(Focus + Context)^3: Distortion-oriented Displays in Three Dimensions

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Abstract

Three-dimensional datasets are becoming increasingly common, especially the use of large 3D datasets in Geographical Information Systems (GIS) applications. Similar problems are likely with 3D datasets as have been found with large two-dimensional datasets; namely the loss of context when examining a particular area of the data in detail. This paper proposes a solution based on three-dimensional distortion-oriented displays, building on previous work on such displays for two-dimensional datasets. Two such 3D distortion-oriented displays are described: the 3D Cartesian Fisheye display and the 3D Polar Fisheye display (after their two-dimensional counterparts, the Cartesian Fisheye and Polar Fisheye displays, respectively). These displays are tested with a very small 3D dataset as proof of concept, and it is proposed that their operation be examined when applied to large datasets.

1. Introduction

The visualisation of data in two dimensions is one application of graphical computer displays that is used widely in many different circumstances, including entertainment, industry and education. If the data can be displayed easily on a traditional computer monitor, the users will be able to glean useful information from that display. However, often the data that the user wishes to examine will be too large to be displayed on the computer screen, while retaining a reasonable resolution of that data.

For example, consider a dataset containing cartographical information about the Australian shoreline. If this dataset is fairly simple, say the map is accurate to within 10km, then the whole dataset can be accurately displayed on the screen at once. However, if the dataset is more accurate, say to within 10m, then there is not enough room on the screen to display the data in full detail.

One solution to this problem has been to approximate the data to the point where it can be displayed on screen in its entirety. Then, users who want more information on a certain area, can select that area for more detailed viewing, and the screen will 'zoom in' to display the selected area instead of the overall view of the approximated data. This approach presents another problem, however, in that once the data has been zoomed in on the screen, the user can quickly forget which part of the overall dataset is currently visible. Essentially, the user has lost 'context' with the rest of the data.

In small datasets, this context problem is not severe, as the user can usually gain a reasonable idea of context by simply zooming out. However, in large datasets, in order to reach the maximum level of accuracy of the display, the user will often have to zoom in a number of times. Being required to zoom back out multiple times to maintain context with the data is annoying at best.

In general terms, the least accurate portrayal of the data, which visualises the complete dataset on screen, is termed the 'context view'. Zooming in on a section of the data, amounts to 'focusing' on that section. The problem, therefore, is usually called the "focus + context problem".

1.1. Distortion-oriented displays & non-linear magnification

The primary approach to solving this problem has been the use of non-linear magnification, or distortion-oriented displays. In a distortion-oriented display, the user can manipulate a focus region, which does not take up the entire display screen. The area under scrutiny is focused on by magnifying the data to the desired level within the focus region. The area outside of the focus region is distorted in such a way that it allows the user to retain context between the area under examination and the rest of the dataset, and usually 'stretches' so as to fill the remainder of the screen. Thus the focus area is magnified to allow thorough examination of the maximum resolution of the data for a certain area of the dataset, and the area outside of the focus area is distorted (de-magnified) to ensure that the rest of the data will fit on the screen in some form.

Until fairly recently, distortion-oriented displays had only been used effectively with relatively small datasets. The major difficulties when attempting to scale to larger datasets were twofold: poor response time and unusable displays at high magnifications. Response time is obviously important, and should be as small as possible. As the user moves the focus area about the screen, focusing on different parts of the dataset, any jerkiness in the update of the display detracts from the useability of the interface, thereby reducing the usefulness of the dual (focus + context) areas. The issue of degree of magnification is also important with large datasets, since the difference in magnification between the context area and the focus area can be very large. Typical distortion-oriented displays become essentially unusable beyond about 10x magnification in the focus area, as the distortion required to display the remainder of the dataset in the context area is too great.

Smith, however, demonstrated that with careful use of display reuse and image degradation, response times for large datasets could be minimised to within a useable range, on standard display hardware. Furthermore, using a frustum display, magnifications of up to 100x could be displayed in the focus area, while minimising distortion in the context area, thus maintaining useful context with the rest of the dataset [9].

1.2. Moving into three dimensions

Distortion-oriented displays have been used with various two-dimensional datasets. One area in which they can now be of particular use is in Geographical Information Systems (GIS). GIS applications typically require the viewing and manipulation of huge datasets, and the ability to view one area of the data in detail while maintaining context with the whole dataset is of great advantage.

However, there are becoming increasingly many situations where the data that is to be viewed and manipulated is three-dimensional in nature. For example, oceanographers and marine biologists may wish to view underwater populations in different areas and depths of the oceans. Mining companies could obtain potentially valuable information from a three-dimensional visualisation of previously located ore or oil deposits in a certain geographical region, including depth underground. The horticultural industry could benefit from information about soil composition at different depths and over different areas of land. All of these applications, and many more, require visualisation of three-dimensional data on the screen.

Up to this point in time, various software programs for visualising three-dimensional data on screen have been developed (e.g. 3D analyst from ESRI). However, when dealing with potentially very large datasets, they suffer from the same problem as their two-dimensional counterparts did: lack of context.

1.3. This paper

The rest of this paper looks at the problem of lack of context in displaying three-dimensional data on a two-dimensional computer screen, and at a proposed solution in development. Section 2 looks at related work in the fields of distortion-oriented displays, non-linear magnification and three-dimensional data visualisation. Section 3 examines two possible solutions to the focus + context problem where three-dimensional datasets are concerned: a 3D distortion similar to the Cartesian Fisheye display, and a 3D distortion similar to the Polar Fisheye display, both from Sarkar and Brown [8]. Section 4 explains where this project is heading, and section 5 lists references used in this paper.

2. Related work

This section of the paper briefly discusses some work related to the current project. Section 2.1 looks at previous work in the field of distortion-oriented displays, while Section 2.2 examines past efforts at visualising three-dimensional datasets.

2.1. Distortion-oriented displays

The concept of distorting aspects of a two-dimensional representation of some sort of data has been around for many decades. Maps, such as those of underground tube train stations in large cities, have often distorted sections of the map to produce a more aesthetically pleasing, if slightly inaccurate, display of the areas mapped. Interactive, computer-based distortion-oriented displays were first developed within the last twenty years, however.

Spence & Apperley developed the first recognised interactive distortion-oriented display technique, the ‘Bifocal Display’, in 1982 [10]. The bifocal display is divided into three regions horizontally across the screen. The centre region is the area of focus; here the data is magnified for close inspection. The regions either side of this central region then display a distorted, demagnified view of those objects not located in the focus region. Since this display distorted data in only one dimension, however, this display was of limited use.

In 1989, Leung proposed an extension of the bifocal display into two dimensions [4]. The 2D bifocal display is divided into 9 regions, with the central region providing the user with a focus area magnified in both dimensions, surrounded by the remaining eight regions, which are demagnified in dimensions depending on their placement. Thus the four corner regions are distorted in both dimensions, whereas the other four regions are only demagnified in either ‘width’ (left and right sides) or ‘height’ (top and bottom regions).

The ‘Perspective Wall’ was developed in 1991 by MacKinlay and others [6]. Its appearance is based on what the user would see if the data were mapped onto a wall, with edges that led back into the distance. The display around the central focal region is distorted based on how close it is to the focal region. It has been noted that the bifocal display is a special case of the perspective wall technique, where the viewer is positioned at infinity, and thus the ‘sides’ of the ‘wall’ have constant distortion throughout [5].

Finally, the ‘Graphical Fisheye’ display was based on the earlier ‘Fisheye View’ [2] and its descendants, and was developed in 1992 [8]. Using this technique, smoothly changing magnifications of different areas of the data could be displayed on the screen, removing this problem of the perspective wall and other techniques. The graphical fisheye techniques have only been used effectively with datasets where the focus point is magnified at less than 10x. Exceeding this degree of magnification has tended to make the context information unusable.

More recently, Smith proposed solutions to the problems faced by these other techniques [9]. By using a frustum model for the distortion, where the focus area is displayed on the ‘top’ plane of the frustum, and the rest of the dataset is distorted along the ‘edges’ to the edges of the display screen, a distortion-oriented display was created that still allowed the retaining of context information to focus area magnifications of up to 100x. The magnification changes across the display are not completely smooth, but this problem is reduced by having a small region around the area of focus that is less distorted than the context region around it. In this way, a more gradual change in distortion/magnification is obtained. Furthermore, through the careful application of display reuse (where portions of the information displayed in one frame can be stored and reused in the next, without need for re-calculation) and image degradation (where those parts of the display that are most out of focus can be ‘degraded’, or simplified, significantly), Smith managed to improve the display update time, and thus interactivity potential, greatly.

In 1998, Keahey described a generalised formulation of the ‘detail-in-context’ problem [3]. The term ‘nonlinear magnification’ was used to describe the effects common to all of these, and other, distortion-oriented displays, and general-purpose methods for dealing with the problem were discussed.

2.2. Some properties of distortion methods

Smith also categorised distortion methods based on some of the properties which they exhibit in distorting the data [9].

They can be usefully divided into cartesian or orthogonal distortions, in which each coordinate of each data point is distorted based on the scalar difference between it and the corresponding coordinate of the centre of focus; and polar or radial distortions, in which each point of the data is distorted based on the actual (vector) distance between it and the centre of focus.

Furthermore, whether cartesian or polar in nature, it is useful to consider a distortion function as distorting the data continuously or non-continuously. A continuous distortion function defines some degree of magnification at the centre of focus, and a continuous mathematical function that decreases that magnification gradually with distance from the central point. A non-continuous distortion function defines some degree of magnification in a region of a certain size, surrounding the centre of focus, and some mathematical function that decreases magnification of points outside of that region.

Smith pointed out that continuous distortions (such as the Fisheye displays mentioned previously) distort data around the area of focus as well as outside, in the context area, which is generally undesirable. Non-continuous distortions, however, define an area of focus explicitly, in which the magnification is constant (no distortion within this region) [9].

Figure 1 shows a plot of original distance of data points from the centre of focus (x-axis) versus distorted distance from the centre of focus (y-axis) for a continuous and non-continuous distortion function (both fictional).

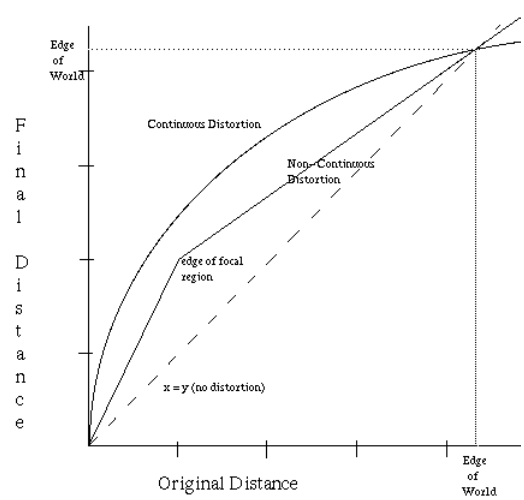

Figure 1. Graph of original vs. distorted distance.

2.3. Display of 3D datasets

There are many commercial applications available that visualise three-dimensional data and display that visualisation on a two-dimensional computer screen. The large field of Geographic Information Systems is especially demanding in its use of visualisation of three-dimensional datasets, which tend to be very large and detailed.

In general, the data is displayed on the screen and can be rotated, tilted and/or zoomed in/out at will. If the user wishes to examine a certain section of the data from a certain viewpoint, he/she can zoom in and position the viewpoint, and the information can be examined. However, in much the same way as with applications for examining two-dimensional data, once the user zooms in on one particular section of the data, the overall view of the whole data set, and where this zoomed-in section occurs within it, is lost.

Two examples of applications for visualising a dataset in three dimensions - one commercial, the other research-based - are 3D Analyst, a 3D extension to the ArcView program, from ESRI [1], and a technique for visualising a system structure with three-dimensional graph structures [7].

ArcView is a commercial GIS for visualising large, complex geographical datasets. The 3D Analyst extension to ArcView provides "…a rich suite of methods for interactive perspective viewing including pan and zoom, rotate, tilt, and fly-through simulations" [1]. It is an impressive-looking package that allows the user to examine a realistic three-dimensional visualisation of a dataset at different magnifications and from different viewpoints.

A novel use of three-dimensional visualisations is that by Quigley to display the structure of a software system as a dynamic, three-dimensional graph [7]. A good interface for such a system would enable the user to view the graph as a whole from whatever viewpoint is preferred, and also to examine any node or group of nodes in further detail. The issue of graph complexity for large programs was not discussed in any great depth, but would be important to maintain useability of the interface.

Existing methods, techniques and applications for displaying three-dimensional data suffer from the same fundamental problem as did two-dimensional visualisations: the user cannot maintain context within a large dataset, while viewing the data at a useful level of magnification.

3. Focus + Context in Three Dimensions

The problem of loss of context when examining large two-dimensional datasets has been addressed, and useful solutions found and implemented. Using Smith's STAR architecture and FRUSTUM display [9], it is possible to visualise parts of a large two-dimensional dataset at a useful level of detail, while retaining context with the remainder of the data on screen.

Increasingly, however, we are finding it necessary to be able to visualise three-dimensional datasets on a computer screen, as discussed briefly in section 2.3. The problem of loss of context in this situation is similar to the two-dimensional case, but the amount of data in a three dimensional dataset is much larger than that in a two-dimensional dataset of similar proportions. To solve the problem, then, and provide a workable three-dimensional distortion-oriented display, we must be able to quickly and efficiently render the relevant data to the required level of detail, while reducing the complexity of data in the (distorted) context region.

MacKinlay investigated the application of 'cone trees' to display large, hierarchical datasets in three dimensions [6], but these are not generally applicable to a wide range of datasets. Further from this, Keahey proposed the application of nonlinear magnification techniques in three dimensions, but did not investigate thoroughly [3].

Building on this small amount of work done with three-dimensional, and on that done with two-dimensional, distortion-oriented displays by Sarkar and Brown [8], the Three-Dimensional Cartesian Fisheye display and the Three-Dimensional Polar Fisheye display were developed. Both of these displays currently distort only endpoints of lines. A more accurate, but more computationally intensive and complicated version of each could also be developed.

3.1. 3D Cartesian Fisheye display

The Three-Dimensional Cartesian Fisheye display produces distortions that are magnified along each axis from the centre of magnification, outwards to the edges. The application of this model of distortion to a test dataset (a 12 * 12 * 12 cubic grid) is shown in Figure 2.

In order to map the original point to the distorted point, the distort function applies a mapping based on the values of the original point's coordinates and those of the centre of magnification, as well as the size of the magnification region and magnification factor. There are two cases that must be considered.

The first case applies when the data point is within the magnification region. When this is true, the mapping from original point to distorted point is simple. Each coordinate of the distorted point (x', y' or z') becomes equal to the corresponding coordinate of the centre of magnification (Xm, Ym or Zm), added to the result of multiplying the magnification factor (M) by the difference between the corresponding coordinate of the original point (x, y or z) and the corresponding coordinate of the centre of magnification (Xm, Ym or Zm, again).

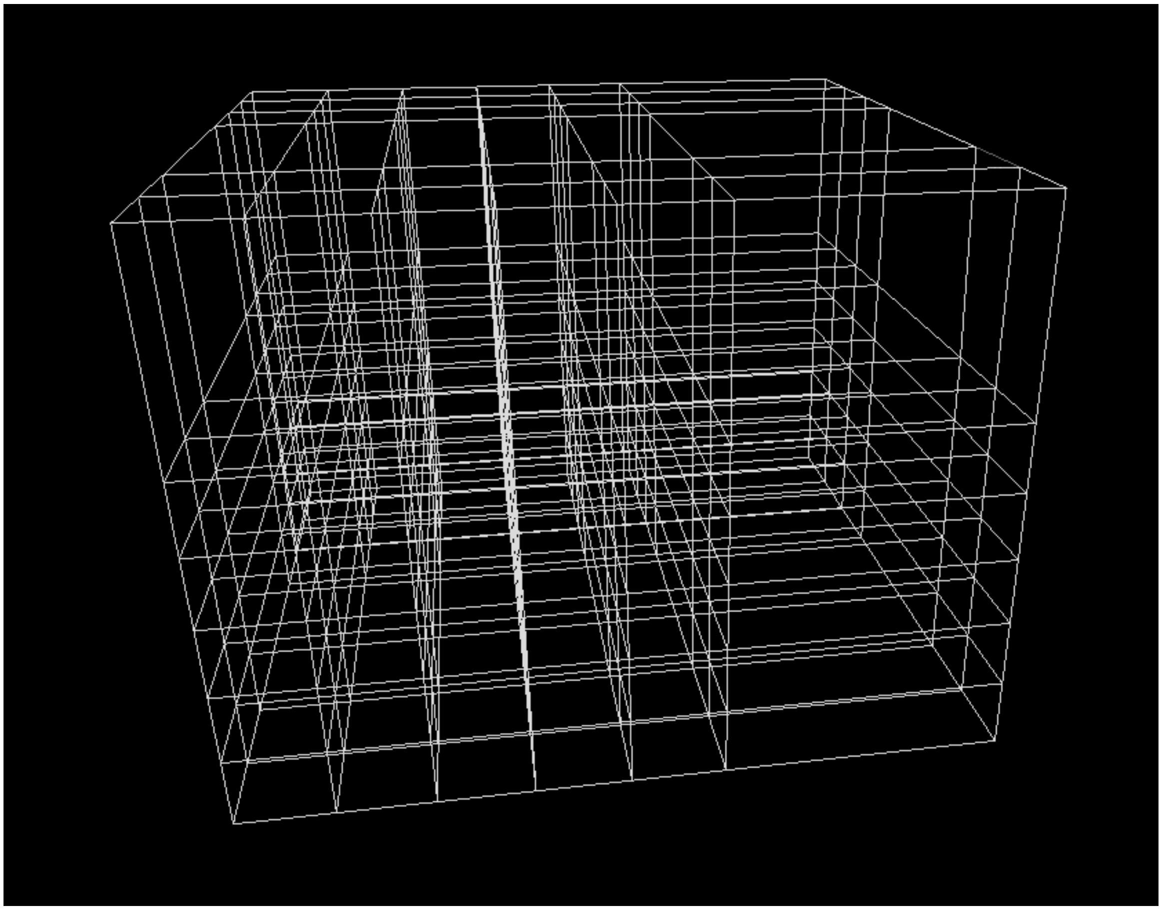

Fig 2. 3D Cartesian Fisheye display of test dataset. Magnification factor is 1.5.

i.e. (x’, y’, z’) = (Xm + M * (x – Xm),
Ym + M * (y – Ym),
Zm + M * (z – Zm))

The second case applies when the data point is located somewhere outside of the magnification region. The mapping applied to produce the distorted point when this is true is identical in form to the above mapping. The distorted point’s coordinates must also take into account the position of the closest edge of the focus region (e.g. Xm + M * MAG_SIZE, for the x coordinate), and some scaling factors (see below), as follows:

x’ = (Xm + M * MAG_SIZE) + scale(x) *
(x – (Xm + MAG_SIZE))

(Note similarity of form to previous equation.)

The scaling factor in this equation (scale(x), and similarly for scale(y) and scale(z)) perform essentially the opposite function to the magnification factor (M) in the first equation; while the magnification factor is the amount by which any points inside the magnification region are magnified, the scaling factors represent the amount by which each of the coordinates of different points outside of the magnification region must be ‘demagnified’, in order to keep the edges of the world constant. A linear distortion is applied across the whole of the context region (i.e. the world outside of the focus region).

The scaling factors must be calculated for each axis before the final (distorted) points can be generated. For any given magnification factor (M), centre of magnification (Xm, Ym, Zm) and size of magnification region (MAG_SIZE), there are two scaling factors for each axis, giving a total of six scaling factors for a three-dimensional dataset (see Figure 3).

If the magnification region is centred on any one axis, then the two scaling factors for that axis are equal, assuming a regular shape for the magnification region and a regular magnification factor.

The scaling factors for any combination of magnification factor, size of magnification region, location of magnification region and size of (finite) world can be calculated as follows: The scaling factor for a given axis in a given direction from the centre of distortion is equal to the distance from the closest edge of the relevant axis to the closest edge of the (magnified) focus region along that axis, divided by the distance from the closest edge of the relevant axis to the closest edge of the magnification region (before magnification) along that axis.

i.e. scale(x) = (EDGE[x] – (Xm+ M * MAG_SIZE)) / (EDGE[x] – (Xm + MAG_SIZE))

(assuming edges of world, focus region and magnification region are on correct axis)

The 3D Cartesian Fisheye display gives predictable and consistent distortions with the current distortion function, and provides a very similar result when applied to a regular three-dimensional grid as does the Cartesian Fisheye of [8] when applied to a regular two-dimensional grid.

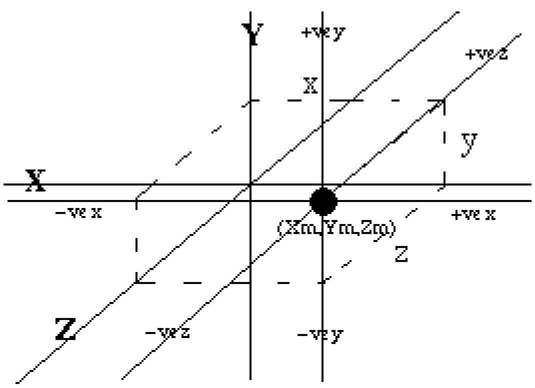

Figure 3. The direction of the six scaling factors (+/-ve x, y and z) for the centre of magnification at (*Xm*, *Ym*, *Zm*).

3.2. Three-Dimensional Polar Fisheye display

The Three-Dimensional Polar Fisheye display uses the radial distance from the centre of magnification to the point under consideration to determine the magnification factor. An example of its application to a test dataset of a 12*12*12 cubic grid is shown in figure 5.

Using this approach, for each point, a 'ray' is projected out from the centre of magnification through the point, and the point is pushed outwards along the ray. The distance that the point is moved is determined by how close its original position is to the centre of the distortion, as well as the relevant distortion region and context region scale factors (see below) and the size of the magnification region. Points closer to the centre of magnification are thus scaled by a greater amount than those further away (see Figure 4).

This is essentially an extension of the Polar Fisheye model of distortion previously used in two-dimensional distortion-oriented displays [8].

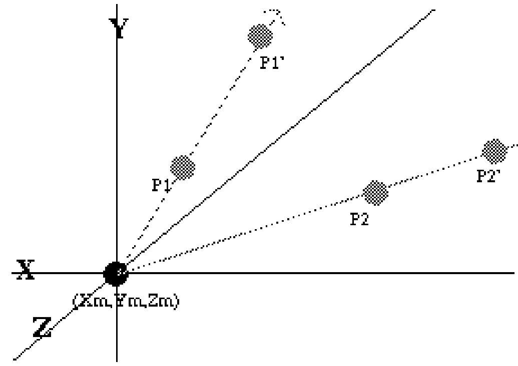

Figure 4. As P1 is closer to the centre of magnification (*Xm*, *Ym*, *Zm*) than P2 is, it's corresponding point is scaled further along the 'ray' than is P2's corresponding point.

As with the 3D Cartesian Fisheye distortion, the input and output to and from the distortion function are the original data point (point[]) and the resultant distorted point (distortedPoint[]), respectively. The data external to the function is almost the same as well, with the small addition of the context region scale factor (CONTEXT_SCALE_FACTOR). Originally, this scale factor has been set to the inverse of the magnification factor (MAG_FACTOR), although it is likely that, for a large dataset, it would instead be calculated to keep the edges of the world constant. For this reason, the edges of the world (EDGE[]) would be required in such a situation, but are not needed for the test dataset (which is very small).

Then, after setting the scale factor based on the location of the point, each component of the distorted point (x', y' or z') becomes equal to the corresponding coordinate of the centre of magnification (Xm, Ym or Zm), added to the result of multiplying the scale factor (scaleFactor) by the difference between the corresponding coordinate of the original point and the centre of magnification (dist[x], dist[y] or dist[z]).

i.e. (x', y', z') = ((Xm + dist[x] * scaleFactor),
(Ym + dist[y] * scaleFactor),
(Zm + dist[z] * scaleFactor))

The 3D Polar Fisheye display also gives consistent and predictable results when applied to the test dataset. The appearance of the distorted grid is similar to that of its two-dimensional counterpart when distorted using the original Polar Fisheye distortion of [8].

3.3. Properties of test distortions

Figure 6 shows another test dataset, a mock landscape consisting of a mountain, some buildings, and a forest

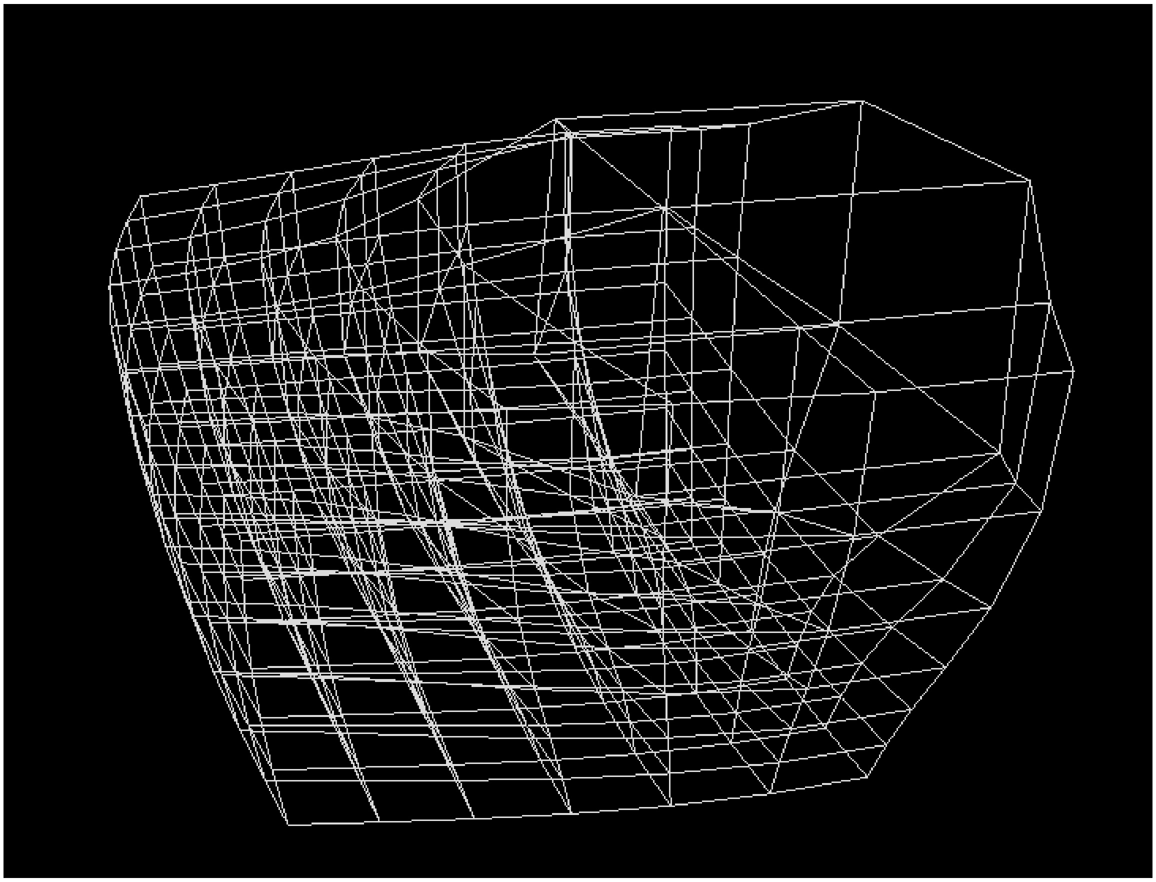

Figure 5. 3D Polar Fisheye display of test dataset. Magnification factor is 1.5.

between them. Undistorted (a), orthogonally distorted (b) and radially distorted (c) images are shown.

The two distortions examined are different to those of [8] in one major way; they are non-continuous whereas the original fisheye displays were continuous. Thus, these distortions define a focus region within which there is constant magnification, and also a context region, in which there is constant demagnification. The definition of these discrete regions has been found to be beneficial in high magnification distortion-oriented displays (e.g. [9]), so the fisheye displays were modified to include them.

4. Conclusions & Future Work

This paper presents work done so far in investigating the application of distortion oriented displays to three dimensions. It has previously been shown (e.g. [9]) that, when manipulating large two-dimensional datasets, contextual gains can be made by distorting the data such that the area immediately of interest is magnified, and the rest of the data is compressed in the area surrounding the focus region. It is proposed that similar gains can be made by applying similar distortions to three-dimensional datasets.

Three-dimensional variations of the Cartesian Fisheye and Polar Fisheye distortions of [8] have been developed and tested on small three-dimensional datasets, with positive results. It is proposed that the distortions be tested with a large three-dimensional dataset, such as those used commonly for GIS applications. The performance and usefulness of these displays for non-trivial 3D tasks will then be able to be examined, and further refinements and modifications made as necessary.

It has previously been found that, although context loss can be reduced by the application of a distortion-oriented display to a large dataset, the usefulness of the context region is typically restricted to magnifications of less than 10x [9]. A more complicated model of distortion was introduced by Smith, which increased the practical application to magnifications of more than 100x. It is also proposed, then, that a distortion be developed, based on the Frustum display explained in [9], to combat the expected problem of similar magnification limitations for three-dimensional displays of large datasets.

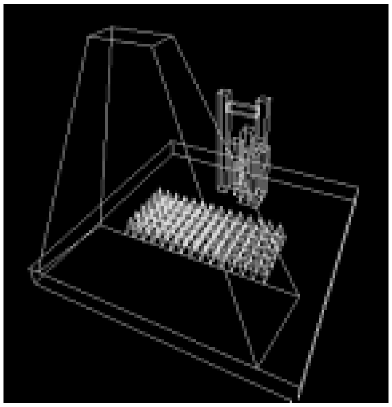

Figure 6(a). Undistorted view of 'landscape' test dataset.

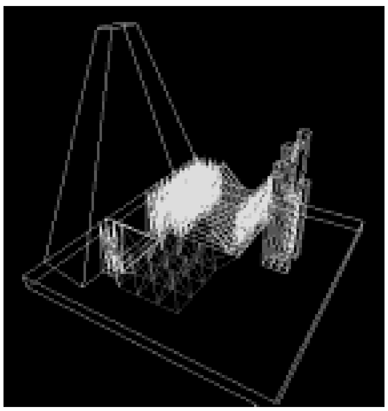

Figure 6(b). Cartesian distortion of 'landscape' test dataset (note magnification of tree area).

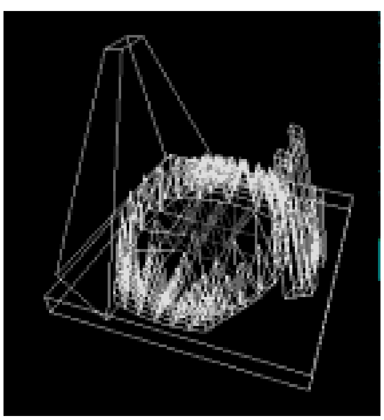

Figure 6(c). Polar distortion of 'landscape' test dataset (note magnification of tree area).

5. References

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