the wave field is not correct in the whole listening area. For each position of a focused source, there exists a "forbidden zone" where the sound source can not be localized correctly by the user. This zone is the area between the secondary sources and the primary focused source itself (Figure 6 (a)). If the listener is in this area, he is not able to hear the focused source, but he will hear the loudspeakers [14]. By taking the position of a single listener and the position of the virtual focused source into account, the secondary source selection of the WFS system can be modified so that the forbidden zone can be minimized or even eliminated [9]. Figure 6 shows the secondary source selection of a common WFS system and the user-optimized selection due to listener position. It is shown that using activated user-optimized secondary source selection a single user can localize the focused sound source exactly at their position at any place in the auditorium.

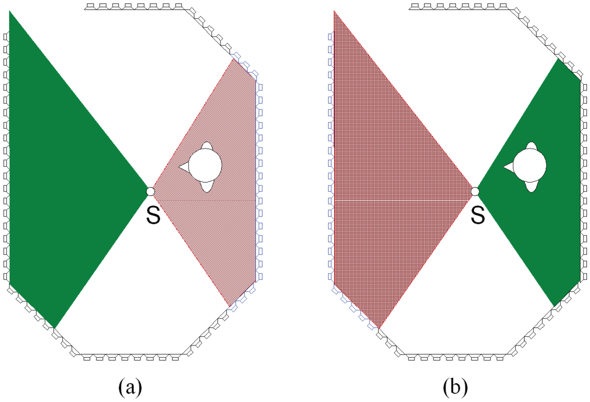

Figure 6: Optimization of secondary source selection for virtual focused sound source S. (a) Secondary source selection of common WFS systems. User is in "forbidden zone" (red) and will hear activated loudspeakers (blue) not S.

(b) User-optimized secondary source selection. User localizes focused sound source at S.

Using the mentioned optimizations for amplitude distribution and secondary source selection the quality of sound reproduction using Wave Field Synthesis can be considerably improved. Taking the position of a single user into account opens new possibilities in terms of sound field synthesis.

Another limitation of Wave Field Synthesis is related to the aliasing frequency. Using WFS it is only possible to create wave fronts up to the aliasing frequency. Above this frequency, which depends mainly on the distance between the secondary sources, the wave field is only controllable in spatial and temporal properties. However, the frequency range up to the aliasing frequency which can be controlled by WFS is sufficient to achieve a very well localization of virtual sound sources [12]. Synthesis of directive sound fields, which is a very important topic for the virtual prototyping, can only be done up to the aliasing frequency. The synthesis of directive sound fields using WFS is also limited due to the number of activated secondary sources. For each loudspeaker it is possible to apply an equalization filter to model the directivity of the primary sound source. Dependent on the primary- and secondary source position, a different number of loudspeakers could be activated for synthesis depending on the secondary source selection algorithm. This can lead to different qualities in the synthesis of the directional sound field for different positions of the primary source. If the position of the single-listener is known, the directivity of the primary sound source S can be calculated out of the angle between the normal n of S and the vector d from S to the listener L [9]. Using this method the directivity of the source can be simulated continuously, independent from the number of active loudspeakers. Using a database approach one certain equalization filter can be selected for each angle α which will be applied to all secondary sources used for the reproduction.

Figure 7 shows the calculation of the simulated directivity of a primary point source using the user dependent directivity. With this approach it is also possible to reproduce the measured directive sound field of a real object to verify or facilitate design decisions during the early design process.
Besides the database approach to simulate the directivity of a virtual sound source, also the use of different methods in real time directivity simulation is possible.

Figure 8 shows a schematic of the mentioned optimizations in WFS to be able to reproduce a high quality simulation of directivity of a virtual sound source.

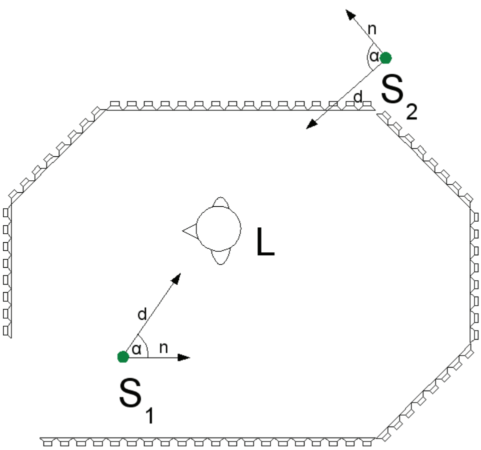

Figure 7: Calculation of user dependent directivity of a virtual point source S_i *(green).*

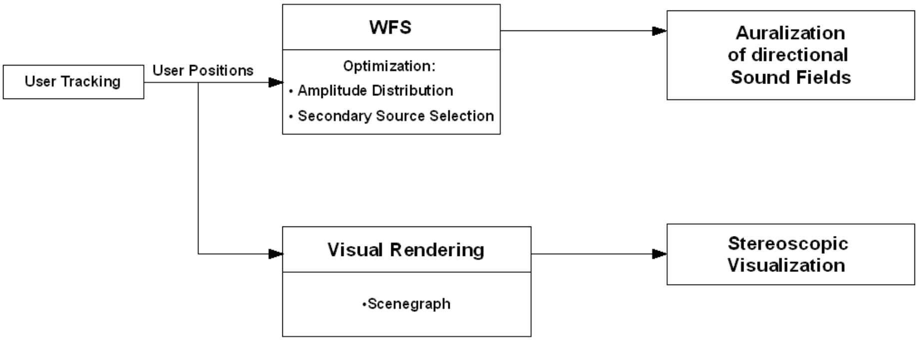

Figure 8: Schematic view of the reproduction process of directive sound fields using user optimized WFS for virtual prototyping

3.4 Research topics for WFS optimization in VR systems

Beside the significant pros of Wave Field Synthesis there are still some further research aspects to be investigated for the use in VR systems and virtual prototyping applications. Following main topics for WFS optimization in VR systems are:

- Current WFS systems use a 2D plane reproduction defined by an enclosed loudspeaker array. One question is, if and how such a reproduction is sufficient for virtual prototyping using VR systems.
- For the use of WFS in projection based VR systems, like the FASP (back projection system), it is necessary to have other reproduction solution for the screen area. Currently the FASP solution is to have a combined sound reproduction system consisting of WFS and Vector Based Amplitude Panning (VBAP) [10]. VBAP is used to auralize virtual objects in the vertical plane. Further research will be done to improve this restriction.
- In virtual prototyping applications the acoustic analysis and synthesis in the early phases of engineering design needs the reproduction of controllable directional sound fields over the full hearable frequency range. The existence of the aliasing frequency in common WFS systems limits the reproduction in the full hearable frequency range. Research has to be done to extend the reproducible frequency range.
- Beside the optimization of reproduction of directive sound fields our work will focus on how to describe, integrate and visualize directivity of virtual sound sources for the use in VR scene graphs.

4. CONCLUSIONS

This paper describes the application of Wave Field Synthesis in VR systems for the use in virtual prototyping process. The main idea is to use WFS in the early design process to simulate the acoustic behavior of virtual prototypes as close to reality as possible. For this the testing environment was presented in this paper. The pros, some limitations as well as research aspects for the WFS sound reproduction in VR systems were presented to virtualize acoustic properties to support the virtual prototyping. The motivation for this work is driven by requirements coming from the automotive, machinery and consumer industry. The virtualization of the acoustical behavior of products during the early design process will lead to new possibilities in faster, more efficient and cost-effective prototyping.

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