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A REVIEW OF REQUIREMENTS AND APPROACHES FOR REALISTIC VISUAL PERCEPTION IN VIRTUAL REALITY

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ABSTRACT

The amount of new virtual reality input and output devices being developed is enormous. Those peripherals offer novel opportunities and possibilities in the industrial context, especially in the product development process. Nevertheless, virtual reality has to face several problems, counteracting reliable use of the technology, especially in ergonomic and aesthetic assessments. In particular, the discrepancies in perception between the real world and virtual reality are of great importance.

Therefore, we discuss these most important issues of current virtual reality technology and highlight approaches to solve them. First, we illustrate the use cases of VR in the product development process. In addition, we show which hardware is currently available for professional use and which issues exist with regard to visual perception and interaction. Derived from the depiction of a perfect virtual reality, we define the requirements to address visual perception and interaction. Subsequently we discuss approaches to solve the issues regarding visual perception and evaluate their suitability to enhance the use of virtual reality technology in engineering design.

Keywords: Virtual reality, Visualisation, Visual perception, Eye tracking, Conceptual design

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1 UTILIZATION POTENTIALS FOR VIRTUAL AND AUGMENTED REALITY

In perfect virtual reality (VR), users would not recognize whether they interact with the virtual or the real world. Such a VR system would be able to address all human senses and could even offer opportunities for interaction with matter. This utopia of an ultimate display was first published by Sutherland (1965) more than 50 years ago, when computer visualization was in its infancy.

Nowadays VR/AR systems offer great potential for business usage. This technology could enable the conduction of aesthetic, ergonomic or various other design evaluations in virtual environments at early design stages. With regard to the aim *responsibility for our future design methods* we can save resources and thus act sustainably, by substituting physical models with virtual ones. This can lead to a significant reduction of development time, because the product developers can perform fast and simple virtual variant analysis instead of building costly physical prototypes.

However, in order to be able to use those systems productively, we must exploit further potential. First of all, there is a need for haptic feedback in virtual environments. Users must be able to feel, what they are interacting with. This haptic feedback varies from feeling the weight of an object to recognize tactile feedback, for example the leather of a steering wheel. Furthermore we must address the visual perception in a realistic manner. Distance and size estimations must not be distorted. In addition, the display resolution and Field of View should meet the real human eye resolution and Field of View. VR / AR offers and requires new user interfaces to interact with virtual content. In order to reach the highest degree of immersion and to take advantage of the tacit knowledge from everyday interactions in reality, we should be able to interact with virtual objects in the same manner as with physical objects.

In this contribution, we present an overview of current research issues that have to be addressed in order to use VR in a productive manner for product design evaluation. Furthermore we address future projects to optimize the visual perception in the near field area (up to 2 meters). To do this, we first present the current use of VR technology in the product development process and outline recent VR hardware developments. The following section describes current difficulties and the inadequacy of VR methods in professional usage. We define requirements that must be fulfilled to achieve perfect virtual reality. Hereafter, the following chapter discusses various approaches to optimize the visual perception in detail. A ranking of the presented solution potentials complete the work.

2 RELATED WORK

2.1 Exemplary use of virtual reality in the product development process

VR opens up the possibility of versatile use in the product development process. According to a study of Deloitte, german companies will invest about 850 million euro in Virtual- and Mixed Reality solution. In particular, innovative new applications will be the economic driver to use VR in the daily work. Some examples of currently used applications are shown below. (Esser *et al.*, 2016) Interaction with components in VR enables intuitive handling, e.g. for assembling processes (Fechter and Wartzack, 2017). Thus, the designer can get intuitive access to various mechanical components, which is particularly advantageous for design modifications. The manufacturing of real physical prototypes is expensive, while the use of existing digital models contributes to cost savings and sustainable development. Riedl (2012) identified potentials to substitute physical models with virtual ones in the case of ergonomic evaluations to save a great amount of time and resources. One objective is to perform a full virtual assessment at the strategic design stage when digital data is scarce. Several automobile manufacturers are currently planning to use this method in the product development process. The purpose for which VR is most frequently used in the product development process is the design review. In such a design review the latest design is discussed by members of various disciplines. VR offers the opportunity, to illustrate the model without the reviewers having to be able to read technical drawings. Further use is coaching employees to handle critical tasks or emergency training (Jarvis *et al.*, 2015). In combination with eye tracking techniques, VR can be used for knowledge acquisition. Matthiesen *et al.* (2013) used this method to analyze the human behavior in understanding technical systems. Even though this study was performed with technical drawings or CAD-models shown on a pc monitor, this can be transferred to virtual environments as well.

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2.2 Typical hardware setup

As depicted above, in order to address all human senses in VR coerrectly, thus reaching the vision of an ultimate display presented by Sutherland (1965), hardware and software has to evolve further. We now want to present a short overview about common hardware components, which can address the most important senses in VR, including visual, auditory and haptic perception. Beside the senses above, we must take into account interaction as well as movement, to obtain our goal of a (if possible) full immersive system.

2.2.1 Display

The history of visual devices extends from early black and white television to today's OLED displays. VR display technology has developed a lot in the past few years. Today you can use large CAVEs (Cruz-Neira *et al.*, 1992) or smaller head-mounted displays (HMD), which can be standalone or wired. In this paper, we only consider HMDs, because they are affordable and applicable for end-consumers. Furthermore, we do not consider see-through HMDs due to their low suitability for immersive design reviews as a result of the issues with a small Field of View and therefore a small grade of immersion.
Since the first head-mounted display, Ivan Sutherland's *Sword of Damocles* (Sutherland, 1968), technology developed a lot. Nowadays, we see lightweight, mobile HMDs that are affordable for enterprises as well as for consumers. More precisely, we have three major subtypes of HMDs:

- **mobile HMDs**, which carry a mobile phone and use only the sensors provided by the phone: e.g. Google Cardboard, Samsung GearVR
- **standalone VR-Headsets**, which do the graphics computing on included chips and therefore can be used without additional devices like mobile phones or computers: e.g. Lenovo Mirage Solo, OculusGo
- **stationary HMDs**, which require a high-end personal computer to calculate the visualization: e.g. Oculus Rift CV, HTC Vive Pro, PlayStationVR

Mobile HMDs offer only limited display resolution and computing power compared to the alternatives. Furthermore, the built-in mobile sensors normally only allow 3-DOF tracking. Standalone VR-Headsets offer great opportunities for the future, but today, there are only a few models available and these are inferior to the stationary ones in terms of computing power. For that reasons, we will consider stationary HMDs with 6-DOF outside-in tracking in order to reach high display resolutions and exact tracking results.

2.2.2 Interaction devices

In order to interact with objects in VR several input devices are available. The simplest interaction method are keyboards or game-controllers without any positional tracking. Currently, most HMD hardware comes with one 6-DOF traceable controllers for each hand. These open up the possibility to move your hands in the virtual world alike in the real world. To obtain real, intuitive interaction, there are several marker-based and markerless approaches for hand tracking without the need of any controller.

2.2.3 Haptics

Haptics are crucial for an immersive experience. In order to stimulate the users haptic perception when interacting with virtual objects, there is a need to use haptic devices. For full body haptic feedback, there are available several force feedback vests e.g. the KOR-FX, which transforms audio signals to haptic feedback. Nevertheless, it will still take some time, until we are able to act with real haptic hands and feel the objects we are acting with in the virtual world. To support a realistic haptic feeling for design or ergonomic studies, it is the current standard to use simplified, physical models. Those devices may contain only one seat and the steering wheel but they have a huge influence on the user experience.

2.3 Issues with perception in virtual environments

Although modern technology allows a rather realistic representation, there are some perception issues, which lower the grade of immersion. In the following we want to discuss issues that mainly involve the visual perception and the interaction with virtual objects. In addition, cyber sickness is an issue that must always be considered.

2.3.1 Spatial perception

Human visual perception handles several signals for object size and distance appraisal (Carbon, 2015) including occlusion, disparity, accomodation and convergence (Cutting and Vishton, 1995; Renner *et al.*, 2013). Which of the cues we primarily use depends on the distance between observer and observed object. In the *personal space* up to 2 m, we mainly use disparity, accomodation and convergence (Cutting and Vishton, 1995). In distances of 2 to 30 m, the *action space*, occlusion and motion parallax have a greater influence according to Renner *et al.* (2013). In contrast, in the following *vista space* we only use pictorial depth-cues like relative size or occlusion (Renner *et al.*, 2013).
Unfortunately there are some technical limitations in HMDs, which affect the visual perception. Several studies, summarized by Renner *et al.* (2013), have shown a significant underestimation of distances in virtual environments up to 25%. In the real world, humans can estimate egocentric distances quite exact. Witmer and Sadowski (1998) mentions only 8% underestimation evaluated by a blind walking test in an real environment. Possible reasons mentioned by Renner *et al.* (2013) are the HMD weight in combination with a limited Field of View. Furthermore disparity has an influence on distance perception of objects in close surroundings (Renner *et al.*, 2013).
Few contributions from literature address the influence of the interpupillary distance (IPD) on the disparity and therefore on the distance estimation. According to Bruder *et al.* (2012) and Renner *et al.* (2015) distances are underestimated, the greater the IPD is set. Nevertheless they disregard the IPD decrease induced by convergence.

2.3.2 Realistic interaction

Since interaction covers a large area, we want to differentiate in *selection/manipulation*, *navigation* and *system control* as introduced by Bowman *et al.* (2001). Users can select and manipulate objects. They can navigate in the virtual environment by changing their position and viewing direction. Furthermore, the third component, system control which means interaction with the VR system like loading or saving, will not be considered here.

Realistic manipulation

At the moment there is no predominant interaction interface in VR and AR environments that could be compared to the WIMP paradigm in setups with a conventional 2D desktop monitor, keyboard and computer mouse (Dörner *et al.*, 2014). In order to enable efficient and effective interaction in virtual environments, several approaches were developed. In the following, we want to discuss the drawbacks of the single hardware approaches with regard to natural real world-like finger interaction.
Since the approaches with gamepads and keyboards were not explicitly developed for VR / AR and do not adequately reflect the natural interaction, we will not consider them into more detail here.
Marker based 6 degrees of freedom hand controllers are state of the art at the moment and they offer powerful capability with excellent tracking quality. At the same time, however, they restrict the users, as they must hold a device in their hands all the time. Therefore, object grasping actions are carried out e.g. by pressing a trigger at the handheld controller and not, as in reality, by fine finger interaction directly with the object. (Jerald, 2016) Approaches where users wear tracked gloves open up the possibility of natural interaction with an object, but obviously restrict them because they have to wear the gloves permanently.
Systems for makerless optical hand tracking offer the great potential of being able to not restrict the user. In addition, the precision of the systems is adequate (Guna *et al.*, 2014). Optical tracking systems often face problems with occlusion. As soon as one or more fingers are not visible to the sensors, the pose of the fingers cannot be determined and the system estimates the location according to probabilities.
Furthermore, the interaction with objects in reality depends strongly on haptic perception. To enable fine interactions, it is crucial to provide realistic haptic feedback. Several researchers developed haptic gloves with the aim of correctly addressing human haptic perception (Blake and Gurocak, 2009). Obviously, the weight and the outer dimensions will have an impact onto the usability of the haptic devices. Carter *et al.* (2013) project ultrasound onto users hands to provide haptic feedback.

Realistic navigation

Langbehn and Steinicke (2018) call locomotion an important method of interaction in VR allowing a more realistic feeling of the virtual world and reducing VR sickness. Unfortunately, real walking quickly reaches the limits of the VR tracking area and therefore isn't feasible for large virtual environments (Langbehn and Steinicke, 2018). To overcome this issue, different researchers present several approaches. Treadmill systems as presented by Feasel *et al.* (2011) have the potential to allow realistic movements in limited spaces. Unfortunately they are quite expensive and inconvenient (Langbehn and Steinicke, 2018). Another attempt is to allow for gesture based movement through, for example, classical controllers, walking in space or arm-swing (Wilson *et al.*, 2016). In this methods there is still a lack of balance information and therefore it can still cause cybersickness. Langbehn *et al.* (2017) try to redirect the users movement to fit large environments into smaller tracking areas. Benefit of this method in comparison to the other ones, is it's multi-user potential and the presence of correct walking cues to our sense of balance.

2.3.3 Cyber-sickness

Cybersickness is defined by Nesbitt and Nalivaiko (2018) as an uncomfortable side effect during the use of virtual environments. It can cause symptoms like headaches, eye-strain, nausea or disorientation. One possible reason is the mismatch between visual motion cues and motion cues send by the human sense of balance, as it occurs when users are moved in virtual scenes while they keep sitting on a chair. Additional frequent occurrence of false visual-clues can encourage appearance of cybersickness symptoms. Nesbitt and Nalivaiko (2018) gives an overview of various influencing factors.

3 REQUIREMENTS FOR REALISTIC PERCEPTION IN HMDS

Based on the previous chapter, for realistic perception the prerequisites shown in 1 can be derived. For a holistic perception audio and smell would be additionally necessary.
We now want to present approaches to achieve a realistic visual perception and interaction in virtual worlds.

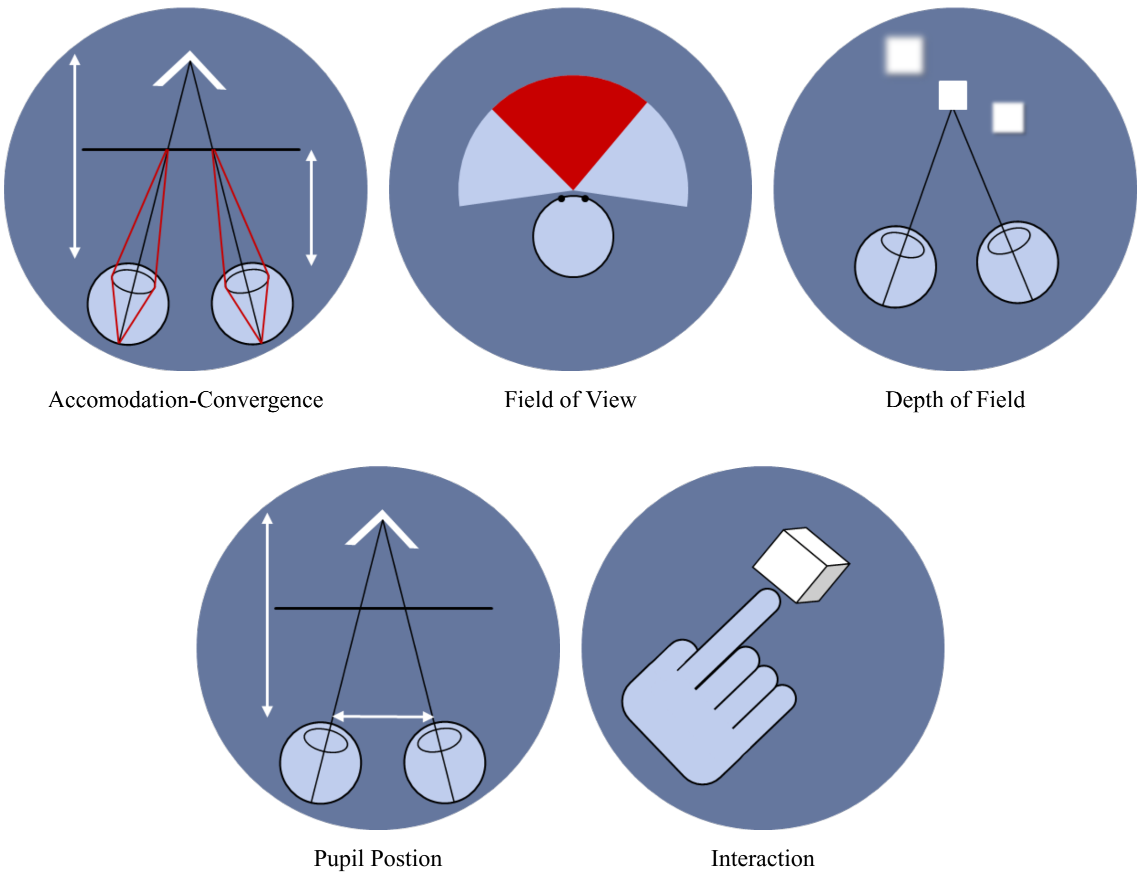

Figure 1. Requirements for realistic perception

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3.1 Visual perception

As mentioned before, humans handle various cues to esteem sizes and distances. Unfortunately, we could notice contradictory depth cues in virtual reality and as a consequence there are several problems with size and distance estimations. Additionally those fighting cues can lead to a feeling of not being fully immersed. Fortunately, literature presents several approaches to overcome those issues.

3.1.1 IPD and pupil position

In VR systems, the image computation for the two eyes is done with two virtual cameras. The initial position of those is determined using the interpupillary distance (IPD) set in the HMD. If the IPD is set incorrectly, perception errors occur. Therefore the IPD has to be measured and set correctly, which could be done by integrated eye tracking systems. Pupil movements induce changes from the default camera separation and must be taken into account as well as the change in viewing direction of the individual eye. Furthermore lens distortions vary at different pupil positions.

3.1.2 Field of view

Humans can cover a Field of View (FOV) of about 190° to 290° (Howard and Rogers, 1996). In current HMDs the maximal FOV is much smaller up to 110° at todays high-end devices. Consequently the users immersion sinks, because users observe black areas at the margin of their FOV. To achieve a natural FOV, larger displays are necessary. Nevertheless, enlarging the display dimensions leads to a lowering of the pixel density and therefore the users can differentiate single pixels. Therefore, the use of displays which have both, greater absolute dimensions and a higher pixel density is essential.

3.1.3 Convergence accommodation conflict

Another problem with HMDs is the lack of accommodation-convergence dependency. When focusing on a near object, the eyes converge inward, while the ciliary muscles deform the lens so that the fovea receives a sharp image of the focused object. Consequently accommodation and convergence are normally linked by a dependency. Since the screen in a direct-view HMD has a fixed distance to the pupil and the various objects are not at different distances from the eye as in a real scene, the accommodation-convergence dependency is distracted. This can lead to incorrect depth perception.

3.1.4 Depth of field

As described above, muscles deform the lens so that the object in focus appears sharp. Objects with diverging distances from the viewer appear blurred. This effect is called Depth of Field (Mauderer *et al.*, 2014). If we want to gain realistic visual perception in VR, we have to take into account the Depth of Field effect. We can only see the object we focus sharp while all others are blurry. According to Moehring *et al.* (2009) fixed focus Depth of Field is not accepted by users. We need to use eye tracking to evaluate the exact actual focus point and the right focus plane for correct Depth of Field. Therefore we need a high precision and low latency tracking system which is not perceived by the user.

3.1.5 Self representation

To archive higher degrees of immersion and a realistic distance estimation it is mandatory to have a full virtual body representation (Mohler and Creem-Regehr, 2010). In order to achieve the greatest possible self-representation we must meet some requirements.

The virtual body has to be an exact equivalent to the users real body, this can be done using a high precision 3D scan. Additionally the virtual bodys movements should be done with a high precision markerless tracking system. Obstruction of the user by additional equipment must be avoided.

3.2 Realistic interaction

In the following we will use the term realistic interaction to describe the interaction with a real object using the hands, like grasping a water bottle and unscrewing the lid. To achieve realistic interaction, several requirements must be met.

The finger tracking must have high precision and low latency. In addition, to correctly address the kinesthetic perception, the spatial calibration between visualization and hand tracking device must be accurate. Tracking lags, that may occur through occlusions in optical markerless hand tracking must

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be avoided. The user should not be restricted by wearing any devices. As described above, addressing haptic perception is crucial for fine natural interaction with virtual objects. In addition, the behavior of the virtual objects should be as expected by the user. This relates to the friction between two objects or of deformable objects, but also to the simulation of liquids.

4 APPROACHES TO ADDRESS REALISTIC VISUAL PERCEPTION

The literature shows some approaches to deal with the previously presented issues to meet the requirements for realistic perception. In the following, we present the most promising concepts to deal with visual imperfections.

4.1 Interpupillary distance and pupil position

Few contributions from the literature deal with interpupillary distance (IPD), which has an influence on disparity. Bruder *et al.* (2012) conducted a study in which the observed objects had distances between 4 and 8 m from the participant. One result is that the greater the IPD is set, the closer the subjects perceive the objects in the HMD. Also Utsumi *et al.* (1994) show this dependency in an early publication. Renner *et al.* (2015) investigate the influence of IPD deviations (70%, 100% and 130% of the measured IPD) on the observation of objects at a distance between 25 and 35 cm in a CAVE. In accordance with previous sources, the measured distance values are below the expected values. What is not taken into account when calculating the expected values of Renner *et al.* (2015), however, is the reduction in IPD due to eye convergence. Position and orientation of the virtual cameras are estimated only by the position of the head. Since pupils are moving relative to the head, this simplification causes discrepancies which leads to misperceptions. To achieve a visually correct display, virtual camera and pupil need to have the same position. Beside convergence, small differences between the distance of the virtual cameras and the interpupillary distance results in great changes in distance estimation (Dörner *et al.*, 2014). A similar aspect is the adjustment of the pre-distorted image in accordance with the pupil position. To be able to compute correct pre-distortions we need to know optical specifications of the used VR-System and the relative positions of pupils, optics and displays (Robinett and Rolland, 1991).

4.2 Field of view

Several papers (Bruder *et al.*, 2012; Kellner *et al.*, 2012) try to correct the underestimation of distances mentioned above by adjusting the Field of View (FOV) in HMD. In order to obtain a correct optical perception, the geometric Field of View (GFOV), i.e. the horizontal and vertical angle of view of the virtual camera, must be precisely matched to the data and the relative distances of the screen, lenses and pupils. Inadequate alignment results in distorted perception of size and distance.

4.3 Accommodation-convergence conflict

In order to avoid distortions of spatial perception by the disturbed accommodation convergence dependency, there is an approach to simulate the Depth of Field by adjustments of the graphical calculation (Carnegie and Rhee, 2015; Mohler and Creem-Regehr, 2010). Eye tracking methods are mostly used to blur objects of the virtual scene that have a different distance to the focus point. These publications examine the effects of the Depth of Field adjustment and may show an influence on the perception of the relative spatial positions of objects (Hillaire *et al.*, 2008; Mauderer *et al.*, 2014) and the preference of DOF visualization over conventional visualization (Hillaire *et al.*, 2008; Mantiuk *et al.*, 2011). However, none of the above publications empirically demonstrate the influence of the Depth of Field effect on distance perception through measurements. Hillaire *et al.* (2007) try to solve the accommodation-convergence-conflict on the software side in addition to the DOF-effect by blurring the objects outside the focus point, no matter how far away they are from the viewer.

4.4 Addressing visual perception issues

As shown, there exist several approaches to enhance visual perception in VR. In the following we would like to discuss the different approaches to gather a realistic visual perception. Although Bruder *et al.* (2012) has shown a significant effect of the FOV on distance estimations, the subjective variation of the Field of View is not considered to be effective. In order to solve the accommodation-convergence

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conflict, there is the need of new display technology. As soon as displays have several focal planes, we are able to send different accommodation cues dependent on the object distance. Until those inventions are available, the effect can be attenuated but not removed by depth-of-field effects. Perception error due to deviation of real pupil and virtual camera position are considered critical and need to be taken into account in more detail. In this context it is necessary to find a method to represent lens distortions according to different pupil positions.

5 FUTURE POTENTIALS FOR THE USE OF VIRTUAL REALITY IN THE PRODUCT DEVELOPMENT PROCESS

In the following we want to identify the future potentials of use-cases presented in section 2.1. Intuitive virtual assembly increases efficiency in the product development process and can reduce time and cost effort. Furthermore, an intuitive user interface can facilitate creativity, since there is no need to think about the correct interaction steps. To achieve this, we need appropriate input devices. Some of these are already available, others are expected to become available in the coming years. Key factors to exploit the potential of VR in ergonomics and to replace real prototypes with virtual ones, are realistic perception and haptic feedback. Visual perception and display technology are part of current research, so there is a presumption that the problems with visual perception mentioned above will soon be solved. Unfortunately, from our point of view it will last about five to ten years until we can use consumer-ready haptic hands. With realistic representation available, decision makers can rely on the virtual model and can make choices without physical models, leading to time and cost savings. Joint design reviews with locally separated development teams may be held from the individual employee’s desk without the need traveling to a common place. In training, we see the potential to repeat several scenarios as often as desired. Some eventualities may only be trained in VR because of the impossibility to carry them out in reality or the need of a vast amount of resources, e.g. emergencies at a nuclear power plant. The playful access to emergency training can furthermore motivate employee’s to execute those tasks. A picture is worth a thousand words, a VR representation is worth a thousand pictures. Summarizing, VR provides an easy access to technical issues for several specialist disciplines involved in the product development process and therefore increases the overall efficiency of the whole process.

6 CONCLUSION AND FUTURE WORK

Virtual reality offers many new possibilities in the product development process. Thus, in the context of *responsibility for our future design methods*, it is possible to save resources for physical mock-ups. Nevertheless, there are many challenges to be solved in order to be able to use VR productively and to achieve a fully immersive user experience.

In this contribution, we first illustrate the use cases of VR in the product development process. In addition, we show which hardware is currently available for professional use and which problems exist with regard to visual perception and interaction. Derived from the depiction of a perfect virtual reality, we define the requirements to address visual perception and interaction. Subsequently we discuss approaches to solve the issues with visual perception and evaluate their suitability.

Further research will primarily address the calculation of the visualization to fit the current pupil positions. Therefore, not only the pupil positions but also the lens distortion that depends on viewing direction has to be taken in to account. Additionally the influence of Depth of Field effects onto depth perception and the user acceptance have to be evaluated.

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