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Measurement of Immersive Technology for Historic Scenes

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Abstract

This paper investigates the creation of historic scenes through engagement with community archaeology and historical investigation. The approach presented here enables both tangible and intangible culture to be explored through the proxy of an avatar controlled by a user. This gives rise to an engaging and interactive experience. Through utilising and developing a flexible open source software infrastructure the historic scenes may be deployed in a range of of scenarios: over the Internet, in mobile multi user exhibitions suitable for public events, as an immersive museum installation and through on site cross reality exploration.

The use of commodity hardware, open source and open standards underpins a collaborative creative process that enables the deployment of installations which articulate interpretations relevant to the locality. This in turn encourages a sense of ownership and dynamic engagement with cultural heritage.

A measurement study of the quality of experience delivered by virtual world systems reveals the client as the critical system component. System performance and the quality of presentation measurements provide system insights which enable user experience to be improved.

Categories and Subject Descriptors (according to ACM CCS): I.3.2 [Computer Graphics]: Three Dimensional Graphics and Realism—Virtual Reality

1. Introduction

The use of interactive historical 3D scenes in cultural heritage contexts offers the opportunity to engage with new audiences and to tap into emergent digital literacies. The success of the Battle of Bannockburn Centre (www.battleofbannockburn.com) demonstrates the power of applying such technology, but the cost of such projects, appropriate for prestige programs and national narratives, acts as a barrier in other contexts. This paper arises out of the Virtual Histories project [MMK*13], which adapts and develops open source virtual world technology and pairs it with commodity hardware to create a Virtual Time Travel Platform (VTTP). This provides the core of a rapid development environment for 3D applications and a platform for the deployment of interactive exhibits within museums.

At the time of writing the VTTP provides exhibits in four museums: a reconstruction of the 16th Century Eyemouth Fort (Eyemouth Museum), 19th Century St Kilda (Taigh Chearsebhagh MUseum, North Uist), the 19th Century Featherland Fishing Station (Shetland Museum and Archives), and the 19th Century Caen Highland Village (Timespan Museum and Arts Centre). All content can also be accessed globally via the Apollo server (openvirtualworlds.org) or as part of mobile multi user "LAN party" exhibitions. The St Kilda exhibition brings together professional production values with community interpretation. The scale of this reconstruction pushed boundaries and demanded informed engineering to ensure both performance & quality.

Previous work suggests that when a user connects to a properly provisioned virtual world service across a properly provisioned network connection they can expect to receive a reliable, and responsive service [UMO*14]. In the study of virtual worlds client performance is an area that has been underdeveloped. It is an aim of this study to address this omission and thereby contribute to the development of an holistic understanding of virtual world QoS. The rest of the paper focusses on client side interaction [CYC13]. The investigation falls into four categories:

1. *fidelity:* the number of polygons or number of pixels.
2. *quality:* how well the graphics are rendered.
3. *content:* character of models and non player characters.
4. *system:* includes graphics card, processor and memory.

A methodology is presented, which enables these to be probed and repeatability to be achieved. The contribution of this work lies in demonstrating the value of the VTTP as a platform for heterogeneous interactive immersive cultural heritage applications and contributing to our understanding of the systems that support them. Quantitative data is placed in the context of user experience. We demonstrate the impressive scale of simulation that can be achieved and show that careful engineering avoids compromising interactivity, quality or performance. This work will enable developers to build systems appropriate for their platforms and users to configure their systems to optimise quality of experience.

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Figure 1: *Two views from the St Kilda reconstruction: Lady Grange's Cliet and the Manse on St Kilda 1880*

2. Immersive Cultural Heritage Scenes

One of the strengths of VTTP architecture is its ability to support multiple deployment scenarios and devices. These include: accessing a network of models remotely, portable multi user exhibitions consisting of several clients networked together that may be deployed in schools [KFM*13] and public spaces, and on site access using tablets and installations for museums [MMK*13]. Modes of display include multiple synchronous projections, stereoscopic headsets and high definition screens. Control may be with the traditional keyboard and mouse, games controllers and natural movement. The Virtual St Kilda installation is discussed further in this section. The introduction to the exhibit can be seen at https://vimeo.com/94653938 and the model may be accessed remotely from virtualworlds.org.

The exhibit is in a dedicated room with an interactive full screen projection controlled by a Microsoft Kinect and XBox controller. The user may browse a series of short videos, ranging from two to ten minutes long, and explore an interactive 3D model of St Kilda. In the design of the exhibit one of the core principles was that of community involvement. North Uist is a remote island with a relatively small population. Many people on the island have direct connections to St Kilda, through links to the people who once lived there or because they work, or have worked there. The contribution of Taigh Chearsebhagh and the people of North Uist is what has made this exhibit both possible and special. Contributions from schools, Uist Films, Island Voices the Spring Chickens and many others each contribute highlights to the exhibit. This was done primarily through the videos. The videos feature footage shot by local groups, recordings of local musicians and videos of local primary school students telling stories of St Kilda. Taken together this means that the exhibit is a combination of documentary and interpretation.

In free exploration the visitor uses the XBox controller to explore a model of village bay, on Hirte, the main island in the St Kilda archipelago. The model covers, several km^2 of real world space (Fig 1). The objective of the reconstruction is to represent enough of the space such that, when standing in the centre of the village visitors get an accurate impression of the geography in all directions. The terrain data is imported Ordinance survey data. The modelling is focused on the village itself. The Church and Manse, Factors House and Feather Store as well as crofts, blackhouses (traditionally Hebridean dwellings with thick walls and doors facing away from the sea) and cliets (dry stone storage structures, unique to St Kilda, which cover the St Kildan landscape, more than 1100 in total) are all modelled. Users interact with embedded multi media content and Non Player Characters. The model is dated to the 1880s.

The videos are intended as short, standalone pieces. They are designed with reference to the youtube format where information is presented in small sections but linked with more information so that interested users can explore further if they wish. Videos cover subjects such as health on the islands, what a blackhouse is and recordings of music with known links to St Kilda. There are also two longer videos. The first, 'The Story of St Kilda' is a seven minute piece composed of a mix of real world footage and virtual footage introducing St Kilda and the different aspects that make it special and some information about the exhibit. The video has a voiceover narration which is split into Gaelic and English. Each paragraph of information is narrated first in Gaelic and then English. The second long video is a ten minute mood piece of the sites and sounds of St Kilda. This is designed to run when visitors first enter.

In the exhibit the local, historical, academic and the virtual all combine together to create something which is multifaceted and tells the story of a unique place in a unique way with a strong local voice. The end result is something that the community is happy to publicise to the world as their perspective on a site of international interest.

Critical to the success of the experience was modeling the surrounding landscape, together with the architecture. The scale and complexity of the St Kilda model means that the exhibit operates at the edge of what it is possible to achieve with current commodity hardware and OVW technology. This motivated our investigation into how to achieve the optimal balance between performance and quality.

Figure 2: *Reconstruction of St Andrews Cathedral 1318: accesible vie the apollo server, vimeo video and @ Madras College*

3. Quality of Service and Quality of Experience

Quality of Service is an objective measurement of how a system performs [ALMR01], whilst Quality of Experience is a subjective evaluation of user satisfaction. In [OMA*13] client, server and network quality of service is considered in relation to user quality of experience. The key idea presented is that there is an inverse relationship between performance, how many frames are rendered per second or how quickly the system responds to user input and how well scenes are presented to the user in terms of both the quality of the images and the overall fidelity.

Study of server performance [SOMA12, UMO*14] shows that measuring the time a server takes to process a frame enables the load to be managed so it does not impinge upon the user experience. Studies of network performance show that virtual world applications require around 500Kb/sec of bandwidth per user. Thus computer labs of 30 to 40 users can be easily supported by LAN infrastructure and broadband is able to deliver high quality experience in the home [OMA10, OMA12]. For installations and mobile exhibitions network infrastructure should not be a bottleneck.

From a Quality of Experience perspective we draw upon and develop the work of Claypool [CC07, CC09, Cla05] undertaken in relation to computer games. Claypool establishes that achieving sufficient frame rate is critical to user performance. They find that systems verge on the unusable with framerates below about 3 fps, that they are usable from around 7 with a sharp increase in usability from 7 to 15 and a slight further increase up to around 30 fps.

Our informal observations conducted in schools, exhibitions and museums reinforce these findings. When framerates drop below 15 fps user experience is compromised. This leads us to deploy the heuristic of improving performance until a lower quartile framerate of at least 30 fps and an average framerate of 45 fps is reached. Above these levels consideration is given to improving the quality of presentation.

4. Methodology

The approach taken here is to use models of historic scenes that are being used in real world contexts, and measure the effect varying controlled parameters has on system performance in repeatable laboratory experiments. The performance metric measured is Client fps for smoothness of display. Factors operative are the fidelity and quality of scene, the scale and complexity of content, and the infrastructure used to deliver the content. First a single walk around the Cathedral reconstruction is analysed, then each class of factor is treated in turn.

A fully automated test harness has been produced for generating results. In the harness an automated character walks a predefined route around a model. The route takes about ten minutes and contains "typical" activities for the model. Walking in straight lines, turning corners and spinning on the spot (looking around). In Fig. 3 left we see a graph of the framerate as a route around the Cathedral complex is undertaken. The three lines represent user walking an avatar around the route, a non player character being moved around the route and the virtual camera being moved.

The QQ plot (Fig. 3 right) verifies that client frame rates for user controlled and automated avatar movements match each other closely. There is a slight discrepancy at the upper quartiles, but we are most concerned with the dips in system performance. Consequently, we verify that the test harness produces results that match real world behaviour.

A systematic process has been developed for producing results which allow comparisons between the effects of different factors as measured through the metrics defined previously. At the centre of the experimental architecture is Chimera a program which enables automated control of avatar position, movement and view. Chimera is discussed further in [MMK*13]. The process by which statistics are recorded is as follows:

1. A script is run which runs Chimera 10 times in sequence.

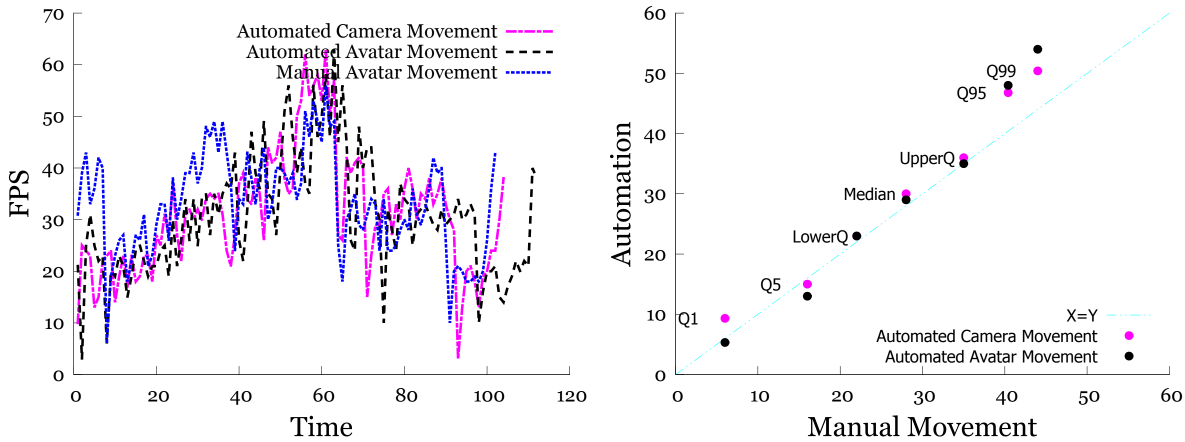

Figure 3: *Comparison of manually controlled avatar, automatically controlled avatar and automatic camera movement: shown as a time series graph and a quantile quantile plot.*

When the first instance of Chimera exits the second one will be executed, etc.

2. Chimera starts up.
3. The route is loaded from an XML file.
4. A pre-specified graphics setting file is loaded.
5. Chimera launches a client, connecting it to the region to be tested and specifying the settings file.
6. Chimera detects the client has been launched and waits for the scene geometry to be loaded in to memory.
7. The avatar is teleported to their home position.
8. FPS, polygon count and ping time are logged once per second.
9. The avatar starts to move around the route, which is specified in XML.
10. The avatar completes its route, the client is closed, and the log buffer written to file.

To ensure each run was successful the script checks the exit code. If it matches the repeat code Chimera is launched again. The pause after the viewer starts to allow assets to download is necessary to avoid conflating two separate effects. Downloading resources from the server impacts performance, both negatively (the process of downloading slows the client) and positively (there is less to render). These effects combine to produce a net negative effect on performance [OMA10]. Waiting until all assets have loaded avoids the performance penalty that is part of loading being misinterpreted as an artefact of the system's configuration.

5. Client Side Measurements

This section presents measurement of factors affecting client side system performance. Before considering each factor in turn we set the scene by investigating a single run from multiple perspectives. The model used in this run is the reconstruction of St Andrews Cathedral (Fig. 2). This model is on a 500m by 750m virtual space. The model has been used widely over the Internet and in schools. A video based on the model made medievalists.net's top ten most important events of 2013, has had over 11,000 views and can be seen here: http://vimeo.com/77928887. The model is made up of some 66,000 objects.

Figure 4 shows box plots of the Client's Frames Per Second, the Number of Polygons on Screen, the Ping Time, the Server Frame Time and the Server Frames per Second for a single run on the St Andrews Cathedral. Time series of frames per seconds and number of polygons on screens followed by a scatter plot showing fps vs polygons and a time series scatter plot of multiple runs.

Considering the box plots first: the median fps is sixty two, with a lower quartile of some 42ms, with a median 11,600 polygons on screen. The median ping time of 15ms represents negligible latency. On the server side there is a median sfps of 55 (the maximum) with a minimum sfps of 52 and a server frame time of 2.7ms. This is 15% of the time available before time dilation would be started and indicates the server is coping easily with the presented load.

The time series diagrams show considerable variation in both the number of polygons on screen and the client framerate. As the avatar walks around the route, the complexity of the view changes. For example when looking out to sea there is little to render, yet when in the middle of the Cathedral the avatar is surrounded by complex models. The scatter plot suggests a negative correlation between the number of polygons rendered and the frame rate. At 120, 260 and 590 seconds sharp downward spikes in the framerate are observed. These are short lived, extreme drop outs. In each case the avatar abruptly changes the direction it faces by more than 90^o forcing a rapid complete reconstitution of the viewed scene. The patterns of fps are repeated if the avatar makes the same journey multiple times.

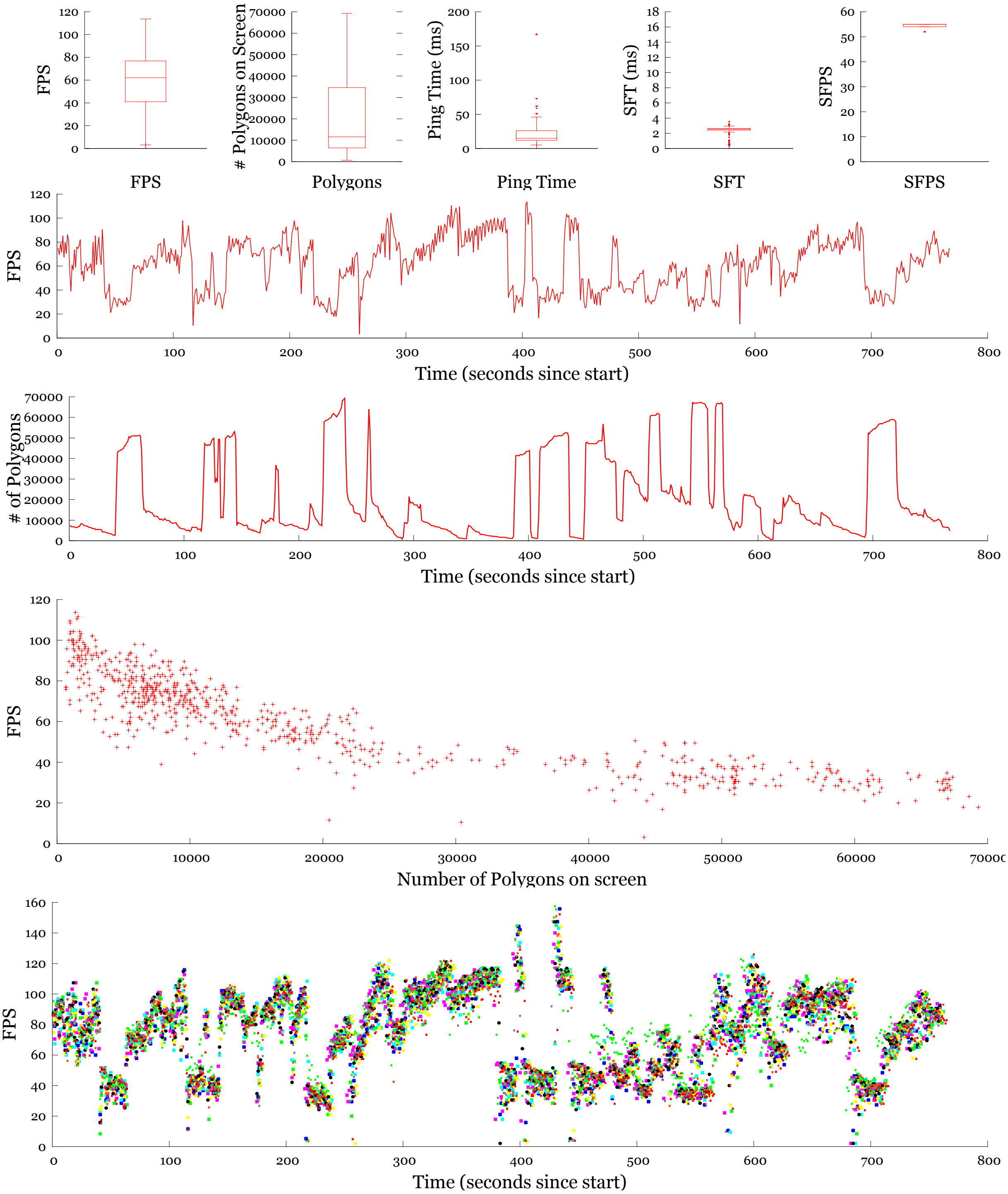

Figure 4: *The boxplots show the Client's Frames per Second, the Number of Polygons on Screen the Ping Time, the Server Frame Time and the Server Frames per Second for a single run on the St Andrews Cathedral. These confirm the importance of client Frames Per Second as a metric for system performance. Time series of frames per second and number of polygon's on screens both show variability as the route is navigated. The scatter plot of fps vs Polygons shows an inverse correlation. A time series scatter plot of multiple runs indicates repeatability of these results.*

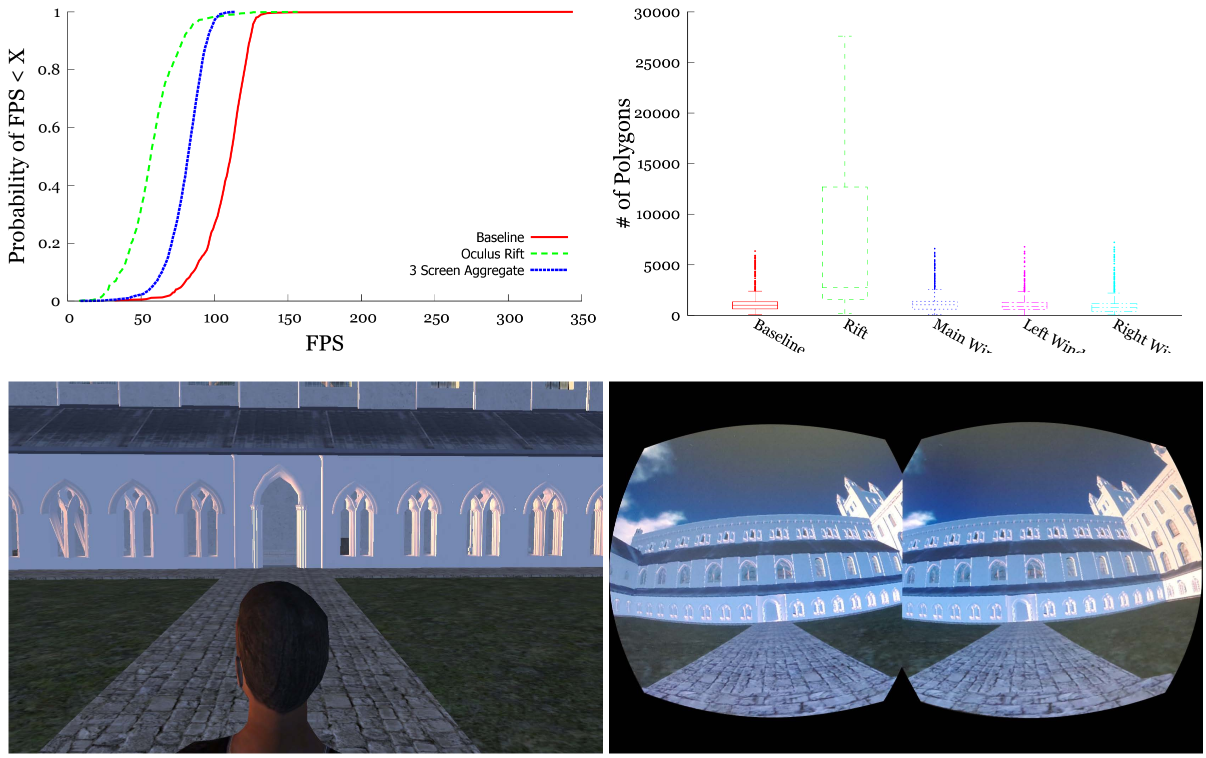

Figure 5: *Cumulative Distribution of Frames per second for Oculus Rift, a synchronised HD set up with three screens and a single screen. Box plots showing the distributions of Polygons on Screen for the same set ups. Image of the cloisters of St Andrews Cathedral on a single screen (1920*1080) and dual images as used by Oculus Rift*

5.1. Fidelity of Scene: of pixels and polygons

By the fidelity of the scene we mean the amount of detail that may be presented to the user. Fidelity can be adjusted in two ways. Increasing the screen resolution increases the detail that can be shown for a given viewpoint. It also increases the number of pixels that need to be drawn on, however it has little effect on the number of polygons that need to be drawn. The reverse is true of the field of view. Changing the field of view will not change the number of pixels that will be drawn. However, increasing it will increase the number of polygons that need to be drawn.

The technology available for presenting 3D content is currently undertaking a shift. 3D TVs have started to become widely available. The Oculus Rift has made virtual reality Head Mounted Displays (HMD) affordable. The flexible nature of the VTTP's architecture means it is well placed to take advantage of these new technologies.

This section presents measurements of three ways of presenting content: the traditional single monitor model (Fig. 5), the Oculus Rift stereoscopic HMD and an immersive, 3 Screen, display. We compare how the novel mechanisms compare to the baseline configurations on the baseline hardware (Geforce 780) on the Cathedral. Testing was done with the same client as for all other tests when quantifying 3 screen performance.

Cumulative distribution functions of the fps for a single HD screen, for multiple (3) synchronised screens and for Oculus Rift are shown in Fig. 5. These show a reduction in frame rate for the three synchronised screens and a further more extreme drop in framerate for the Oculus Rift. It might be expected that framerate would drop as the number of pixels goes up. However the Oculus Rift, with a resolution of 640*480 for each eye, has smallest number of pixels (614K) of the three configurations. High Definition has 2,073,600 and the three screen HD configuration 6,2m pixels.

The Oculus rift has a wider field of view (150^{o}), which in turn means a higher number of polygons rendered per frame. This is shown by the boxplots in Figure 5. From this we draw the conclusion that number of polygons has a stronger negative correlation with performance than number of pixels.

This section has shown that: it is possible to use OVW based VTTP instantations to render existing cultural heritage content on the next generation of visual display devices at acceptable framerates. Rendering using the Oculus Rift is considerably harder than simply rendering the view twice. On contemporary hardware it is possible to render the same scene multiple times using multiple viewers and still maintain acceptable framerates.

Figure 6: *The nave of St Andrews Cathedral with the range of graphics settings*

5.2. Quality of Scene

The VTTP client is a modified version of the OpenGL Firestorm. The graphics processing pipeline, turns raw geometry and 2D texture data into a 3D scene. Steps in the pipeline are implemented as shaders, small programs run on the graphics card which in turn process and transform data to create the final scene. The geometry of a scene is expressed as vertices, which may be associated with normal or colour/texture information. Vertices are combined together to create the geometry of the world. Textures provide colour information when rendering the shapes. Information about vertices can be pre-loaded by filling Vertex Arrays with Vertex Buffer Objects (VBOs).

The first step in the pipeline is to select the vertices which are to be rendered and to load their data. The vertices are then combined together to make triangles. Once all the triangles in the scene have been assembled the scene is projected onto the 2D array of pixels. Rasterization is done by Vertex shaders. Graphical options, which map to shaders, can be enabled, disabled or altered in the client. These features all bear some relation to the OpenGL platform with which the viewer renders the scene. Enabling or disabling different graphical options can have a significant impact. This section looks at the effect settings have on performance and presentation. Before the investigation is presented a description of the graphical effects, and how they are produced, is introduced.

Basic Shaders: Shaders are programs which will be run for each vertex or fragment. The number of shaders, and their complexity, can have a major impact on performance and visual impact.
Shadows: To produce shadows on the fly the scene is rendered from the perspective of each light, in order to discover which objects are in shade and which are not.
Ambient Occlusion: Ambient occlusion is a graphical shortcut designed to approximate the real world effects caused by light reflecting off various objects in the scene before illuminating the object which the camera is observing. This effect adds depth and shading to a scene. Enabling it adds checks on nearby objects to the graphics pipeline.
Anisotropic Filtering: Anisotropic filtering stores multiple low resolution versions of textures optimised for different view angles. It allows large textures which will be viewed at an angle to be compressed along only one axis so that when viewed at a severe angle the texture is full resolution across but compressed as it extends away from the viewer.
Antialiaising: Aliasing is the appearance of jagged edges due to the way textures are sampled. Basic antialising mitigates against this by rendering the image at a higher resolution than required then downsampling so the colours of multiple pixels from the high resolution image are averaged to create a single pixel in the low resolution image.
LOD Scale Factor: The viewer supports complex geometric meshes. The viewer supports multiple versions of the same mesh with different polygon counts. The fewer

pixels a mesh covers the lower the quality of mesh used. The LOD Scale factor controls where the cutoff will happen.

The graphic in Fig. 6 shows eight of the effects combined in an image of the inside of St Andrews Cathedral reconstruction. Fig. 8 present the FPS values across different settings on a CFD plot. In general fps is impacted relatively little by altering graphical settings. The cathedral is impacted heavily by the synchronous occlusion setting because most pieces of geometry are occluded from any given vantage point. Whichever direction the camera faces there are many objects which could need to be depth buffered. St Kilda is an open space so occlusion calculations are simpler.

Enabling shadows has a large performance penalty associate, however the visual impact of enabling shadows is also large. The impact of turning on all other effects as well as shadows is most pronounced in the higher frame rates. As well as producing a notably lower quality image turning off basic shaders can also degrade performance quite severely. Aside from shadows, turning off or turning down graphical features does not have a significant impact on performance.

5.3. Scene Content

The three models being investigated in this Section are the St Andrews Cathedral, the Caen Township and St Kilda. All three have been used in real world case studies. Each model has different properties. Each model's characteristics, a brief description and a map, with the route that is walked to test it, are given below.

1. Cathedral has high object count. Made of prims rather than meshes. Built as a series of enclosed spaces: from any given point in the building most of the rest of the building will be occluded. More processing for the vertex shaders but inputs into the fragment shader will be from fewer objects. Route covers internal and external areas with views through the centre of the model as well as facing away from it.
2. Caen Township is largely open space. All objects cluster toward the centre of the model. There is an even mix between meshes and prims. It covers a large area but all of it is often in view simultaneously. Object count and PPC both a quarter of the cathedral's values.
3. St Kilda: Largest model on the Apollo grid. Covers a virtual area of nearly $2km^2$, 10x that of the Cathedral. Similar object count to Cathedral. Percentage of meshes notably higher than the Cathedral. Emphasis on meshes rather than prims produces a PPC more than twice as large as the cathedral. It has a large total area combined with high prim count and high polygon count.

The breakdown of polygon count over time for each model is plotted as a CFD in Figure 8. In this format it is possible to see that for almost all of the time while walking around the Caen model there are fewer than 1500 polygons on screen. The Cathedral and St Kilda CFDs highlight different patterns in their distributions of polygons. The majority of frames while exploring the Cathedral feature between 1000 and 2000 polygons. Only 10% of frames fall between 2000 and 7000 polygons and they are distributed quite evenly over that range.

By contrast St Kilda has a broader distribution across frames with lower polygon counts. Even these lower polygon frames have notably more polygons visible than the Cathedral. In the 50% of frames with higher polygon counts there is a much broader distribution. The polygon counts between 2000 and 8000 are spread fairly evenly between approximately 40% of frames. This leads to a higher variance in framerate. The model the client is connected to has a significant effect on client performance. Large models with a high number of high polygon meshes are the hardest to render. Even extremely large ($2km^2$) models with large numbers of objects (68000) and polygons on screen (16000) can run at an acceptable level on today's hardware. Older hardware is capable of running less complex models at frame rates that are more than adequate for user experience.

5.4. System Infrastructure

This section looks at the variation of system performance on different platforms. More powerful hardware will often translate into higher framerates and and the ability to turn on more graphical settings. Hardware that is likely to be relevant to graphical performance is the amount of memory available, the graphics card and the processor. The graphics card should have the most impact on performance but the other components may also produce bottlenecks. The hardware configurations which were used for testing are shown below. Each hardware configuration was tested against the St Kilda, Cathedral and Caen models. Graphics settings were set at the baseline settings discussed.

1. 780TI Nvidia Geforce 780TI (3GB memory) Intel i7 4930, socket 2011, 3.4ghz (6 core) 32GB
2. 780 Nvidia Geforce 780 (3GB memory) Intel i7 4770, 3.4ghz, socket 1150 (4 core) 16GB
3. 570 Nvidia Geforce 570 (1GB memory) Intel i5 3570, 3.8ghz (4 core) 8GB
4. 7700 Radeon HD7700 (1GB memory) Intel Core2 Quad Q6600, 2.4ghz (4 core) 4GB

The framerate CDFs are shown in Fig. 9, Caen left, Cathedral Centre and St Kilda right. Across the three regions the results follow a similar pattern. When plotted as a CFD each model has the same shape of curve for each of the four configurations. The Cathedral has quite a straight, vertical line, Caen starts off straight but then has a long tail and St Kilda is at more of an angle. Changing hardware does not impact on the shape of the distribution. The exception is the AMD 7700 on St Kilda. On this model the 7700 is not able to produce an acceptable framerate for installations and holds relatively

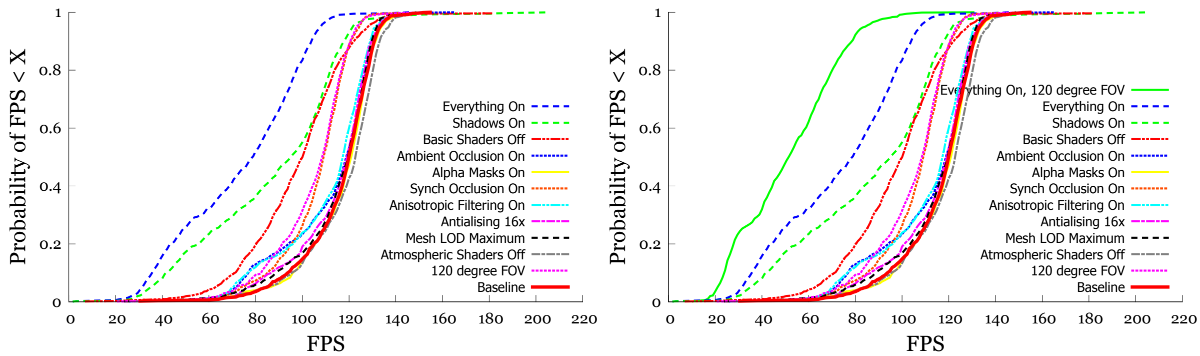

Figure 7: *The cummulative Frequency Distribution for Frames per Second on the Cathedral and St Kilda model for the range of graphics settings*

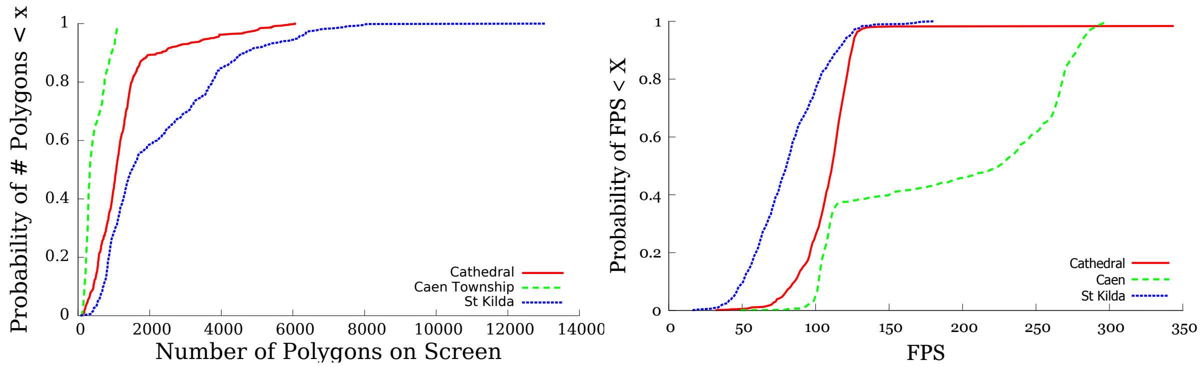

Figure 8: *Distributions for the numbers of polygons on screen and the framerates, for three models: St Andrews Cathedral, The Caen Highland Township and The St Kilda Village Bay*

steady at between 10 and 20fps. The curve on the 7700 is more vertical than on the other hardware configurations, indicating less variation in frame rates. This may be a result of the extreme load the model places on the hardware. Being somewhat older than current day hardware it is not capable of running the model, so the highest fps it can achieve is severely limited.

As well as demonstrating that the system can function on less up to date hardware, and that todays hardware is capable of running complex models at high framerates, another notable result is the difference between the 780TI and the 780. The results for both are very similar. The only model where a noticeable difference appears is Caen. Given that the framerates are much higher than required the extra improvement is of little value. On St Kilda, the toughest model and therefore the model where extra power would be most helpful, there is almost no difference.

5.5. Summary of Results

Across a range of hardware and a range of content it has been shown that the VTTP architecture, implemented through OVW technology, can run at acceptable levels. Content, display mode and hardware available all have an impact on what can be run. Graphical options can be adjusted to meet a range of requirements, from accommodating less powerful hardware to creating the right lighting for a specific scene.

The hypothesis that graphical options have a linear relationship with performance is an oversimplification. The interplay of content, hardware, display mechanism and graphical settings is not on a linear scale. Turning off graphical options is not enough to guarantee good performance in a stressed system. Equally in many situations turning on graphical options will have little impact on performance. The primary graphical setting which impacts performance has been shown to be shadows. Enabling shadows radically changes the image being displayed and incurs a severe performance penalty. Other graphical settings have less of an impact. When the system is toward the limit of what it can handle turning on graphical settings can have the effect of pushing the system past the limit of what it is capable of. When this happens settings that might otherwise have had little impact may cause an unexpectedly large drop in performance. Field of view has been shown to have a relatively consistent effect on performance. Reducing field of view may be an overlooked way to increase performance in

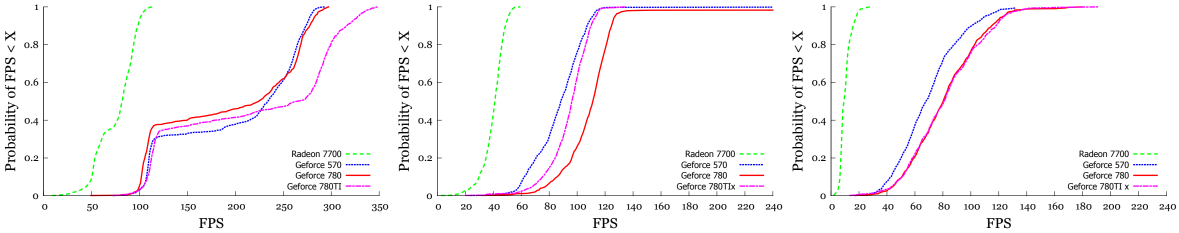

Figure 9: *Framerate CDFs for four hardware configurations: for from left to right the Caen, Cathedral and St Kilda models.*

marginal situations. Resolution has been shown to have a comparatively small impact on performance.

Models built with large numbers of meshes are likely to be more challenging to render than those built with prims. If a computer is struggling with a high mesh count model disabling shadows will increase performance. When shadows are enabled sunrise and sunset will produce high impact graphical effects, with shadows disabled the same light settings appear incongruous. These measurements show the importance of making informed decisions about model creation, hardware and graphical settings.

6. Conclusion

The measurement study presented in this paper has underpinned the creation of historic scenes built using virtual world technology, that have been installed in museums across Scotland. The impact of these has been exciting. For example Taigh Chearsabhagh museum experienced a year on year increase in visitor numbers of 23% and Eyemouth Museum an increase of 44%. It has opened up new audiences for cultural heritage by tapping into the digital literacies that are fast becoming common place in younger generations. Marri Morrison summarises the experience of school students exploring the virtual St Kilda: *They seemed to master the technology, on the whole, swiftly and competently and were mesmerised and enchanted by the opportunities it gave them for movement, visualisation and imagination as they travelled through an unfamiliar terrain and yet a tangible world. Their feedback was instantaneous and heartfelt. 'Awesome', 'It's the best thing ever', 'Tremendous', 'It feels like youŠre really there'* [Mor14]. For these experiences to be realised, 3D technology needs to be cheap, accessible and to work. This paper has demonstrated that complex, interactive, 3D environments can be developed using Open Virtual World technology, deployed on commodity hardware and provide an appropriate quality of experience for high quality installations.

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