

Using high resolution displays for high resolution cardiac data

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The ability to perform fast, accurate, high resolution visualization is fundamental to improving our understanding of anatomical data. As the volumes of data increase from improvements in scanning technology, the methods applied to rendering and visualization must evolve. In this paper we address the interactive display of data from high resolution MRI scanning of a rabbit heart and subsequent histological imaging. We describe a visualization environment involving a tiled LCD panel display wall and associated software which provide an interactive and intuitive user interface.

The oView software is an OpenGL application which is written for the VRJugler environment. This environment abstracts displays and devices away from the application itself, aiding portability between different systems, from desktop PCs to multi-tiled display walls. Portability between display walls has been demonstrated through its use on walls at both Leeds and Oxford Universities. We discuss important factors to be considered for interactive 2D display of large 3D datasets, including the use of intuitive input devices and level of detail aspects.

Keywords: High resolution displays, cardiac imaging, visualization

1. Introduction

Many of the problems investigated in the life sciences involve datasets with increasingly large volumes of data that span multiple spatio-temporal scales and modalities. This trend is driven by the increasing resolution of modern imaging technologies. Resulting 2D slices and 3D volumes are significantly larger than those that have typically been handled on desktop computers for viewing and analysis. This means that the methods of data extraction, rendering and display must adapt, ideally in a way that is scalable to address the certain future increases in resolution.

The long-term context is the drive towards personalised medicine, which builds on the appreciation that medical interventions need to be tailored for the patient, not ‘just’ the disease. Increasingly detailed medical imaging data require new tools for visualization, exploration, annotation, evaluation, and training. These tools need to support medical decision making in real time, or at least within a time frame that is comparable to modern laboratory parameter assessment (hours, not weeks).

In this paper we illustrate our contribution to data visualization, exploration, and annotation, focusing on two datasets from a project addressing the individual histo-anatomy of a rabbit heart. The heart was first scanned non-invasively, using

high-resolution magnetic resonance imaging (MRI), providing a uniquely detailed 3D dataset of cardiac anatomy. Subsequently, the whole organ was serially sectioned for histological staining and light microscopy, providing a stack of 2D extended histological sections. The scale of the data (1.5 GB for the MR data, 1.4 TB for the histology stack) prohibits their viewing in full resolution on conventional display equipment (Plank *et al.*, 2009)).

Our aim was, therefore, to develop a visualization environment, both hardware and software, that would allow scientists to examine as much of the image data in high resolution as possible, whilst maintaining context for the entire scene. This has led us to exploit high resolution display technology capable of rendering over 50 million pixels. Equally important is the development of software that allows use of this technology in a way that is both interactive and intuitive.

2. High Resolution Displays

Standard computer display devices are designed for use “at arm’s length”, for which a density of around 100 pixels per inch (ppi) is generally regarded as optimal for viewing. This corresponds for example to a 17 inch monitor, with resolution of 1280×1024 (SXGA), just over 1 million pixels, or a megapixel. The problem for cardiac images with a resolution of 32000×32000 , i.e. just over 1 gigapixel (10^9 pixels), is obvious: they contain two orders of magnitude greater detail than can be displayed on standard equipment.

The only option available today is to increase the physical size of the display. One possibility is to use projection; a single projector does not offer sufficient resolution (currently limited to 8 megapixels), but arrays of projectors can be used to provide a tiled display. For example, the GigaPixel laboratory at Virginia Tech uses an array of VisBlocks (<http://www.visbox.com>) to provide a large screen, high resolution facility: each of the 18 VisBlocks has resolution of 1280×720 pixels, totalling over 16 megapixels. However there remain limitations: despite successful research into blending, the alignment of projectors still poses a challenge; projectors are expensive; and require considerable space between the projector and the viewing surface. Moreover, a person standing in front of the screen will cast a shadow unless back projection is used, which further increases demands on space and expense.

A cost-effective solution is to build an array of LCD screens, arranged so as to provide a single large display surface. These tiled LCD panel displays are becoming increasingly popular: they allow a pixel density equivalent to a desktop monitor. This density is much higher than can be achieved for equivalent expense using projectors. Moreover the space required is considerably less. This makes them attractive for applications such as biomedical image inspection. Another advantage of the tiled LCD panel is with respect to the brightness of the display, which is greater than with a projection solution, allowing operation under normal room lighting.

A broad overview of high resolution display technologies is given by Ni *et al.* (2006). In this paper we focus on our own experience of using a tiled LCD panel display, the *Leeds Wall*. This tiled display, shown in Fig. 1, is comprised of 28 flat panels, each of resolution 1600×1200 , arranged in four rows of seven. This constitutes a 52.5 megapixel display. The LCD panels are connected to seven computers, all equipped with two nVidia 7800 GTX graphics cards running two panels each. The computers are connected via gigabit (Gbit) ethernet to each other and to



Figure 1. View of a histological slice of a rabbit heart on the LeedsWall. Histology data courtesy of Rebecca Burton, Fleur Mason and Fahd Mahmood, Oxford University

a central filestore. The total hardware cost, including the custom-made stand, was under £30 000, which compares favourably with multi-projector solutions (Johnson *et al.* 2004). For full details of the construction of the wall see Hodrien *et al.* (2007).

One disadvantage of the tiled LCD panel displays is the potential for distraction by the monitor frames, or bezels. We have experimented with two approaches to rendering. The first is to simply ignore the gaps, and render every pixel in the image leaving the user to neglect the borders. In our experience users can do this easily, especially when immersed in a scene. The second option is to set up the display software to automatically adjust for the gaps, as though the user was looking through a window with bars across it. The disadvantage of this method is that additional processing power is required to set up the multiple viewports. Also, part of the data is obscured from view. The latter may be an important consideration if the display wall is used to search for detailed targets that may be obscured. Mackinlay and Heer (2004) consider this problem in depth, arguing for a solution where the window metaphor is used so that geometry looks natural (diagonal lines will cross boundaries as straight lines with a gap, which the user finds easy to ‘fill in’) but where any labels are always displayed in full.

The successful application of a large display wall to bio-medical applications does not only depend on the screen hardware, but also on the input devices used to control applications. A standard keyboard and mouse would not be appropriate for users standing in front of the display, possibly walking along the length of the display. We have therefore experimented with a gyromouse, a FrogPad keyboard, Flock of Birds controllers, and a wireless games controller. For our cardiac application we have used primarily the games controller joystick. This provides both analogue and digital control options, including a variety of configurable buttons. This has proved to be a suitably intuitive device for new users, regardless of whether they have experience of using similar input tools on computer games consoles.

3. Software for Tiled Displays

Several different packages support synchronised visualization across multiple displays, based on a range of computational resources. We have evaluated Chromium, SAGE, Distributed Multihead X (DMX), VNC and VRJuggler. The last package proved to be most suitable for our cardiac application.

Chromium (Humphreys *et al.*, 2002) is a tool for cluster-based rendering. It wraps existing programs, intercepting the OpenGL calls and distributing them to the machines of the cluster for rendering. This minimizes the effort required to adapt existing software for a tiled display, but it also imposes fairly important limitations. Significantly Chromium can only be used with OpenGL applications. In addition, we found that Chromium is very demanding on the network, especially the head node, unless one uses display lists. When the network is heavily loaded, synchronization between the screens can be compromised.

SAGE (Jeong *et al.*, 2006) was designed to provide a flexible environment for running multiple applications on high-resolution tiled displays. It allows for separation between the back-end systems that create visualizations, and the front-end systems that render them. This separation, as with Chromium, means that high bandwidth interconnects are required for good performance. Even with 1 Gbit networking we found SAGE provided low frame rates and delayed interaction, and the performance appeared highly dependent on the resolution of the displayed windows, unlike non raster-based systems.

DMX (<http://dmx.sourceforge.net>) allows a logical X-server to be created across multiple X-servers. The entire wall can thus be treated as a desktop allowing windows to be dragged around freely. Our attempts to utilise DMX were not particularly successful: testing on 4 screens suggested potential, but with 28 screens the latency of interactions outweighed the benefits of this solution.

VNC (<http://www.realvnc.com>) provides a very simple method for rendering onto high resolution displays. A single VNC server has an off-screen X server, set to the size of the wall. Each cluster machine then runs a VNC viewer and displays the relevant part of the image. Any X-application can thus be run on a display wall, as with DMX. However, this approach places a heavy load on the off-screen X server, as it is forced to handle the entire wall area on a single machine, which affects scalability. Slave machines also receive a large volume of data across the network, a problem common to all image-based systems. A more promising approach is to embed a VNC viewer within a VRJuggler application, since this reduces the resolution of individual VNC servers to the size of the displayed window. Multiple applications may also then be rendered on the wall.

VRJuggler (Bierbaum *et al.*, 2001) is an application framework that replaces GLUT (the OpenGL Utility Toolkit which provides a portability layer shielding programmers from operating system and window system dependencies) in the traditional OpenGL software stack. It is necessary, therefore, to rewrite the application, although the work involved in doing so is fairly minimal. Window creation, viewport/camera management, and input handling are all different from GLUT. The benefit is that one can write an application that works on a desktop or a display wall, with no need for modification to the code. A configuration file is supplied at run-time which describes the system in use, and input and shared variables are distributed amongst the cluster nodes. Our experience with VRJuggler has been

very promising. The effort required to convert a program is minimal, and the process is well-documented. Since the geometry and resulting rasters are generated separately on each node, VRJuggler has the advantage of greatly reducing network traffic, compared to Chromium. In fact, the minimum traffic required with VRJuggler is in the order of hundreds of bytes per frame which is unproblematic.

4. Application: Histology Image Viewer

An OpenGL image viewer was created that can load an image and render it on the wall using VRJuggler. Application of compressed textures was also explored as a way of reducing memory usage of the graphics cards, although this either places a burden on the graphics cards at run-time (causing stuttering) or requires a pre-processing step. The largest image tested thus far was an example with 170000×100000 pixels (or 17 gigapixels), although there are no architectural limits other than those imposed by the use of the TIFF format. Images are first converted into pyramid tiled TIFF files, and then rendered on the display wall using VRJuggler and a pixel-perfect scaling system, i.e. one pixel on the display wall is equal to one pixel in the image. Images are loaded dynamically, streamed across the network from a networked file server. A wireless joypad allows the user to control image viewing without restrictions to movement in front of the screen. This provides the user with the ability to navigate an image with analogue controls for panning and zooming.

Figure 1 illustrates the appearance of a trichrome-stained section of cardiac tissue, as described by Burton *et al.* (2006). The native tissue sections have dimensions of up to 3×5 cm; their 2D digital images therefore are composed of up to 2000 individual microscopic projections (each with 3.3 megapixels), which are tiled together to generate one extended high-resolution image of the section, with pixel dimensions of $0.546 \mu\text{m} \times 0.546 \mu\text{m}$ (Plank *et al.*, 2009). As highlighted above, images of this size cannot be viewed efficiently on normal desktop hardware. User inspection is vital, however, as the tiles sections are obtained in semi-automated runs, with no need for qualified user intervention or observation. Thus, the development of tools to generate large-scale high-resolution histological data has thus far not been complemented by approaches to actual interactive assessment of results. The solution presented here offers a powerful new approach for bio-medical staff to visually inspect their data at native resolution.

The image tiles are loaded as required, rather than at start-up, both to avoid the time cost of loading the full dataset, and to allow handling of images larger than the available RAM of the machines. This then necessitates the loading of image data during run-time, while maintaining the performance of the interface for the user. A separate texture manager thread loads the required images, so that they are available to the draw thread as necessary. Rendering is performed using lower resolution textures if this texture thread falls behind the user's interaction, so the user is left with a lower resolution view, but one that still pans and zooms freely. This enables the application to maintain a high frame rate ($>30\text{fps}$) at all times.

Additional facilities are provided to assist with navigating around such a large image. A thumbnail view in the top-left corner of the display wall provides the user with an overview of the current display relative to the overall image. The user can place annotation markers on the image, which appear both in the full and the

thumbnail view. These markers provide a visual cue to points of interest in the image, and serve as direct navigational aids as the user can jump between markers.

The system records sessions to disk, so that they can be replayed later. Every interaction is recorded, so the replayed session appears identical to the original run. This has applications for training, and provides information that may help to quantify the efficacy of the system.

5. Application: 3D MRI Viewer

Full 3D reconstruction of rabbit cardiac histo-anatomy has become possible thanks to high quality MRI data, provided by the team of Jürgen Schneider at Oxford University. The MRI data voxels have an in-plane dimension of $26.4 \mu\text{m} \times 26.4 \mu\text{m}$, and an out-of-plane size of $24.4 \mu\text{m}$. In total, 1440 16-bit TIFF images with a resolution of 1024×1024 pixels were used for post-processing. The segmentation of this near-isotropic 3D dataset from the original scans, as described by Goodyer *et al.* (2007), removed minor imaging-related artifacts, so that clear boundaries between tissue surface and non-tissue create effectively a binary volume. From this volume we used isosurfacing techniques to interconnect the boundaries of the tissue, employing the freely available VTK libraries (Schroeder *et al.* 2006). This approach is described in more detail below, and follows the method described earlier by Young *et al.* (2008) for CT data of bone structure.

To perform the isosurfacing we employed the *ContourFilter* routine in VTK. Surfaces produced by the above procedure tend to be noticeably jagged. This is caused by the rectangular acquisition grid, and will tend to generate sharp joints at ‘corners’. We know *a priori* that such boundaries are smooth in biological samples. Thus, by applying a smoothing algorithm, we generate surfaces which mirror the overall shape of the data without being constrained by the ‘false precision’ of the boundaries. This smoothing operation is not only important in terms of providing visual realism, but also for subsequent use of data in simulations of cardiac behaviour or external interventions such as defibrillation (which otherwise would cause spurious current peaks at sharp changes in surface geometry). It is, however, imperative not to smooth too much, as real features in the data, such as fine processes of the Purkinje network in the heart, could be lost.

The final step of data pre-processing is a reduction in the number of triangles generated. In smooth sections of geometry it is possible to map a surface using significantly fewer points than originally generated. Again, we used VTK for this operation, to produce good quality surface reconstructions with a reduced number of triangles. For the whole heart used in our example, a high resolution geometry can be based on 45 million triangles.

In order to speed-up the rendering routines, we have further post-processed the generated output files. By reordering the triangle strips into smaller sub-volumes within the entire set, it is possible to write the visualization application in such a way that any section that is not visible in the viewing window will not be processed.

The software package that we have developed, called *oView*, loads previously defined surfaces, generated as described above. Some aspects have been explained previously by Goodyer *et al.* (2007). The advantage of isosurfacing and smoothing during the pre-processing stages is that computationally expensive operations on large datasets will be performed only once, and then loaded as many times as needed

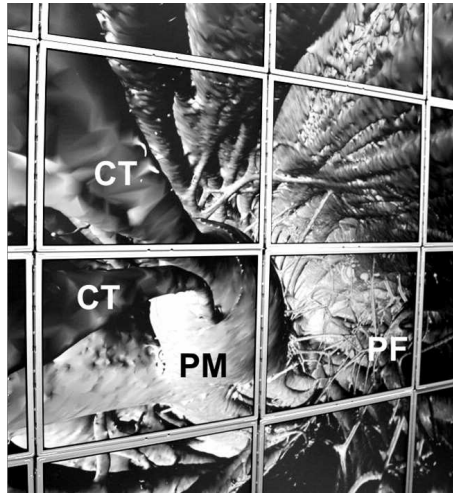


Figure 2. Detail from the tiled display wall

(The visualization shows baso-apical inside view of left ventricle with chordae tendinae (CT) projecting upwards from papillary muscle (PM). Also visible is the fine Purkinje fibre (PF) network of cardiac ‘telegraph lines’, which conduct the electrical signal swiftly all over the cardiac chambers. MRI data courtesy of Jürgen Schneider and Patrick Hales, Oxford University)

for different visualization purposes. This reduces loading times to a few seconds, compared to isosurfacing and smoothing, which can take from minutes to an hour, depending on size of dataset and the quantity of smoothing operations performed.

The visualization program employs standard OpenGL features to apply realistic lighting effects for enhanced realism, as illustrated in figure 2. This shows a detail view inside the left ventricular chamber. It is possible to include other data in the same space, such as text markers, or the segmentation of the vasculature. This provides an excellent opportunity for the development of anatomical teaching and assessment tools, with potential extension towards functional representations based on mathematical modelling-derived illustration of electrical potential gradients during the spread of normal or disturbed cardiac excitation, or the consequences of external electrical shock application for defibrillation of the heart.

The isosurfaces generated correspond to the sum of all interior and exterior surfaces of the heart. These include small voids within the myocardium (such as interstitial clefts and vessels; for example inside the ‘open’ papillary muscle representations in figure 3A), and also fine structures within the cavities (such as free-running Purkinje fibres between papillary muscle and left ventricular free wall in figure 3A). In the absence of an indication of tissue versus non-tissue volumes, visual distinction between muscle and cavity can be difficult. To aid visual perception, it is helpful to superimpose MRI images onto the tissue surface rendering. This provides good visual cues for tissue identification (see figure 3).

Important features implemented for navigation of the datasets include translocation along any path in the 3D coordinate system, panning, rotation, and zooming. Another important navigation technique is the use of an additional cutting plane. As opposed to zooming, where the magnification (and hence projection of the data

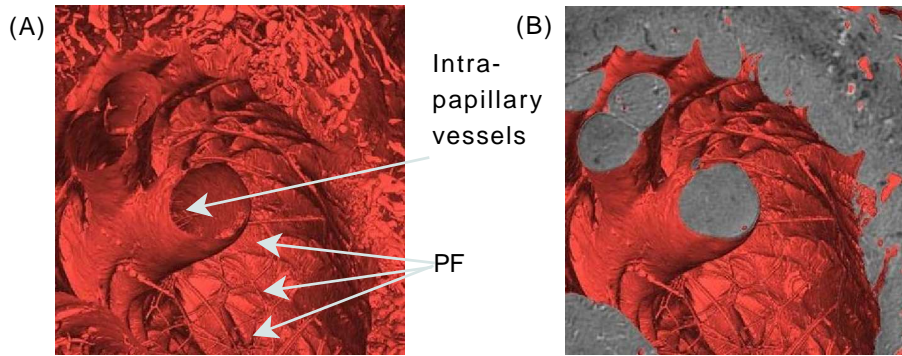


Figure 3. Comparison between two identical views of the isosurfaced left ventricle in the absence (A) and presence (B) of additional MRI slices overlaid onto the 3D surface

onto the display) changes, a cutting plane allows a steady projection area on the screen, whilst revealing successive sections that would otherwise be hidden from view. This is helpful when scanning for regions of interest, such as insertion points of free-running Purkinje fibres into the solid cardiac muscle, or tissue abnormalities arising from re-modelling, for example related to myocardial infarction. By first approaching the area, using progression through cutting planes, followed by zooming to increase detailed presentation, this allows unprecedented ease of exploration of complex 3D datasets.

Additional benefits arise from the inclusion of extra data modalities, such as text labels and navigational reference points. Labels are an important guide to help users in identifying structures or locations, and aid independent multi-user evaluation of data as well as training and assessment. For text labelling, key features are initially identified manually, assigned to a coordinate, and then displayed on screen whenever the relevant coordinate is in the field of view. Navigational reference points are stored as ‘way-points’, containing viewing position, angle and magnification, to allow one to re-trace a trajectory, or to map out features of interest. Automated transition between these positions allows one to create a continuous guided fly-through. In addition, navigational points can be exploited to identify regions of interest, which may then be re-visited off-site, using more generally available equipment. This extends the utility of display wall applications from a few reference sites to more general and distributed access by bio-medical personnel.

The major advantage of using a high resolution display is that very fine detail can be seen without losing the contextual information about where in the dataset one is. Orientation is further aided by a ‘thumbnail’ image of the whole 3D structure (figure 4) showing where the user’s view is located, relative to the whole organ. When the view ‘enters’ the tissue, a cutting plane is applied to the thumbnail, in order to provide positional information, while projection of reduced-resolution MRI slices ‘behind’ the cutting plane aid histological substrate identification.

In order to increase the performance of the software we have also generated an additional highly decimated volume. The relatively small amount of extra memory used for this is more than outweighed by the advantage provided by visualization of this dataset (rather than the higher quality one) whenever the user is moving the scene. This means that the overall user experience is dominated by ‘movie-like’

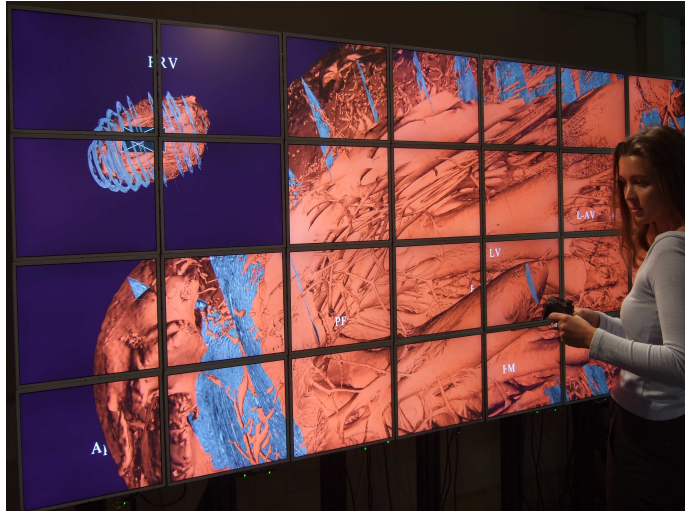


Figure 4. Display wall user viewing the long-section of the whole rabbit heart. Navigation is performed using the handheld wireless controller

quality of translocation, achieved by a frame rate of 25 per second, even when the maximum number of triangles is viewed.

6. Conclusions and Future Work

In this paper we have shown how high resolution displays can be applied to the large datasets that emerge from modern life science applications. It has been shown that 2D images of arbitrary size can be interactively controlled across multiple computational resources. The use of the pyramid tiled TIFF image format supports instant access to the appropriate sections for display at an optimum resolution. For 3D geometries we have demonstrated how high resolution geometries can be displayed in a visually helpful format. Interactivity, when moving through the volume, is enabled by background-use of a lower resolution dataset. Both for 2D and 3D applications, thumbnails, labels and navigational markers have been implemented in order to offer additional functionality for the user.

This technology is not limited to one site. A similar display wall has recently been commissioned at the Oxford e-Research Centre, and is now used to display way-point based reconstructions of explorations conducted at Leeds.

Future work aims to combine the two sets of source data (histology and MRI) in a more accurate and efficient manner. Full 3D registration of each histological slice to the MRI volume is a challenging task, which is at the heart of an ongoing BBSRC-funded research initiative (Plank *et al.*, 2009). Once this has been accomplished we intend to apply textured sheets of histology onto the volume dataset, to provide high resolution cut-planes at any angle, independent of the original alignment of native sectioning planes.

In anticipation of the increase in 3D data size, required to address clinically relevant scenarios, we will assess the use of off-screen rendering. At present, the full 3D cardiac data volume can fit into RAM on each machine, and the generated geometry can be stored in the graphics cards' memory. However, it is not difficult

to see that larger datasets would exceed these limits, as data requirements increase faster than computational memory. By splitting the data up onto a remote renderfarm, it would be possible to add another level of detail, or expand visualized tissue dimensions. Other potential developments will come from better integration with emerging technologies which may include the use of 3D displays, haptic feedback controllers, touch screens, and tracking of user position and observation target.

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