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Just Noticeable Difference of Dead Pixels in Monochrome Computer-Generated Holograms

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Abstract

Computer-generated holography (CGH) is a method for replicating scenes that incorporates depth, making them potentially much more realistic than traditional displays. Because CGH uses diffractive optics to generate scenes, holograms are also significantly more robust against dead pixels: while a single dead pixel is often noticeable in traditional displays, in holography much higher numbers are needed before a viewer realises the issue. This work is a pilot study to determine the Just Noticeable Difference of the number of dead pixels of a hologram, i.e., the minimum amount that need to be added before a viewer notices the difference. From these JNDs a quality ruler will be generated, which later work will use to compare the impact of other distortions on the perceived quality of a hologram. Results thus far suggest an addition of 4% dead pixels is required to notice a difference, which is significantly greater than the tolerance observed for traditional displays, where the fault class threshold is less than 0.05% [10].

1. Introduction

The greatest challenge facing Computer Generated Holography (CGH) is the high computational resource required to generate the holographic patterns, particularly when attempting to produce one without distortions [WDC*20]. There is currently little understanding of the relative impact of different distortions, making it difficult to prioritise limited resources [GFPP22]. This research is the first step in a collection of work that is designed to develop and utilise a quality ruler [KU03] to compare the perceived impact of different distortions.

This paper covers a pilot study carried out in preparation for a full user study to determine the Just Noticeable Difference (JND) of dead pixels in computer-generated holograms. These results can be used to quantify the tolerance of SLMs for holography and can be used to generate a quality ruler to compare the perceived impact of other holographic distortions.

1.1. Computer Generated Holography

A traditional display shows a single, final view of a scene, while a hologram replicates the behaviour of light originating from the scene . This is done by refracting the light, causing it to interfere constructively and destructively to generate a scene [SCS05]. Typically a Spatial Light Modulator (SLM) is used, a device that can manipulate light on a pixel-wise basis [Jul20]. As light consists of both amplitude and phase it would be ideal to manipulate both, however current devices are typically limited to one or the other.

Provided the light source is monochromatic, each of the reflected rays will have the same wavelength and will therefore interfere with each other constructively/destructively (based on their relative phases) [You32]. Therefore a scene can be simulated by calculating the required pattern on the SLM to generate that scene. One drawback of using monochromatic light is speckle noise, where any physical defects in the SLM will lead to scattering and will be observed in the replay as added noise [Goo07].

Typically the pattern on the SLM is referred to as the hologram/holographic pattern and the scene observed by the viewer is referred to as the replay. The scene generated by the hologram can only be viewed if the participant's eye is located in the region in 3D space where the light converges, referred to as the eyebox [CHB19]. For single colour scenes, green wavelengths are typically used due to the higher spectral sensitively of the human eye to these wavelengths.

When viewing a traditional display a user's eyes can only focus at a single depth, i.e. the distance between your eyes and the display. A common problem in trying to depict a 3D scene using conventional displays is Vergence Accommodation Conflict (VAC) [HGAB08]. Vergence is the angle between a person's eyes, which they brain can use to estimate the distance of an object as it will be greater for nearer objects and less for objects that are farther away. Accommodation refers to the focus of the eye, which is controlled by muscles in the eye.

Traditional displays can simulate the correct vergence of the eyes by providing a similar but slightly different view of the scene to each eye. There is however no way for these displays to make the human eye focus at a distance other than the actual distance between the user and the display [WRM95]. In CGH the depth focus of the scene can be controlled. This not only means that the eye focuses correctly, but also that a scene can contain elements set at different depths.

This paper focuses on far-field holography, where the eye is sufficiently far from the SLM for the hologram pattern to be approximated by the Fourier Transform of the image [BES20]. However, as SLMs are not able to manipulate both amplitude and phase, the replay of a hologram generated using the Fourier Transform is highly distorted [HSJ*21]. As such, algorithms that improve on the Fourier transform have been adopted to generate higher quality holograms.

One method for increasing the quality of a hologram is time multiplexing. Time multiplexing occurs when single frames of holograms are shown at a rate faster than the human brain can process. This results in the viewer's brain registering the frames as a single image, equivalent to the mean of the frames [SSMG20]. For holography this can be used to significantly reduce the observed noise in images. The limiting factor in this case is the frame rate of the SLM, with CABLE [Cab06] predicting that 250 frames would be required to produce an apparently noiseless hologram, requiring a display running at 15 kHz.

1.2. Dead Pixels

The term *dead pixel* refers to one or more pixels that are no longer functioning. For traditional displays a viewer is able to notice the impact of just a single dead pixel [Kim06] because every dead pixel corresponds to a distinct spatial region of the image. Alternatively, when using an SLM to generate far-field holographic replays the pixels are better thought of as a piece of information used to generate the entire replay.

Dead pixels on an SLM don't appear as missing image pixels, instead introducing noise and decreasing brightness of the overall replay [SCS05]. This means the impact of each dead pixel is less observable and holograms have a significantly higher tolerance to dead pixels than traditional displays. Furthermore holography is a computational display, meaning that it can be influenced by software as well as hardware. This means that if the location of the dead pixels of an SLM are known, the generated hologram pattern can accommodate for them and further increase the tolerance to this distortion.

1.3. Just Noticeable Difference

JND is the minimum amount of distortion that needs to be added to an image/hologram for that distortion to become noticeable to a viewer. The principle is to take advantage of the natural optimisation the human brain has developed to only register above a given threshold [LG21].

1.4. Contribution

To the authors' knowledge this would be the first published work on JND within CGH. The aim of this research is to determine the JND of dead pixels on an SLM used to generate monochromatic, single depth holograms. This work is also intended to be the first step in a series of work used to compare the perceived impact of different distortions on the quality of a hologram. The resulting JNDs will be used to generate a quality ruler, which itself would be used rate different distortions. Due to the high computation resources of CGH such understanding could be used to prioritise and potentially produce the highest-perceived-quality hologram for a given set of available resources.

Figure 1: *Image from which the distorted holograms were generated, selected from the Div2K dataset as the image with the greatest distribution of black pixels.*

2. Method

This section covers the methodology of the study. The subsections cover how the holograms were generated and the implementation of the user study itself.

2.1. Hologram Generation

This section describes how the holograms were generated. The subsections describe the methodology for generating the hologram, the hardware used to display it and the image from which the hologram was generated.

2.1.1. Algorithm

Due to the nature of the experimentation there is no need to produce the holograms in real time and therefore they can be pre-generated. The method used to generate them was an over-fitting function using the Adam optimiser [KB17] and Mean Squared Error (MSE) to determine the loss between the simulated replay and the original image. This was implemented using the PyTorch library, setting learning rate to 0.1 and running 500 epochs of iterations. Using these tools, an array of random phase could be iteratively fit to a hologram where the replay was a close match to the original image. By generating the replay for each frame of the hologram and generating an image from the mean of these frames, the effect of multiplexing could be simulated. As such, the multiplexing achieved from the generated frames should have had a greater noise reducing impact than frames that rely purely on different random phase. The biggest limitation of this method is that it relies on the simulated replay of the hologram, which will not be a truly accurate representation of what is seen when viewing the hologram.

2.1.2. Phase Light Modulator (PLM)

A PLM from Texas Instruments was chosen as the SLM for the setup. PLMs consist of an array of piston-controlled mirrors which can each be independently extended from the surface of the display. By changing the distance the light has to travel to each pixel the phase of each ray can be controlled.

The biggest advantage of this device over the most common Liquid Crystal On Silicon (LCOS) type device is a lack of cross-talk noise, which is where pixels are small enough such that the current applied to each pixels leaks to its neighbours. Another significant advantage is the increased frame-rate, with the PLM able to achieve 8 times the number of frames per second compared to typical LCoS devices. This allows for a significant reduction in observed noise due to the extra frames of time multiplexing available. As such, it was considered that the PLM had a significantly improved base image quality over a typical LCOS device and was most suited for these experiments.

2.1.3. Dead Pixels

The holograms were distorted to different levels by simulating the effect of having a given percentage of dead pixels. This was achieved by first generating the hologram and then setting the desired number of pixels to a set value. The aim was to simulate a pixel where the mirror is stuck at a given value and will always change the light at that location to the same value regardless of the value sent by the computer. This was done in an iterative fashion; a random set of pixels were set to the dead value, the hologram with that level of dead pixels was saved and then more random pixels were set to the dead value.

2.1.4. Stimuli

To obtain images of high enough resolution, images from the Div2K [AT17] dataset were analysed. Six images were selected to be used in the full user study based on their overall intensity, standard deviation and distribution of 0/255 pixel values across the image. Of these images, Figure 1 was selected for the pilot study. This was because it was considered the simplest image in which to notice distortions because it had a much higher level of black pixels in the image — more than double the number of black pixels of the other images.

The hologram was generated in as simple a manner as possible, limiting the potential factors affecting the observed quality of the hologram. By limiting the hologram to a single wavelength, the experiment avoided the ambiguity of participants potentially seeing colours differently, typically referred to as *metamerism failure* [LF14]. A wavelength of 520 nm was selected due to the high sensitivity of the human eye to green light, particularly in darker conditions where the rods are more prominent [GC21]. The hologram was generated on a single depth plane due to the lack of research in the relationship between depth and quality. The intention of these restrictions is to remove any confounding factors from the experiment.

2.2. User Study

This section explains the implementation of the user study. The first subsection details the Two Forced Alternative choice (2AFC) methodology and how it was applied. The second subsection describes how the participants were selected and the demographics of the participants. The third subsection details the equipment used to generate the holograms.

2.2.1. Design

2AFC [Bla53] was chosen as the method by which users could select the higher-quality version of the two holograms. Participants were shown two holograms generated from the same image and asked to choose the hologram with the least distortion. To simplify the information for the participants they are told that the hologram with the least distortion will have the higher quality. The method is coined *forced choice* because participants are not given the option of 'no difference', i.e. they must choose one to be better. When 2AFC is used to determine JND it is common to declare a difference to be noticeable when 75% of participants select the correct image of the pair [MKT85].

2.2.2. Participants

For this pilot study the participants were recruited from employees of VividQ, a company that develops software for the generation of holograms. In total 17 participants took part in the study: 5 where 25-29 years old, 3 30-34, 1 35-39, 2 40-44, 1 45-50, 1 50-54, 1 55-59. The ratio of male to female (assigned at birth) was 13:4. All participants had viewed holograms before, with 7 having significant experience with holograms due to their role in the company. Participants were asked for verbal consent to take part in the study: as they were all employees of VividQ and knew the potential risks of viewing a holographic projector.

2.2.3. Apparatus

The holograms were shown to participants by illuminating the PLM with a monochromatic, green laser of wavelength 520 nm. Lenses were used to magnify the size of the image forming from the PLM, and a lens was used to focus the hologram for viewing by participants. Observers could see the hologram by finding the eye-box projected in front of the focal lens.

In total there were 30 pairs of holograms, varying in number of dead pixels and thus displayed quality. Each pair consisted of a standard and a comparison, both being a hologram selected from the pre-generated list of holograms with given percentage of dead pixels. The list of pairs was chosen by creating a list of the standard holograms, creating a list of how many more dead pixels the comparison hologram would have relative to the standard hologram and combining them to generate pairs.

The chosen list of standard holograms was 0%, 1%, 2%, 4%, 8%, and 16%, with the list of additional dead pixels being 1, 2, 4, 8, and 16 percentage points. A comparison between identical holograms was not included as participants were not given a neutral option.

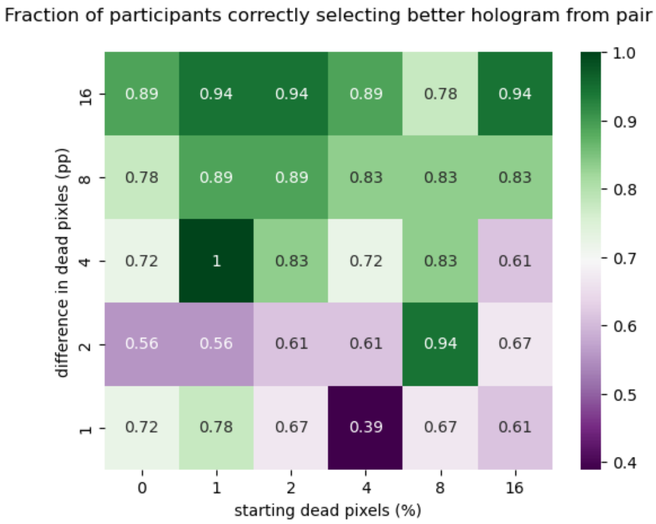

Figure 2: *Fraction of participants correctly identifying the less distorted hologram for different differences and levels of distortion*

2.2.4. Procedure

Before the participants were shown the hologram pairs they were shown a grid designed to only be visible in its entirety if a participant's pupil covers the entire eye-box. Participants could then provide any keyboard input to begin viewing the pairs.

Participants were asked to select the hologram that was less distorted, with it being emphasised that this would be the higher quality hologram. Each hologram was shown for three seconds, with a blank hologram separating the two for a half-second. The holograms were shown in sequence, with each hologram repeated once only.

Participants were asked to input the higher quality hologram using a traditional keyboard laptop, pressing either the 1 or 2 key on the keyboard.

3. Results

The answers given by each participant were recorded as a correct/wrong answer. For each hologram pair the fraction of correct answers was calculated across the 17 participants. Figure 2 is a heat-map visualising the fraction of correct answers for each of the hologram pairs, with green indicating that at least 75% (13/17) were correct.

In general participants were able to tell the difference when there were at least 4 percentage points (pp) of difference in dead pixels between the two holograms.

Participants were asked whether there were any particular regions that they focused on when determining image quality. It seemed many participants, particularly those that did better than average, focused on either the black sky or the fence at the front of the scene.

4. Discussion

It seems that at the highest level of dead pixels (for the better hologram) the accuracy typically decreases, which is likely due to the difficulty in noticing the same level of difference when the absolute distortion is higher. At low levels of dead pixels the number of dead pixels added relative to the number of active pixels is higher and could therefore decrease the impact. There is also a possibility that bias creeps in at the extreme low/high levels of dead pixels, where the participant might be more likely to be biased by the observed quality of the first hologram.

By not giving participants a training period beforehand there could be an initial period of the experiment where participants are still learning how to differentiate between holograms. As such, participants' ability to notice a difference between a pair of holograms could have been noticeably influenced by how early in the experiment they were exposed to that pair. This was potentially exacerbated by not having a standardised set of holograms for participants to view before beginning the experiment.

5. Improvements for full study

Participants will be given a training period to familiarise themselves with holograms, the setup and how to compare the quality of holograms. The blank screen shown in the pause between holograms will be replaced with holograms showing A/B/Vote, in accordance with the BT standard for subjective assessment [BT02].

In addition the script will be adapted to ensure that participants cannot input their preference until both holograms are shown at least once and record the pair order. Participants will be given the option to use a forehead rest for support and to help maintain their head position. Based on the feedback of where the most successful participants focused has been decided to select images that contain/lack black and/or high frequency elements within the image. As such, it is intended to select 4 images, selecting combinations with the most/least black regions and the highest/lowest frequency within the image.

6. Conclusion

The results obtained from this research indicate a difference of roughly 4 pp dead pixels is required to notice a difference, with a distinct possibility that participants are able to notice differences less than that. This tolerance is significantly higher than traditional displays, where the industry standard tolerance is a maximum of 0.05% (500 per 1 million) [10]. The findings indicate there is a sufficient case to proceed with the full study, where more insightful conclusions would be obtained by including more participants and using more than one source image.

From feedback of regions of focus, it seems that the presence of black regions and potentially whether there are high frequency elements in the image are important factors in how noticeable a difference in dead pixels is and the images selected for the full study will focus on these elements. By building on this pilot study it is hoped to confirm the threshold of dead pixels which is noticeable to participants, to what degree that threshold is influenced by the source image and what factors within the image influence any change in JND.

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