AN EVALUATION OF RECONSTRUCTION FILTERS FOR A PATH-SEARCHING TASK IN 3D

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ABSTRACT

The choice of reconstruction filter used to interpolate between sample points when generating images from volumetric data sets can have an impact on image quality. There are a range of reconstruction filters as well as methods to determine the quality of these filters. While it is well documented that stereoscopy can improve the performance of spatial search tasks, it is not clear how artifacts introduced by the choice of reconstruction filter will impact the performance of these tasks. In this study we report the results of a path-tracing experiment where we assess the effectiveness of stereoscopy and three reconstruction filters in terms of accuracy and response time. Our results suggest that the reconstruction filter can have a significant effect on path-tracing tasks and that stereoscopy can significantly improve accuracy results whilst slightly increasing response time.

***Index Terms*—** Direct Volume Rendering, Stereoscopic, Reconstruction, Path-Searching

1 Introduction

Stereoscopic displays can be used to assist in the understanding of complex 3D data sets such as those generated by medical scanners with direct volume rendering. Tasks that require a greater spatial understanding of the data have been shown to demonstrate an increased performance with stereoscopic displays. Such benefits over conventional 2D displays have been reported to include aiding in relative depth judgment, spatial localization, perceiving camouflaged objects and surface material as well as interpreting the curvature of the surfaces [1]. However, stereoscopic images are susceptible to 2D image artifacts that can impact the quality and perceived depth of the scene. Aliasing can lead to a range of artifacts that are unique to stereo images that include inaccurate positions and sizes of objects in the scene as well as errors in disparity up to a pixel leading to inconsistent depths [2]. The attenuation of high frequencies that reflect fine details in images and is visualized as blur can also impact the perceived depth of a scene. Whilst there is evidence to suggest that the human visual system (HVS) has some tolerance to minimal amounts of blur, larger amounts greatly reduce the smallest depths that can be perceived [3].

A recent review into the effectiveness of stereoscopic displays within the medical domain has found that in some cases task performance is improved when compared to monoscopic setups [4]. For example, in [5] improved accuracies are found with simulated data sets for depth tasks. However, the results of these studies are not conclusive and further research is required to ascertain exact improvements found with stereoscopic displays. This is especially true in the case of medical images rendered using direct volume rendering (DVR) that are subject to a large number of parameters, including the choice of reconstruction filter.

In this paper, we evaluate three different reconstruction filters used in DVR in terms of their accuracy and response times when used to produce images for a path-tracing task. We compare trilinear, Catmull-Rom and interpolating B-spline reconstruction schemes in stereoscopic and monoscopic environments. Despite current research into the analytical behaviour [6, 7], image quality and subjective opinion of reconstruction artifacts [8] it is not well understood how the choice of reconstruction filter may impact task performance or whether task accuracy relates to the analytic quality of the reconstruction filters tested. Further we seek to determine the possible benefits that stereoscopic displays may have against monoscopic displays when used with DVR for a task similar to those performed within the medical domain.

The contributions of this paper can be summarized as:

- We present the first paper to compare reconstruction filters in DVR using a path-searching task.
- Our results suggest that the choice of reconstruction filter can have an impact on task performance where spatial understanding is required.

2 Background

2.1 Reconstruction in Volume Rendering

Volumetric data, produced either from medical scanners or via a process such as voxelisation, are represented in the form of an array of sample points on a 3D grid lattice. To render volume data it is necessary to reconstruct values at points x between the grid nodes k. This can be written as [9]:

$$f(x) = \sum_{k \in Z^3} f_k \varphi(x - k) \qquad x \in R^3 \tag{1}$$

where the value $f(x)$ is the linear combination of samples f_k that are evaluated at integer coordinates k, and φ is the reconstruction filter. For computational efficiency the reconstruction filter should have finite support. Such filters will always introduce artifacts into the reconstructed signal that can be classified as post-aliasing, smoothing and ringing [6, 8].

One of the few user studies that perceptually evaluate the reconstruction filters is that of Mitchell and Netravali [8]. Images displaying typical blurring, ringing and anisotropy artifacts were shown to participants. Test images were then generated using a range of parameters from the BC family of splines and these were compared to the artifact images with the participants being asked to match which of the artifacts the test images most exemplified. Their results determined that different parameters of the same family of spline filters can introduce very different perceptual artifacts.

2.2 Stereoscopic Volume Rendering

Whilst there is evidence to suggest that stereoscopic volume rendering can improve the results of tasks, this is not conclusive neither is it consistent even between similar tasks. In initial investigations into stereoscopic DVR, Hubbold evaluated the effectiveness of stereoscopic displays with spherical volumetric data sets [10]. Users were asked to determine which sphere from a set of three were closest for a set of different voxel disparities. Only the rendering where the shells were embedded within a semi-transparent shell showed improvements with stereoscopic displays. In a further experiment to determine how aliasing may impact the perception of depth and comfort, the quality of depth perception improved for sub-sampled volumes with high resolution images, where as there was little impact on comfort.

Ropinski tested the effectiveness of different depth cues with angiography images when requiring users to determine the relation of two vessels [11]. Overall, auto-stereoscopic display of the data led to increased error rates and response time with a possible reason being given as inexperience of the users with the display hardware used.

The kinetic depth effect has also been studied with Kersten finding that stereoscopic display of the data improved users ability to determine the correct rotation of a cylinder rendered using purely absorptive volume rendering [12]. Overall, stereo display of the task was found to improve accuracy rate. Agus reports similar results using a multi-view auto-stereoscopic display [13]. Further quantitative and qualitative tasks comparing different levels of immersion were performed in [14]. Improved grades were found for complex search tasks, yet degraded performance with stereoscopic displays was reported when slicing of the data sets was required. In a depth discrimination task using angiography-like data sets, higher levels of immersion have been suggested to provide more accurate results than with 2D display of the data. In a task requiring users to determine the relative depths of translucent cylinders, stereo displays provided improved results over 2D displays [5]. Yet, in a similar task requiring users to determine the orders of cylinders embedded in a CT data set, no significance was found for stereoscopic against monoscopic display setups [15].

A possible reason for the range of results is the variation in the parameters used for rendering the images. These include data set resolution, transfer functions as well as stereo settings. In this evaluation we seek to maintain settings between trials with only the selected interpolation filter changing to determine how this parameter may effect the results of a spatial task in stereoscopic and monoscopic environments.

3 Experimental Methodology

3.1 Path-Tracing

In deciding upon a task to perform, there are two key requirements that must be fulfilled. First as DVR is commonly used in the medical domain, the task should be relevant to the medical profession. Yet, there are no standard viewing procedures that can be used, a problem noted by prior studies [11]. Further, as the participants will be novices, it is required that the task itself does not require medical expertise. Angiography images containing overlapping and connecting vessels are structurally similar to interconnected-graphs, as such a path-tracing task whereby participants must find a path between nodes in a graph can be used. Such tasks have been used in prior experiments due to their similarity with the task of interpreting vascular data sets [4, 16, 17].

The setup follows that of previous experiments using graph based-networks [17, 18] with the difference being the use of DVR to produce the images. In each image a graph was displayed with nodes connected via arcs. The participant had to determine whether two nodes highlighted in red were connected via a path of two. For each image there was a 50% chance of either the highlighted nodes being joined by a path of two or there being a path of a different length. If the participant believed there was a path they were instructed to press the 'y' key on the keyboard else to click the 'n' key. The nodes were divided into three equal sized groups, two of which were labeled as leaf nodes and the third labeled as intermediate nodes. In the stereoscopic tests the intermediate nodes were placed on the zero-disparity plane, leaf group 1 were placed within the volume so that they were displayed at a distance of $50mm$ in front of the display and leaf group 2 were placed at a distance of $50mm$ behind the screen. These depths were chosen as they are within a range that allows the image to be viewed with minimal discomfort [19]. The monoscopic test used the same node layouts with only the perspective cue used. The x, y position of each node within the three layers were randomly distributed. The arcs between each node were determined by connecting each node in both leaf groups to two randomly selected intermediate nodes.

Aside from the changes of the rendering method used between this experiment and prior [17, 18], there were two more key differences. Firstly, the nodes that act as junction points between the arcs were given the same density value as the arcs. This resulted in them being rendered with the same colour as the arcs connecting the nodes. The reasoning is that in typical blood vessel data sets the junctions where the vessels branch are part of the vessel itself and will therefore have a similar density to the rest of the vessel. The second difference was that with the transfer function (TF) used the nodes and arcs were rendered semi-transparently with the transparency dependent upon the density of the object. This produces images that are typical of DVR and reflects prior experiments in the stereoscopic DVR literature [5, 12, 20]. For the purposes of this experiment the number of nodes have been set at 90, a number consistent with previous trials.

3.2 Reconstruction Filters to be Analyzed

The choice of reconstruction filter used for the experiment is motivated by the requirement of satisfying the interpolation constraint as well as using filters that cover a range of quality. First, the trilinear interpolation scheme has been chosen due to its simplicity and generally acceptable results. Second, the Catmull-Rom spline has been selected as it is the only BC-spline that is interpolating and is used when high-quality rendering is required. Finally the interpolating B-Spline represents one of the highest quality interpolation schemes that can be used. The chosen interpolation schemes are in common usage and exhibit a wide range of quality in terms of the error function notation (N-EF) of [7] and their smoothness ranging from C^0 to C^2.

3.2.1 Trilinear

Requiring only eight neighboring sample points, trilinear interpolation is the simplest reconstruction scheme capable of recreating a continuous function from a discrete set of 3D samples and is a C^0, 3-EF filter.

3.2.2 Catmull-Rom Spline

A universally respected interpolation filter, this spline function is within the family of BC-splines with a support of 64 in the 3D case. The filter is just C^1 continuous allowing the function to be differentiated once but resulting in discontinuous curvature reconstruction and is a 3-EF filter.

3.2.3 Interpolating B-spline

The B-splines of degree 3 and above are not interpolation filters, rather approximation filters. Despite this the filter has a history of use with DVR due in part to its C^2 smoothness, allowing continuous curvature reconstruction, as well as providing smooth reconstructions of inherently noisy data. For medical data sets where the accuracy of the reconstruction is of paramount importance the smoothing property of the B-spline means it is not suitable for use in its naive form.

Via a process known as *generalized interpolation* [21] the interpolating B^3-spline can be derived from the approximating B^3-spline. Equation 1 is in this case modified to produce:

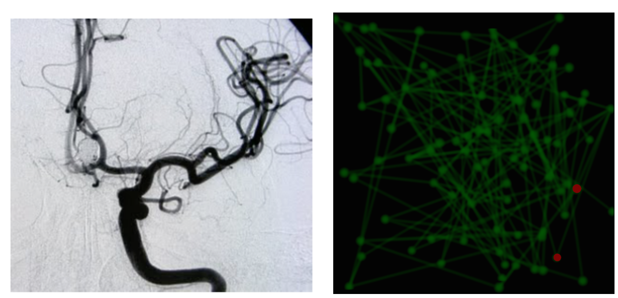
$$f(x) = \sum_{k \in Z^3} c_k \varphi(x - k) \qquad x \in R^3 \tag{2}$$

where the coefficients c_k are computed from the sample data f_k after applying the inverse of the filter. The interpolating cubic B^3-spline produces a C^2 continuous 4-EF filter having a continuity and accuracy greater than the Catmull-Rom spline.

3.3 Stimulus Generation

The graph images were rendered offline prior to the start of the experiment. The *vxtrl* [22] package that implements the truncated distance fields method of voxelisation was used to generate the volumes with the resolution of $(256 \times 256 \times 256)$.

An in-house software-based raycaster was used to generate the images with the sample rate set above that of the Nyquist rate of the data set. The same transfer function was used to generate all images with a constant green value of 0.35 and an increasing linear opacity of $0 - 0.6$. Figure 1(b) shows a graph generated with these settings.



(a) (b)

Fig. 1. Figure (a) shows a typical angiography image from [16]. Figure (b) is from our experiment showing the graph with two highlighted nodes in red

3.4 Equipment and Viewing Conditions

A True3Di 24″ HD-SDI Monitor was used for displaying the graph images in both the stereoscopic and monoscopic test setups. The display has a resolution of 1920×1200 pixels for each eye with a refresh rate of $60Hz$. In order to view the 3D images linear polarized glasses were worn. The glasses were worn in both viewing conditions to remove a possible source of bias. Participants were placed at a distance of $60cm$ from the display. The experiment took place in a darkened room with the light levels kept consistent throughout.

3.5 Participants

18 participants were recruited to take part in the experiment. In total there were 4 women and 14 men with ages ranging from 18-27 and a mean age of 21, each of the participants were paid £5 to take part in the experiment. All participants taking part in the study were screened for vision by using the Bailey and Snellen chart and for stereo-vision using the Titmus fly stereo test. Some of the participants did have prior experience with 3D displays, however all were novices in regard to the nature of the task and none had any medical training or experience with studying medical data sets. Participants were informed that accuracy and response time would be recorded during the task. Whilst the use of experts instead of noivces can produce highly relevant domain specific results, prior knowledge can confound the results. In contrast, novice users may have minimal preconceived ideas.

3.6 Procedure

A trial test was performed with graphs containing 30 nodes, the test continued until the user felt ready to begin the main experiment. For the full experiment there were three trials for the stereoscopic and monoscopic presentations corresponding to the three interpolation filters for a total of 6 trials. 20 images were presented for each trial with a short break after each trial in order to reduce the impact of fatigue. The ordering of the trials were determined by a Latin Square design to reduce learning effects. Although the task duration was somewhat dependent upon the individual participant, in general it lasted for approximately 60 minutes.

3.7 Hypothesis

Our goal is to understand the influence of interpolation when measuring accuracy and response time for a path-searching task. Our first question is therefore: What are the benefits to using higher quality interpolation methods when performing spatially complex tasks with vascular-like data sets? Secondly we are interested in how task performance may differ between display types with the different interpolation methods. Our second question is then: Does the display type have an impact on results when different interpolation methods are considered?

In the literature, the assessment of interpolation filters for volume rendering has taken place either via juxtaposition with images produced by different filters, typically using the Marschner and Lobb data set or via some metric. Aliasing can lead to inaccuracies when stereo depth perception is required [2]. Further when excessive blur is introduced into a stereo image the ability to perceive depth correctly diminishes as the amount of blur increases. It may be expected then that interpolation filters with poorer pass-band behaviour and therefore greater smoothing will exhibit a decrease in accuracy and an increase in response time during the experiment. Interpolation filters that more accurately reflect the sinc filter are expected to produce an increase in task performance.

4 Experimental Results

The response times and accuracy rates were subjected to two-way repeated measures analysis of variances (ANOVAs). The reconstruction method and display setup, either monoscopic or stereoscopic, were the independent variables and the accuracy and response time were the dependent variables. The mean correct responses for each condition are shown in Table 1 and the mean response latencies are shown in Table 2.

Table 1. Mean Accuracy (percentage)

	Monoscopic		Stereoscopic	
Reconstruction	Mean	SD	Mean	SD
Trilinear	54.720	23.556	68.335	16.646
Catmull-Rom	60.000	18.075	68.055	11.586
Interpolating B-spline	58.335	21.197	74.720	17.699

Table 2. Mean Response Latencies (seconds)

	Monoscopic		Stereoscopic	
Reconstruction	Mean	SD	Mean	SD
Trilinear	16.385	23.804	17.654	26.152
Catmull-Rom	17.193	26.871	18.382	26.057
Interpolating B-spline	16.579	24.329	17.926	23.441

4.1 Display

For accuracy a two-way analysis of variance collapsed across the interpolation method determined that there was a significant effect from monoscopic to stereoscopic display setup with $F(1, 17) = 22.586$, $p < 0.001$. There was an increase in accuracy from 11.648 ± 0.430 to 14.074 ± 0.372 a statistically significant increase of 2.426 (95% CI, 1.349 to 3.503).

A repeated measure two-analysis of variance collapsed across the interpolation method was used to determine whether there were any statistical significance between response times of displays types. There was a weakly significant effect from monoscopic to stereoscopic display setup with $F(1, 359) = 3.366$, $p = 0.067$. The response time increased from monoscopic to stereoscopic with the averages increasing from 16.719 ± 1.214 to 17.987 ± 1.203 a marginally significant increase of 1.269.

4.2 Reconstruction Filter

A two-way analysis of variance collapsed across the display type was used to determine if there were statistically significant differences in accuracy between the interpolation schemes used. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated $\chi^2(2) = 0.098$, $p = 0.952$. The interpolation scheme used elicited statistically significant changes in accuracy with $F(2,34) = 6.800$, $p = 0.03$ with mean accuracy increasing from 12.306 ± 0.343 for trilinear interpolation to 12.806 ± 0.339 for Catmull-Rom interpolation and to 13.472 ± 0.397 for interpolating B-spline. Post hoc analysis with a Bonferroni adjustment revealed that accuracy was significantly increased between trilinear and interpolating B-spline reconstruction with $p = 0.004$ an increase of 1.167 (95% CI, 0.356 to 1.977). There were no significant differences between the accuracies for trilinear interpolation and Catmull-Rom or interpolating B-spline and Catmull-Rom. A further one-way ANOVA considering only the stereoscopic trials determined that there was a weakly significant effect between interpolation types with $F(2,34) = 2.850, p = 0.072$. Bonferroni pair-wise comparison found there were no significant differences between individual pairs of interpolation methods.

For the assessment of interpolation on response time the Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated with $\chi^2(2) = 2.462$, $p = 0.485$. The ANOVA determined that there was no statistical significance between interpolation type and response time with $F(2,7128) = 0.724$,$p = 0.485$.

4.3 Display with Reconstruction Filter

A two-way repeated measures ANOVA was used to examine the effect of display type and interpolation scheme on accuracy. Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated with $\chi^2(2) = 10.489$, $p = 0.005$, therefore a Greenhouse-Geisser correction was applied ($\epsilon = 0.675$). No statistically significant changes were found with $F(1.351, 22.960) = 0.953$, $p = 0.367$.

A two-way repeated measures ANOVA was conducted that examined the effects of display type and interpolation scheme on response latency. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated with $\chi^2(2) = 3.759$, $p = 0.153$. No statistical significance was found with $F(2,718) = 0.007$, $p = 0.993$.

5 Discussion

Reviewing the research questions and the hypothesis the results confirmed that higher quality interpolation methods can produce higher accuracy results for spatial tasks, further stereoscopic displays can produce improved results for these tasks. In comparing the benefit of stereoscopic displays, the significant increase of accuracy of 12.1% is comparable with the 11.4% increase found in a prior experiment to determine the required number of stereo view points [23]. However the accuracy rates are below those of prior studies with similar graph complexities in both display conditions [17, 23, 24]. The results are comparable to those found in [5] whereby participants were required to determine the correct ordering of a set of semi-transparent volume rendered cylinders. This implies an increased level of difficulty when transparency is introduced in graph networks.

When comparing reconstruction filters the results suggest that there was a significant impact on accuracy when display type is not considered, specifically between trilinear interpolation and interpolating B-spline. Further investigation comparing the stereoscopic trials implies that there may be differences between the reconstruction filters, although the exact nature is not clear. The display and reconstruction filter results yielded no significant impact on accuracies. An explanation might be, as mentioned above, the complexity of the task that may be obscuring further differences causing a flooring effect. The low accuracy percentages when compared to prior experiments provides evidence to support this. Although the trends suggest that interpolation filters of higher quality according to the N-EF notation may produce more accurate results further research is required to determine the exact nature of the effect with a range of task complexities and a broader range of interpolation filters.

Regarding response time, only the display type had a marginally significant effect with the stereoscopic trials producing larger latencies. Although these results are different to previous path-searching studies that suggest that stereoscopic displays decrease response times [17, 23] it is in line with studies from the stereoscopic volume rendering literature [11, 14]. A possible explanation is that having multiple layers in depth may extend search time because each depth must be searched separately.

6 Conclusions

In this study we have examined the effect of interpolation filters in DVR with stereoscopic and monoscopic display conditions for a path-searching task. Results showed that stereoscopic display of the data significantly improved accuracy with no significant impact on response time. The results suggest that the interpolation type can have an effect on tasks that require spatial understanding with the general trend implying that as the interpolation quality increases accuracy also increases. In relating the practical implications of this study to the medical domain it is apparent that the filter for rendering vascular-like data sets cannot be made arbitrarily and should depend upon the context within which the rendering is to be used. Although further research is required to clarify the results with a wider range of filters and tests, the results suggest a possible explanation for the wide range of results found in experiments involving stereoscopic volume rendering.

The study presented does have limitations, the primary of which is the inability to separate the image artifacts of post-aliasing and smoothing on the response of the task. Smoothing is known to effect the results of stereoacuity tests and aliasing can also have an impact on tasks requiring depth perception [2, 3]. Further work may seek to classify the interpolation filters using the frequency domain metrics of [6] to provide additional insight. A second limitation is the use of simulated data sets that express a regularity in terms of vessel thickness, junction connections and lack of noise that are not found in medical data sets.

7 References

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