A Question of Time:
Importance and Possibilities of High Refresh-rates

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***Abstract*—This work will discuss shortcomings of traditional rendering techniques on today's wide-spread LCD screens. The main observation is that 3D renderings often appear blurred when observed on such a display. Although this might seem to be a shortcoming of the hardware, such blur is actually a consequence of the human visual system perceiving such displays. In this work, we introduce a perception-aware rendering technique that is of very low cost, but significantly improves performance, as well as quality. Especially in conjunction with more recent devices, initially conceived for 3D shutter glasses, our approach achieves significant gains. Besides quality, we show that such approaches even improve task-performance which makes it a crucial component for future interactive applications.**

***Index Terms*—Temporal upsampling, Hold-type Effect, High Refresh-rate Displays, Stereo Vision.**

I. INTRODUCTION

LCD displays have seen a tremendous development and off-the-shelf screens are constantly improving in brightness, contrast and resolution as well as size. The quality of new devices reached a level where further improvements can only be achieved by taking the human visual system (HVS) into account.

The resolution of the displays increase which makes viewers move closer to their devices to fully enjoy image details. The resulting enlarged field of view has an impact on angular velocities which directly influences the perceived blur of moving objects.

This effect can be explained as follows: The HVS is tuned to stabilize moving objects which is achieved by so-called *smooth pursuit eye motion* that tracks moving objects. Most modern displays (so-called *hold-type* displays) present the moving objects in discrete positions, while they are continuously tracked by our eyes. This discrepancy leads to the perceived blur.

The easiest way of reducing blur is to shorten the time duration of each frame. This requires higher frame-rate, which is an expensive solution in terms of rendering. This is the context investigated in this work. We propose a temporal upsampling scheme that was recently published [1]. It is particularly well suited for 3D content and we show that such solution reduces the *hold-type* blur significantly.

II. PERCEPTION OF BLUR ON DISPLAYS

Image sharpness is an important factor which decides on the perceived image quality [2]. Several studies [3], [4] indicate that people prefer sharp images. Thus an additional blur introduced in an image is usually perceived as an artifact. In our work we focus on a blur which is due to the technical limitations of today's predominant hold-type displays (e. g. liquid crystal displays (LCD)). Such devices expose two kinds of blur: *response time* blur and *hold-type* blur [5].

Response time blur is caused by the fact that the display needs a non-zero amount of time to switch between two levels of intensity. However, it was shown by Pan et. al. [5] that even for slow 16 ms displays, only 30 % of the perceived blur is due to the response time. For modern displays with response time below 5 ms this factor becomes negligible.

Hold-type blur is a purely perceptual effect that arise from misalignment between smooth-pursuit eye motion and the discrete nature of displays which hold a static image fixed for an extended period of time. The effect can be seen as inverse of motion blur: In motion blur, objects move while the eye remains fixed, leading to blur. In case of hold-type blur the eye moves while the image is kept fixed. This phenomena can be modeled as a convolution with a box filter oriented in the motion direction, having a size proportional to the distance traversed by the eye in one frame. At this point it becomes clear why a shorter frame duration reduces the blur.

III. PREVIOUS WORK

There are many solutions to decrease the frame duration and the main question is what information to display in the additional frames.

The simplest solution is *black data insertion* (BDI). The additional frame (so-called *in-between frames* are black frames that are interleaved with original frames. A more sophisticated version of this method is *backlight flashing* (BF) [5], [6]. In this solution, instead of interleaving the original signal with black frames, the backlight of the display is used to limit the duration time of each frame. Even though such solution are commonly used in off-the-shelf displays, the results are limited by possible artifacts such as flickering, brightness reduction or color desaturation. Another possible solution is to increase frame-rate by adding blurred copies of original frames [7]. Although such approaches reduce blur of sharp edges, they produce visible ghosting because no motion compensation is performed.

Nowadays, the commonly used solution in TV-sets is *frame rate doubling by interpolation* (FRT) [8], where additional frames are created by interpolation between original frames, based on computed optical flow. Such solutions give good results in many cases. However, they introduce lag of one frame and they are limited by the quality of the underlying optical flow which is a difficult problem and requires a lot of computational power. Also, overly simple motion flow leads to perceivable artifacts in complex scenes.

In 3D rendering, the problem of displaying more frames is related to morphing, a classic computer graphics problem [9]. There are many approaches trying to solve this problem [10], [11], [12]. One disadvantage of those methods is that all of them produce lag, which might be an issue for reactivity. Another problem is that they are expensive in term of computation, which makes them unsuitable for real-time application.

IV. OUR APPROACH

To reduce hold-type blur we propose a new upsampling method which draws advantage from available 3D information. We make the process of in-between-frame rendering very fast by extrapolating one or more frames via motion flow. Further, we blur the warped frame in required places to remove possible artifacts [7]. The loss of high frequency is compensated in original frames what allows our method to produce plausible results efficiently.

Motion flow: In contrast to motion flow used in TV-sets, we can compute accurate motion flow using the 3D information of the scene. Basically, we simply take the movement vector of each vertex and output the color coded displacement in a buffer by rendering the scene.

Morphing: We then use this input to warp the current in a new in-between frame. To make our solution efficient we deform the current view via an overlayed grid deformation. Nevertheless, such 2D warping strategies might map pixels to the same location. We resolve these ambiguities by using the depth information of the scene. Another problem are edges, which might be shifted due the deformation. To prevent such situation, we snap grid vertices to discontinuities (i.e. optical flow) and assure that edge positions are preserved.

Blur: Even though our method can handle new occlusions as well as preserve edges in correct locations, the problem of disocclusion is still challenging. In such areas some high frequency artifacts can be visible.

Fortunately, we can exploit the fact that blurred in-between frames are integrated easily by the visual system when the frame rate is high enough and no flickering is perceived. Basically, the observer only perceives the entire sequence as slightly blurrier. We compensate for this loss of high frequency by adding high frequencies to the original frame (which cannot contain any artifacts). Consequently, the resulting sequence appears sharp, but problems in in-between frames are hidden. We found that such method is efficient and give plausible results. However, issues like gamma correction and clipping need to be handle carefully.

V. RESULTS

For efficiency, we relied on a GPU-implementation. We measured the performance on an 3.0 GHz Core 2 Duo CPU with NVIDIA GTX260 using 5 scenes which contain moderate geometric details, many occlusions and disocclusions as well as heterogeneous movements. On average our method needed 6ms to compute two in-between frames for a 1024x1024 resolution.

We conducted a user study to understand how our results (120Hz) compare to the original low (40Hz) and high (120Hz) frame-rates. Subjects were asked to judge the level of blur in scale from 1 to 9. An average score of low refresh-rate animation was 2.0, high refresh-rate 7.8 and our method 7.1. This shows that our method we can reduce hold-type blur significantly. We also asked people if any artifacts were apparent. Only visual artifacts of the original streams were reported and no shortcomings of our method were mentioned.

We finally demonstrated that our approach can improve task performance, by creating a game. The user has to differentiate a 3D model of a Landolt circle and from a closed circle. The object flies over the screen and the user was asked to press a key when the Landolt shape was perceived. Our method (120Hz) leads to significantly better scores than 40Hz or 60Hz. At the same time, in average, these scores also matched the original 120Hz scores.

VI. STEREO VISION

Another application of our work is the synthesis of stereo image pairs out of a single image, by warping from central view into the view of each eye [13], as illustrated in Fig. 1 within a few milliseconds. For simplicity we used anaglyph stereo, but other passive and active stereo techniques would work. 10 subjects in our study were shown a video and were then allowed to freely navigate in a virtual environment. They were asked to compare the synthesized stereo image with the ground truth rendered for two eyes. No subjects reported any perceived differences.

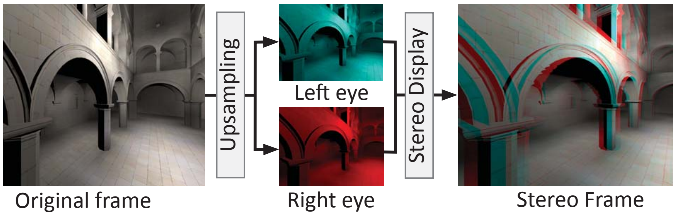

Fig. 1. Generating stereo frames using our upsampling.

ACKNOWLEDGMENT

We would like to thank Gernot Ziegler and David Luebke of NVIDIA corporation for providing us a Samsung SyncMaster 2233 RZ display as well as Matthias Ihrke for helpful comments on the design of our user study. This work was partially supported by the Cluster of Excellence MMCI (www.m2ci.org).

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