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Live Delivery of Neurosurgical Operating Theatre Experience in Virtual Reality

Marja Salmimaa*, Jyrki Kimmel*, Tero Jokela*, Peter Eskolin*,
Toni Järvenpää*, Petri Piippo*, Kiti Müller**, Jarno Satopää***
***Nokia Technologies, Tampere, Finland**
****Nokia Bell Labs, Espoo, Finland**
*****Department of Neurosurgery, Helsinki University Hospital and University of Helsinki, Finland**

Abstract
A system for assisting in microneurosurgical training and for delivering a live surgical experience was developed and experimented in hospital premises. An interactive neurosurgery experience from the operation theatre was presented together with associated medical content on virtual reality eyewear of remote users. Details of the 360-degree capture, signal delivery, and display systems are presented, and the presence experience and the visual quality questionnaire results are discussed.

Author Keywords
Virtual reality; 360-degree camera; Stereoscopic VR; Neurosurgery.

1. Introduction
Virtual reality (VR) imaging systems have been developed in the last few years with great professional and consumer interest [1]. These capture devices have either two or a few more lenses for consumer use, providing only a monoscopic view, or for instance eight or more cameras to image the surrounding environment in stereoscopic, three-dimensional (3-D) fashion. The user is then dependent on various display media to view the content. These include computer monitors, where the full 360-degree field is visualized by mouse and keypad gestures; mobile phones, where the imagery is rendered by the user turning the device itself toward the desired direction of the view; or by dedicated eyewear that is able to render the 360-degree visual field in its entirety by the user wearing the eyewear while turning his or her head in the desired direction. Especially the latter way of visualization has gained popularity in the last few years, and dedicated VR eyewear is available from many vendors. This eyewear either utilizes its own display [2], or it can utilize a smartphone display [3].

In addition to pure entertainment, the eyewear and associated VR imagery can be utilized in professional use, such as training and education [4]. Especially for those use cases, delivering a sufficient quality VR experience is important yet challenging as VR systems introduce various features potentially affecting the visual experience and the perceived quality of the content. For instance, the displayed content can either be synthetic or captured using ordinary or 360-degree camera systems (or a combination). In addition, the visual display of the VR environment can consist of either 2-D (monoscopic) or 3-D (stereoscopic) images (or a combination). Typically the user can observe only a limited field-of-view (FOV) at once, and when the viewer rotates his or her head, the system responds to that by rendering the content accordingly. Furthermore with streamed VR content, inefficiencies or limitations of the streaming systems may have some influence on the viewing experience.

Perceptual dimensions affecting the quality of experience can be categorized into primary dimensions such as picture quality, depth quality, and visual comfort, and into additional ones, which include *e.g.* naturalness and sense of presence [5]. Especially with stereoscopic systems, many of these dimensions are affected by the sensation of depth in the content, and thus the proper reproduction of depth can be considered as one of the most important aspects for the user experience.

Stereoscopic 3-D images can be perceived to some extent sharper [6], and can potentially provide better image quality than conventional 2-D images [7]. However disparity as such does not automatically lead to superior user experience, as stereoscopic or other image artefacts may have some implications to how users perceive or rate the quality. For instance, binocular image asymmetries may reduce the visual comfort [7, 8] and depending on the content (composition of the images), viewers may actually prefer non-stereoscopic versions.

A number of studies have shown that stereoscopic 3-D images have a greater psychological impact, *e.g.* they enhance the viewers' sense of presence (provided that the depth magnitude is natural) [9]. Several other factors may contribute to the feeling of being present as well, *e.g.* interactivity and the control over the task, multimodality in the presented content, if the user is able to modify objects in the virtual reality environment, the meaningfulness of the experience, and the realism and the consistency of the information [10, 11, 12].

Figure 1. Partial view of an interactive neurosurgery experience from the operating theatre.

Virtual reality technologies are emerging in the medical field in many areas, such as in VR therapy, planning of surgical procedures, and in many training applications [13]. One of the emerging use cases for VR eyewear is, indeed, training in the medical field, such as in surgery, which is expected to grow to the second-largest market position in medical and healthcare VR, only after therapeutic applications [13].

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This paper describes a VR imaging system and its use in live delivery of stereoscopic 360-degree scenery from an operating theatre to multiple users wearing VR gear. More precisely, the displayed content was a combination of the captured live 3-D 360-degree video combined with 2-D still images and live streamed 2-D video contents, see Figure 1.

The demonstration took place in June 2017 at the Helsinki University Hospital (HUH), where The 17th Helsinki Live Demonstration Course in Operative Microneurosurgery was concurrently organized [14].

A Nokia OZO camera [1] was placed in an operating theatre, the feed was transmitted to a server where the image stitching was performed in real time, and the imagery was delivered to a PC-based system with Oculus Rift eyewear, embedded with an interactive feed of the surgeon's microscope view. As far as we are aware, this was the first time an interactive live feed from the neurosurgeon's microscope camera was included in the VR view. A system description is given, followed by a discussion on the user experience questionnaire that the participants were kind to fill in and return.

2. Stereoscopic 360-degree VR delivery system

The system for 360-degree virtual reality delivery was built in the premises of the HUH neurosurgery department, see Figure 2.

Imaging subsystem: Nokia OZO camera was used for capturing a general stereoscopic 360-degree view of the operating theatre. The main properties of the OZO camera are summarized in Table 1.

In addition to VR view generated by the OZO camera, other cameras integrated into the medical equipment of the operating theatre were used for augmenting the VR scene. These included a camera providing the "lamp" view that renders a wide perspective image of the operating field, the "microscope" camera that captures the surgeon's view through the operating microscope (the main view in microsurgical operations), and the "endoscope" camera used instead of the microscope for some operations. Operating theatre personnel could select which of these cameras were streaming to our system and more importantly, to the multiple display screens in the operating theatre.

Table 1. Basic properties of the OZO camera [1].

Property	Value	Unit/Note
Number of sensors	8	Progressive scan global shutter
Sensor resolution	2048x2048	Pixels
Lens FOV	195	Degrees
Lens aperture	f/2.4	
Angular resolution	6	' (Minute of arc)
Speed	30	frames per second
Diameter	16.9	cm

Image transmission subsystem: The OZO camera was placed in the operating theatre close to the patient. Its image was sent as a 3G-SDI signal over an optical cable to a remote live video stitching server outside the operating theatre. The video stitching server combined in real time the separate video streams captured by the OZO camera sensors to produce a single 360-degree panorama stereo video stream. The stitching server was configured to send the resulting video as a RTMP stream over a local TCP/IP network to the streaming server. A NGINX server with the NGINX-RTMP module was used as the streaming server. The server converted the RTMP stream to the MPEG-DASH format used by the developed player application and forwarded the stream to all playback devices.

Video streams from the lamp/microscope/endoscope cameras were streamed using another NGINX server. This server also had the HTTP module installed. It was used to provide medical imaging data and other 2-D images to the player application. The same server also managed the configuration files for the player applications. All servers were accessible both from the operating theatre and from the demonstration area that was more than 100 m away. All traffic was delivered over a dedicated TCP/IP network that was separated from the main hospital intranet and the public Internet due to security reasons. Two sets of PCs with Oculus Rift eyewear were used to run the player application and to show a live augmented virtual reality view of the operating theatre.

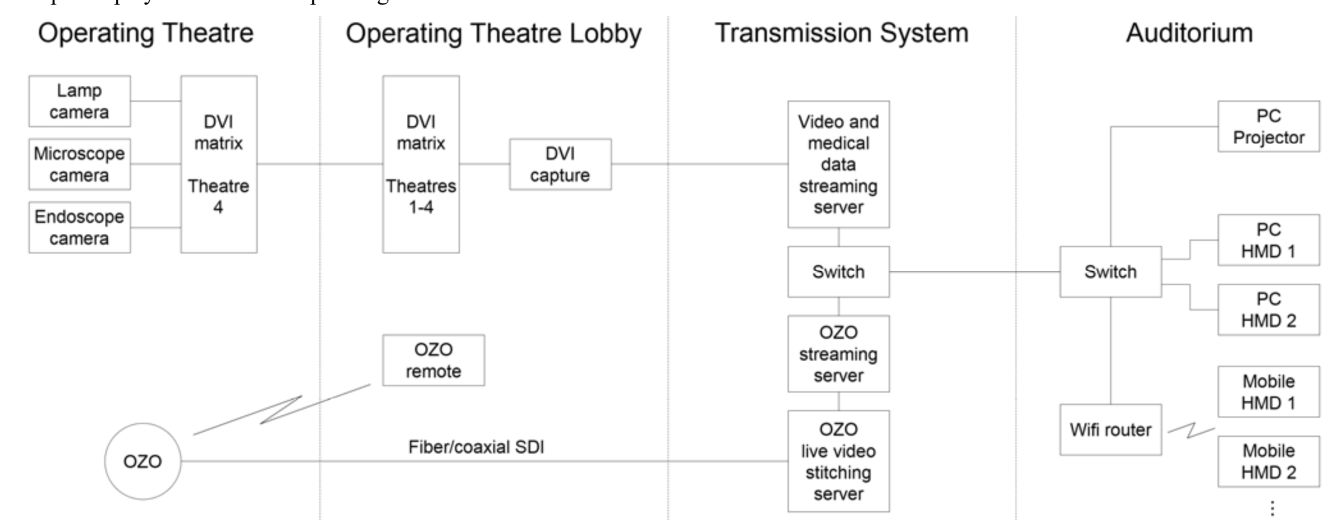

Figure 2. Block diagram of the image delivery setup for the augmented VR demonstration.

Player software and display subsystem: A dedicated player application was developed with a support for different VR displays. The player was implemented using the Unity 3D game engine. This game engine was chosen because it supports the Nokia OZO player SDK that was used for rendering the VR background video. It also has a built-in extendable system allowing users to interact with augmented objects in the VR scene. Further, the game engine allows targeting several virtual reality platforms with minor or no code changes.

We prepared a player with basic 360-degree viewing capability for the mobile Samsung Gear VR devices. This setup was used for making participants familiar with the concept of live-streamed VR video. The main player application with more features was however run on PC-based hardware with Oculus Rift VR goggles and hand-held Touch controllers. On top of the VR video, a selection of augmented visual elements could be displayed, including images, image stacks, and video streams. Medical imaging data of the patients and other 2-D still images were drawn to simple 3-D image planes using standard billboarding technique. Billboards with movie textures were used for embedding the lamp/microscope/endoscope camera streams to the VR scene. Player application read a configuration file from the server that defined the image files and video streams, as well as their initial spatial locations in the scene.

For interaction, scaling and positioning of image and video billboards was supported. The billboard size was scaled instead of moving the billboard plane in depth dimension because of the possible convergence issues that could make the viewing experience uncomfortable. The user could select any of the floating billboard objects with the controller and freely change its size and position. For image stacks, browsing the images with left/right keys of the controller was also supported.

Figure 1 illustrates the VR player view on the Oculus Rift display. The observable field-of-view of the Rift depends on the user. The close to rectangular left and right display areas do cover diagonally an angular field of almost 110 degrees, binocular coverage being slightly less. However due to the very limited exit pupil of the optics, as is common with most VR displays, edges of the field-of-view get blocked. Depending on the distance between the eyes and the optics, users can typically observe a round angular field of around 80-90 degrees. The floating image and video objects supported viewing of high-resolution content (e.g. 1080p) and their sizes were adjustable by the user to even fill the whole viewport, though initially their angular sizes were set to cover around 20-30 degrees.

Experimental setup and participants: The participants in the experiment were received in a small conference room and assisted to put on the eyewear (Figure 3). The viewing device was the Oculus Rift eyewear, equipped with a handheld controller. The participants were instructed to turn around and explore the environment. They were also instructed to use the Oculus controller device that was operated by the user wearing the device in their right hand. With this pointer, it was possible to move and resize the augmented content, as the user wished. After viewing the interactive real-time neurosurgery experience, the participants were asked to fill in a questionnaire regarding the experience.

Altogether 22 neurosurgeons (17 male, 5 female) completed the questionnaires fully and provided their opinions on the experience. The participants represented different nationalities from around the world.

Figure 3. Participants using the system delivering a live interactive neurosurgery experience.

The mean age of the participants was 39 years and they had on the average 9 years' experience in neurosurgery. All had normal vision or corrected to normal vision (eyeglasses or contact lenses).

3. Results

The participants evaluated the image quality, perceived depth, naturalness and overall viewing experience on a seven step scale from excellent to bad, see Figure 4 for the results.

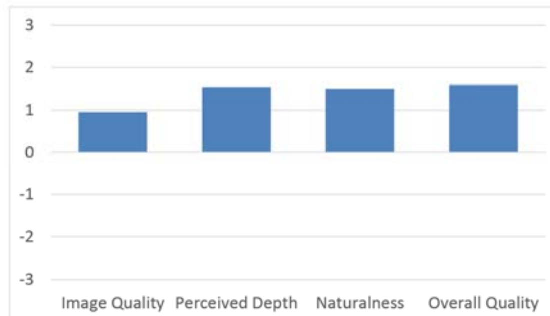

Figure 4. Mean opinion scores for image quality, perceived depth, naturalness, and overall quality.

In general it seems that the participants evaluated the quality of experience positively, as all the measured perceptual dimensions were rated clearly positive. The mean opinion scores and the standard deviations for the Image Quality and the Perceived depth were 0.95 (1.13) and 1.55 (0.96), respectively, and for Naturalness and Overall Quality 1.50 (0.91) and 1.59 (1.14) respectively.

The results of the evaluations of the Colors, Contrast, Sharpness and Distortions can be seen in the Figure 5. The mean opinion scores and the standard deviations for the Colors of the VR view and the Close-Up view were 1.50 (0.96) and 1.63 (0.95), respectively. The mean opinion scores and the standard deviations for the Contrast of the VR view and the Close-Up view were 1.40 (0.95) and 1.59 (0.91), respectively. The mean opinion scores and the standard deviations for the Sharpness of the VR view and the Close-Up view were 0.55 (1.30) and 1.27 (1.12), respectively. And finally for the Distortions the mean opinion scores and the standard deviations for the VR view and the Close-Up view were 0.72 (1.45) and 1.13 (1.32), respectively.

Comparison of the Sharpness and the Distortion scores seem to indicate that in these dimensions the Close-Up view (augmented objects) were evaluated better. However, because of the nature of the data and the experimental setup comparative statistical tests were not used in the analysis.

Figure 5. Mean opinion scores for the colors, contrast, sharpness and distortions evaluations for the VR View and the Close-Up View.

In addition to the opinions on the visual experience, the sense of presence was measured by using IPQ, igroup Presence questionnaire [15]. The results of the IPQ are reported in the Figure 6.

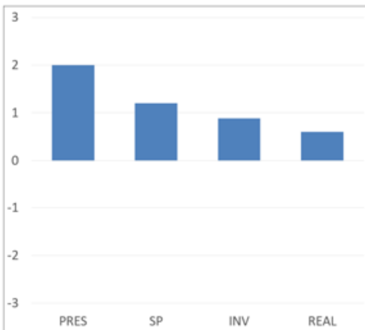

Figure 6. Results of the igroup Presence Questionnaire. PRES = General presence, SP = Spatial presence, INV = Involvement, REAL = Experienced realism.

The mean opinion scores and the standard deviations were as follows: General presence 2 (0.81), Spatial presence 1.2 (1.07), Involvement 0.88 (1.31), Experienced realism 0.60 (1.04). Based on the IPQ results the participants clearly experienced sense of being present in the operating theatre.

4. Discussion

For the first time, participants in the Helsinki University Hospital Live course were able to interactively and remotely participate in the neurosurgery demonstrations. The difficulty in the course so far has been that only 5-6 course participants can attend the surgery in the operating theatre itself, and the rest of the participants must view the operation from flat screens on a lecture area. In principle using this developed new setup, the neurosurgery operation could be broadcast worldwide without sacrificing the quality. The participants evaluated the experience as positive, as the questionnaire summary shows. The authors see great value in developing the technology further.

5. Impact

For the first time, a live stereoscopic 360-degree camera view was augmented by a live video feed from a neurosurgery microscope camera as well as with auxiliary medical image data with a means for the user to interactively resize and reposition the augmented images. The demonstrated system can be utilized in many fields of remote presence participation, medical surgery training being only a prime example of the capabilities.

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7. References

[1] J. Kimmel, A. Baldwin, and V. Rantanen, "Optics for Virtual Reality Applications," Proc. European Optical Society Annual Meeting (EOSAM 2016), 82-83 (2016).

[2] Oculus Rift https://www.oculus.com/rift/

[3] Samsung Gear VR http://www.samsung.com/global/galaxy/gear-vr/

[4] Y. Pulijala, M. Ma, A. Ayoub, "VR Surgery: Interactive Virtual Reality Application for Training Oral and Maxillofacial Surgeons using Oculus Rift and Leap Motion," In: Ma M., Oikonomou A. (eds) Serious Games and Edutainment Applications. Springer, Cham (2017).

[5] Subjective methods for the assessment of stereoscopic 3DTV systems, ITU-R Recommendation BT.2021 (2012).

[6] M. Emoto and T. Mitsuhashi, "Perception of edge sharpness in three-dimensional images," Proc. SPIE **2411**, 250 (1995).

[7] F. Kooi, A. Toet, "Visual Comfort of Binocular and 3D Displays," Displays 25, 99-108 (2004).

[8] H. Self, "Optical tolerances for alignment and image differences for binocular helmet-mounted displays," Technical Report AAMRL-TR-86-019, Harry G. Armstrong Aerospace Medical Research Lab, Wright-Patterson AFB, USA (1986).

[9] W. IJsselsteijn, H. de Ridder, R. Hamberg, D. Bouwhuis, and J. Freeman, "Perceived depth and the feeling of presence in 3DTV," Displays, **18(4)** 207-214 (1998).

[10] B. Witmer and M. Singer, "Measuring presence in virtual environment: a presence questionnaire," Presence: Teleoperators and Virtual Environments **7(3)** 225–240 (1998).

[11] T.B. Sheridan, "Musings on Telepresence and Virtual Presence," Presence: Teleoperators and Virtual Environments **1(1)** 120–126 (1992).

[12] M. Lombard and T. Ditton, "At the heart of it all: The concept of presence," Journal of Computer-Mediated Communication **3(2)**, 20 (1997).

[13] "Virtual reality in medicine and healthcare," Market report, ABI research (2017).

[14] The 17th Helsinki Live Demonstration Course in Operative Microneurosurgery https://finland.aesculap-academy.com/go/?action=AkadEventData&event_id=145706&evdate=145713

[15] T. Schubert, F. Friedmann, and H. Regenbrecht, "The experience of presence: Factor analytic insights," Presence: Teleoperators and Virtual Environments **10(3)**, 266-281 (2001).