Virtual Reality supported Visualization and Evaluation of Noise Levels in Manufacturing Environments*

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—— **Abstract** ——————————————————————————————————

Virtual Reality (VR) provides users advanced visualization and interaction technology for designing, analyzing and exploring complex data. To address the issue of noise in manufacturing environments, we developed a VR-supported method allowing users to explore noise behavior. This method consists of an implementation of acoustic simulation and visualization for both desktop and Cave Automatic Virtual Environment (CAVE) based VR systems. It enables user-oriented, interactive analysis of simulated data, where there capability to immerse oneself in the data is especially valuable. In a real-world factory, the acoustic measurements obtained essential input data for simulation settings and validation data for simulation results. Furthermore, some political and legal aspects are addressed to enhance the evaluation of results and the visualization. By using the implemented software tool, users are able to understand and investigate the noise issue in manufacturing straightforwardly.

1   Introduction

1.1   Virtual Reality

The Virtual Reality (VR) is applied in this paper to support the investigation of noise issues in manufacturing industry. With a virtual environment, the acoustic simulation and visualization are implemented. The simulation results and enhanced analysis capabilities in VR provide a new point of view to fulfill this special requirement during factory planning. As a comprehensive and widely developed technology, VR is originally defined as: „a system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real" [24].

   In recent years the VR technology is improved significantly by increasing demand of industrial applications and shows following changes, such as increased hardware power, reduced acquisition costs, integrated methods with simulation and visualization. And on

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implementation level, the Virtual Reality Modeling Language (VRML)/Extensible 3D (X3D) standard is widely used and further developed.

The VRML standard is originally developed as a modeling language for web applications and later accepted by the International Organization for Standardization (ISO) [2]. It is implemented for different applications, e.g. virtual assembly, machining processes simulation, visualization of facilities, and employee training parallel to the running production [17, 10]. Some web-based applications are also found in literature review. For example, Qiu et al. demonstrate an implementation of automation animation using VRML and identified fundamentally their advantages like assembling CAD-objects and their interaction [19]. And remarkable of Ranga and Gramoll [20] are the introduction and implementation of JavaScript into VRML and the performance in 3D FE-analysis. They realized a web-based virtual environment and included a customized user interface. As successor to VRML, X3D is also standardized by ISO and contains mostly all VRML features. For current applications X3D has no remarkable advantages comparing VRML. On the other hand, VRML has more developed Nodes, APIs and extensions. With Java or JavaScript, different programming solutions like mathematical descriptions can be implemented in VRML. The Nodes offer a customized link to different positioning and allocations between different objects. Therefore, VRML is used as modeling language and scene graph standard in this paper. Due to the internet nature of VRML, in this paper a web-server based concept is developed.

According to different user immersion levels, VR systems are classified into non-immersive and immersive systems. A non-immersive VR system, such as a desktop-based display system, is according to some VR definitions not understood as a real VR system. The full-immersive VR systems, such as the CAVE system, provide most costly and complex solution with unique benefits. Compared with non-immersive system an immersive VR system has higher sense of situational awareness, wider field of view, higher scale perception and sense of immersion. However, a non-immersive VR has advantages of lower costs, shorter development time, and better implementation conditions. For example, the desktop-based VRML viewer enables users implementing and viewing the developed virtual environment with simple configuration.

At the Institute for Manufacturing Technology and Production Systems (FBK), we use the both VR systems to satisfy different demands of research and industrial projects [8, 9]. The proposed concept in this paper is also first developed and tested in a desktop-based environment and further in CAVE system. The implementation and visualization in both systems are to be discussed in latter sections.

1.2   Noise in Manufacturing

The factory workers are exposed to any of occupational hazards every day, such as, chemical solvent, heat, noise, vibration, etc. Noise is becoming one of the most frequent occupational hazards in manufacturing. The noise in a factory could from machinery, powered tools or other activities, which influences employees' health and can even cause diseases. According to DIN 1320 and VDI 99, the noise is described as unwanted sound causing disorder, harassment and other health problems. As the noise exceeds specific limits, the risks of hearing loss or other sicknesses are increasing. According to the investigation of Federal Institute for Occupational Safety and Health (BAUA), about five million employees are exposed to noise in Germany. And this number in USA 1991 was over six million [12]. To protect health and safety of the employees, there are existing laws and guidelines to follow, e.g. the Federal Ministry of Labour and Social Affairs (BMAS) limits noise and vibration levels within Germany's Occupational Safety Law "Arbeitssicherheitsgesetz" (ASiG), German ordinance "Lärm- und Vibrations-Arbeitsschutzverordnung" (LärmVibrationsArbSchV) and

other additional guidelines. In the European Union the minimum requirements to protect the workers from noise is determined with directive 2002/44/EU.

According to the influence effects, the impacts of noise to the workers in manufacturing systems are classified from three main points of view: occupational safety, negative health impacts, and preservation of work performance.

- The occupational safety: According to regulation ISO 7731 [5], the loudness of a warning signal in industry must be 15 dB over the ambient noise. The warning signal will not be effective if the factory is too noisy. Also, communication among workers deteriorates [7] due to noisy working environment, which causes potential unsafe factors.
- The negative health impacts: the health damages can result from exposure to repeated or very loud noise at work, e.g. permanent hearing loss and heart disease. More noise related health risks such as physiological effects or the risk of accidents are listed by [26, 27, 14].
- The preservation of work performance: much research work has been done to determine the influence of noise on workers' performance. Different authors found a significantly poorer performance when employees are exposed to noise [22, 11, 16].

The laws and guidelines require the employers to worry about the noise, namely eliminate or reduce the risks from exposure to noise. The specific duties on employers are also placed when the average sound pressure level and peak sound pressure level reach certain limits. Different methods and instruments are deployed in practice [21]. According to the solution methods, these methods are classified into three categories [18]: reduction of noise emission, reduction of sound propagation, and reduction of sound pollution. In manufacturing, the latter two methods are often implemented. Important methods to reduce the sound propagation are changing the room shape, optimizing division of work areas, and using the sound absorbing building structures as well as materials. The methods to reduce the sound pollution are workstation related, such as arrangement of workstations and sound shielding around workstations.

1.3 Acoustic Simulation

Acoustic simulation enables the investigation of the behavior of sound propagation, which determines the influences of noise. Nowadays, many established methods for sound simulation and sound visualization exist, which are widely implemented for computer games, multi-sensory user interface, or acoustic prototyping. They are mostly wave-based or geometric methods. Such as the Finite Element Methods (FEM), Boundary Element Methods (BEM), and Finite Difference Time Domain (FDTD) are widely discussed and compared in [25, 23].

A geometric approach called Phonon Mapping is also developed in [13], which is implemented to achieve the object in this paper. Analogous to seeing light as particles called photons sound sources emit sound particles called phonons. With each reflection the phonon's sound pressure is decreased according to the material's absorption coefficient. At each reflection position the current sound pressure of the phonon is stored. Calculating the influence of all phonons to a particular listener position the information of all reflection positions is collected and weighted according to their distance to the listener. Tracing the pressure for different frequency bands and using a Dirac impulse as sound source this calculation provides the room's impulse response. Convoluting an anechoic signal with this we get the exact sound in the simulated room with specific source and listener positions. Furthermore in [13] acoustic properties of simulated rooms are extracted like understandability of speech or suitability for concerts.

In addition to room acoustic methods, an outdoor acoustic simulation and visualization method is developed in [15]. It enables the industry to make the assessment of industrial noise in the neighborhood. However, the outdoor noise issue is not concerned in this paper.

Adjusting or rescheduling a manufacturing system is expensive and time consuming. It is necessary to take the noise issue into account both during the planning and design stage of the manufacturing. In this paper, the simulation is used to calculate the sound level at arbitrary listener positions. Then the simulation and visualization are implemented in a virtual environment using VR, which enhances the understanding of noise influence in a factory.

The rest of this paper is organized as follows. Section 2 gives an overview of the implementation concept and involved tasks.The experimental acoustic measurements are shown in section 3. In section 4, an interactive sound simulation and visualization approach is presented. To implement this approach in VR, a web/client structure is introduced. Further, the simulation results is visualized using a CAVE system. The final section concludes the paper and gives an outlook of future research.

2   Method and Workflow

The VR-based concept presented in this paper includes several subdivided objectives. They are design and implementation of acoustic measurements, an investigation of legal regulations, 3D modeling of a virtual environment, modeling of a sound source, parameter setting and simulation implementation, design of a graphic user interface (GUI), development of a web server as interface between VR and simulation etc. Figure 1 shows these tasks within a basic workflow.
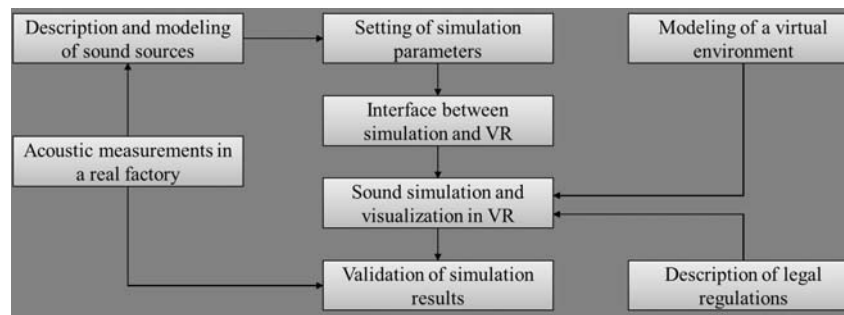
Figure 1 Workflow of a VR-based Method

An acoustic measurement consists of sound level measurement and sound intensity measurement, which provides input and validation data for simulation. Before simulation start the parameters are specified according to the acknowledgement from measurement. However, the validation part will not be included in this paper due to current research status. At the same time, a mechanical laboratory is rebuilt into a 3D model, which provides a virtual environment for simulation and visualization. In this process several modeling software are used, such as SolidWorks and 3ds Max. An interface is made to enable users to change the simulation settings. An additional interactive 3D user interface is created to navigate and to control the simulations in a virtual environment. Combined with investigation of legal regulations for manufacturing, the visualization of simulation results facilitates further the analysis of noise issue in a factory.

Several requirements are considered, such as, the efficient and safe data transfer and file

converting, a straightforward user interface, and extendable software structure with function modules. In this paper not all tasks are discussed, the focuses are acoustic measurements, acoustic simulation and visualization, and the implementation in VR. These three main issues ensure the usability and efficiency of intended approach. The design and implementation of both sound pressure measurement and sound power measurement are firstly shown in the next section.

3 Acoustic Measurement

The acoustic measurements are classified into sound pressure level measuring and sound power measuring. The sound pressure level indicates the effective sound pressure relative to a reference value and the sound power shows the total energy of a sound wave per unit time and measured in watts. The former allows a sound source description which is input data for the simulation, and the latter provides the data basis for simulation result validation. The measurement environment is a mechanical laboratory at the University of Kaiserslautern. In this laboratory, the employees usually work with two manually operated lathes, a CNC (Computerized Numerical Control) cutting machine, a CNC tool grinding machine, a universal milling, a CNC drilling center, and some other small equipment. The layout of this laboratory is shown latter in Figure 3a.

3.1 Sound pressure level measurement

(a) Measuring parameter setting **(b)** Microphone calibration **(c)** Measurement configuration
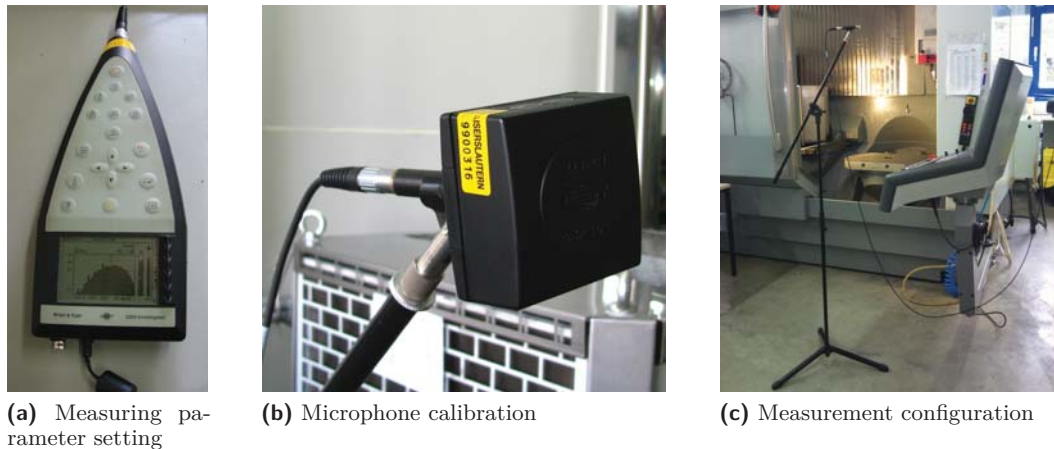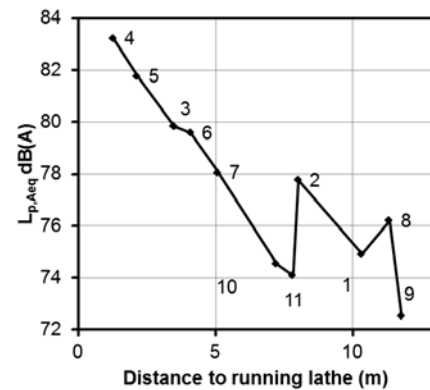
■ **Figure 2** Sound pressure level measurement

Sound pressure is estimated by the difference between local pressure and atmospheric pressure caused by a sound wave. This index is often used to identify the impact of sound to the human. The sound pressure level is measured by using the sound level meter. A portable computer allows users to make measurement settings, to store the measurement results, and to view visualized results (shown in Figure 2a). According to regulation ISO 11202 [1], the acoustic pressure level is described by continuous sound pressure level, sound from foreign sources, and maximal sound pressure level. A combined measurement design is based on DIN series 45635, in which the measuring requirements for different manufacturing processes are defined. For example, the measurement for a lathe is based on DIN 43635-1 [3]. A calibration shown in Figure 2b is done before measuring. For each single sound source

the measurements are made at 11 different positions (shown in Figure 3a) and at 3 typical machining procedures: idling, normal machining and high speed machining. During the measuring, the microphone is positioned using a tripod with extension arm. The microphone is adjusted 10 cm behind the head position at a height of 1.55m. In Figure 2c, the microphone is for example placed facing the control panel.

(a) Measuring points in a real factory   **(b)** Measurement results

**Figure 3** Position-based sound pressure level measurement

Figure 3b shows a measurement example of a running lathe (machine "DB1" in Figure 3a) at normal machining speed. Position 4 is directly in front of the lathe and shows the highest continuous sound pressure level. The sound pressure levels at different positions are basically proportional to the distance to the running lathe. Using the same analysis method, the measured maximal sound pressure level is summarized as well. The sound from foreign sources has no essential influence in this case and therefore not investigated. A validation between these results and simulation will be made in the future.

3.2   Sound power measurement

A sound power investigation enables the description of a sound source. To describe the sound power, the sound intensity description is usually implemented. In [4] the measuring equipment is defined as intensity probe. Prior to measuring, a calibration of the sound intensity probe is necessary, which is implemented by using a piston phone.

The intensity probe is placed 0.5m from the measured machine surface. The average during 30 seconds measuring time is determined as measurement result. Based on ISO 9614-1[6], it is necessary to repeat the measurement at least once per square meter. Therefore, a grid is used to fix the measurement points on the side of a machine (shown in Figure 4a). This grid is made by several wood frames and thin cords, which defines the sub-surfaces for measuring and helps the operator to find the right position to place the intensity probe.

The intensity measurement is repeated in the middle of each sub-surface for all five machine sides, except the bottom side. Based on the measurement data, a visualization of power distribution around the sound source is made, which facilitates the understanding of sound propagation in the vicinity of the sound source (Figure 4b and 4c) and further enhance the modeling of sound source in a virtual environment.

(a) Measurement setting   **(b)** Power distribution   **(c)** 3D visualized sound power distribution
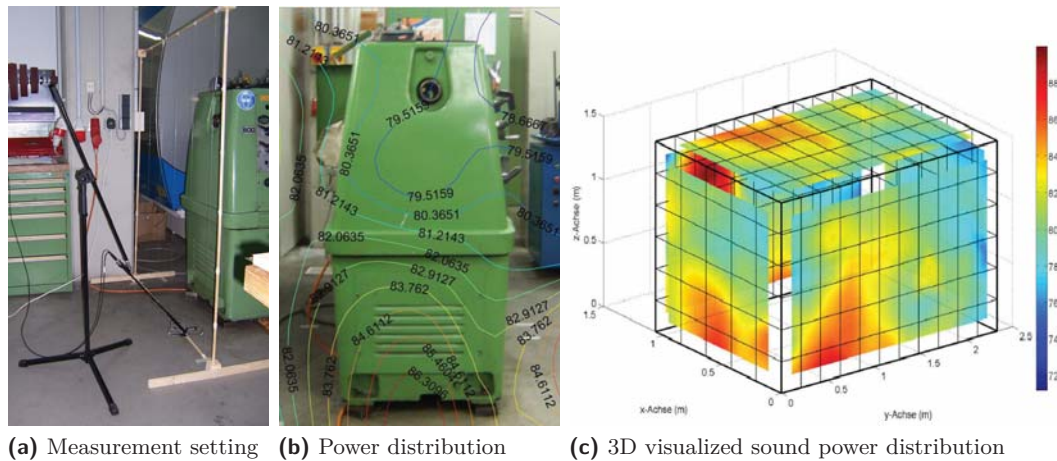
■ **Figure 4** Visualization of sound intensity distribution

4 Sound Simulation and Visualization in VR

4.1 Server/Client structure

The objective of in section 2 discussed concept is to have an application for interactive noise investigation in a virtual environment. To do this, VRML is used as a front-end to users. It provides capabilities to render complex scene graph, to animate object motion, or to interact with the user. VRML a well established standard which supported by any important platform and operating system. Although VRML provides programming interfaces through JavaScript and Java. As a server/client concept is used, an existing C++ implementation of the acoustic simulation can be used and extended for the purposes. Figure 5 shows the method for interactive acoustic simulation and visualization. The geometric data is transferred firstly from modeling software to VRML editor, and then loaded into a web server generated viewer application. All the objects are built with 3ds Max and then exported using the VRML standard. Using VrmlPad as VRML editor, the Sensors, Events or other interaction Nodes are constructed in a VRML file. At the same time, Java and JavaScript descriptions are embedded into VRML directly. It enables interactive user interface, simulation launching, and data converting. After these steps, the data for the application is prepared. The simulation application acts as a server, which loads the model of a virtual factory and adds user interface elements. The resulted VRML code is delivered to VRML compliant VR platform via HTTP.
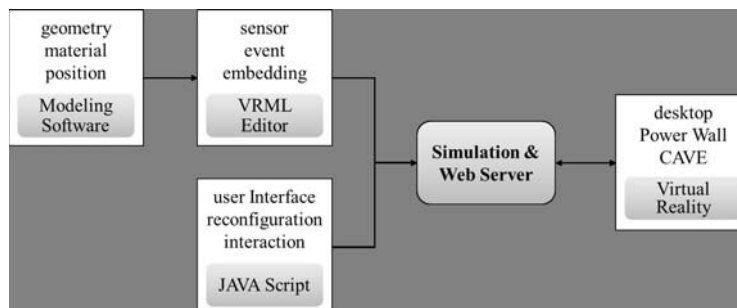
■ **Figure 5** A web server method for acoustic simulation and visualization

4.2   Simulation using web server

As the simulation is started, the server loads the VR model (VRML file) and adds additional VRML script describing basic user interface elements for interaction within the scene. Buttons and sliders are implemented using simple VRML geometric codes and JavaScript. This geometry is connected to a TouchSensor for buttons and to a PlaneSensor for sliders. These sensors emit events which are routed to Script Nodes containing simple interaction logic written with JavaScript. Commands are sent back then to the server by loading a special URL which encodes the action. The server computers the simulation and delivers the data to the VRML viewer again. These communications are done via HTTP connections. The viewer opens a new connection using an HTTP request asking for a file encoding commands in the filename. The server does its calculation and answers with a new VRML file delivered by this existing HTTP connection.
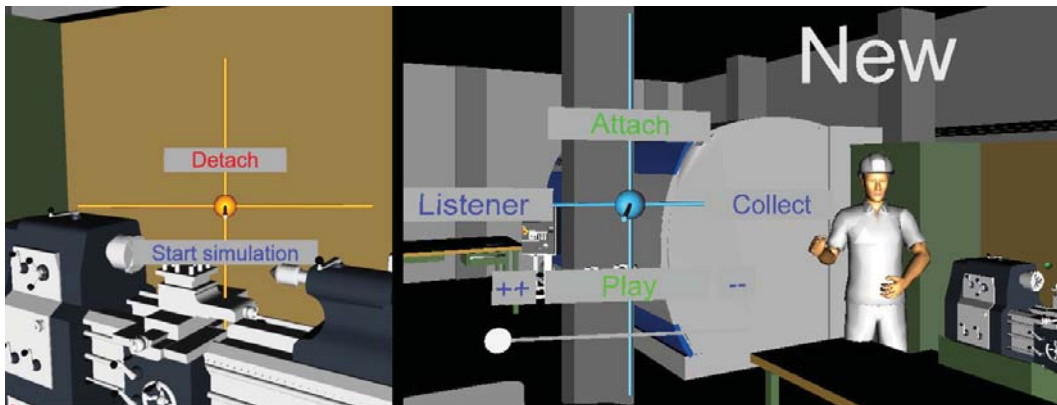

■ **Figure 6** Simulation user interface

To implement the phonon tracing simulation, several input parameters are required. It is a geometric approach, the algorithm needs first the geometric model of the room and the objects inside. Each surface of the objects is assigned to one material with specific sound absorption property. Usually, the material's absorption coefficients are taken from the coefficient tables.

Then the position of sound source and the sound pressure at 1 meter distance to the sound source are required. The sound pressure can be estimated by using the measurement data. Better results are achieved by providing an anechoic signal of the sound source, i.e. the sound pressure at several frequencies. Furthermore, the user may define an arbitrary number of listener positions. Other settings such as the number of phonons, the speed of sound wave etc. are also made before simulation. For more details on the simulation and input settings, refer to [13].

After parameter settings, the model is loaded into the viewer application. The user can explore the room and place the sound source within the viewer application and starting the acoustic simulation. In Figure 6, two modules are shown. On the left is the module for sound source setting and simulation start. Using the right module, one or more listeners are placed in the room according to common operation positions, and then the phonon collection step can be performed. In 1.3, the simulation algorithm is already described.

4.3 Visualization in VR

When the simulation is done, users can investigate the sound propagation inside the room by view the animated phonon paths. In Figure 7a, the phonons are visualized as green spheres. A 3D user interface facilitates the user experience. The playback speed can be adjusted with the "++" and "−" buttons and the current simulation time step can be specified with a slider. The tool enables the user to place and remove listeners depicted by workers interactively. Then, a command for the calculation of the sound pressure levels at the defined listener positions is issued. The scene graph in Figure 7b is updated with corresponding listener colors according to the sound pressure level: green for low sound pressure levels <80dB, yellow/orange for critical sound pressure levels <84dB, and red when the sound pressure level is higher than the upper action value according to German ordinance LärmVibrationsArbSchV. The visualization of the sound propagation and noise level helps users to identify possible noise problems/positions and find out the matching solutions. The effect of different materials on the spectral energy/pressure distribution can be observed as well. Scene materials of high reflectance can be identified and replaced in the virtual environment. The potential improvements of the changes can be viewed directly after one more simulation, thereby reducing the noise level.

(a) Sound propagation

(b) Color scaled sound level
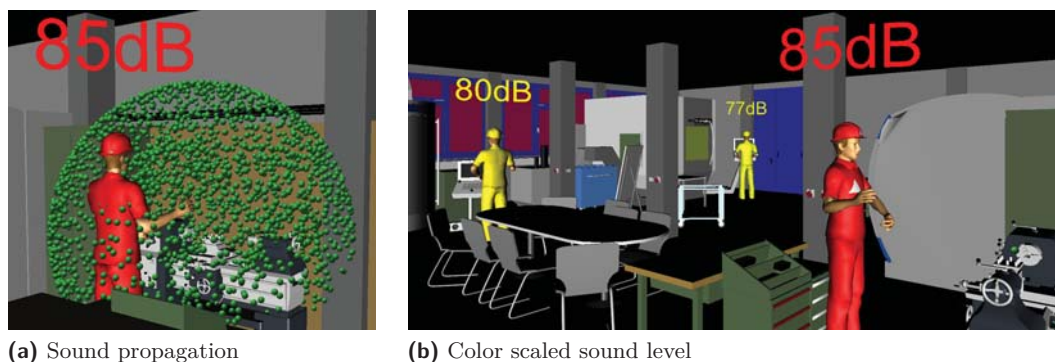
■ **Figure 7** Visualization of sound level

After the successful test with desktop system, the application is implemented in CAVE-based VR. The CAVE system located at the FBK institute Kaiserslautern consists of 8 projectors, projecting on 4 walls (front, left, right and floor). It offers an immersive virtual environment more than 17 cubic meters. In this system, the passive stereo technology with circular polarization is used for stereoscopic rendering of the 3D scene. The CAVE is driven by a VR cluster, which contains 1 master and 8 clients. Four infrared (IR) cameras from are used for position/motion tracking. Users interact with the VR system via different input devices such as a fly stick. "COVISE" is selected as software platform to operate the CAVE, due to its wide range of hardware support and the variety of different functionality modules. For wide industrial applications, COVISE enables straightforward integration of different modules as well as visualization functionalities.

The web server opens a HTTP port for COVISE modules and gets feedback from COVISE. The two necessary COVISE modules are "VRML renderer" and "VR" modules. The former enables the VRML visualization of a scene graph in CAVE and the latter provides basic interaction functions, such as the navigation and user tracking. In Figure 8, the CAVE-based application is shown. The user explores the virtual factory and simulates the sound propagation to analyze the noise issue during workstation or layout planning.

(a) IR tracking system   **(b)** Sound pressure level visualization in CAVE

Figure 8 Interactive visualization of sound level using CAVE

5   Conclusion and Future Work

In this paper, a new method for interactive and fast noise investigation in virtual manufacturing is introduced. A software tool is implemented, which can be used to determine the noise level at operation positions in a factory and test different improvement scenarios in VR directly. A web server is used as data interface and user interface between simulation and VR. Users are allowed to set the simulation parameters and view the results through an interactive user interface. Further, the method provides facilities to check the limits of sound pressure level against federal laws and regulations. The proposed concept is effective and produces realistic results.

However, the industrial noise in outdoor area is not considered in this concept, which is the further research focus. Combining the wave-based simulation algorithm can enhance the phonon tracing results. However the integration of both methods needs high performance computing and optimized software structure. Also, this tool provides only basic human-computer-interaction facilities the sound investigation, which is to be extended in the future. Changing acoustic properties of the room has to be made in original room model and exported to VRML again. This process has to be improved to an more intuitive process within VR, e.g. the interactive adjustment of absorption coefficient for simulation of different floor materials. And based on the server/client structure, an implementation of web-based collaborative simulation and visualization is also considered in the future.

6   Acknowledgments

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