

Virtual Haptic Exploratory Visualization of Line Graphs and Charts

Jonathan C. Roberts, Keith Franklin and Jonathan Cullinane

University of Kent at Canterbury, Computing Laboratory, Canterbury, England, UK.

ABSTRACT

This paper describes ongoing research investigating how visualizations, especially line-graphs and charts, may be represented by haptics both to understand the structure and the values associated with the graphical realization. Much of the current research has focused mainly on the structure of the line-graph; some more recent work has used sound to depict the value of the curve. There has been limited work on multiple curves and more complex charts, with problems occurring between the crossover points of (say) a curve. We use the PHANToM Haptic interface to feel objects within the virtual world. Our investigations are focussing on a three-stage methodology: (a) unguided exploration, where the user may wander and explore the haptic visualization in their own time, (b) Constrained navigation, where the user's point of interest is constrained to a particular path, but the user can still explore within these constraints, and (c) Tours, where the user is completely guided round a predefined path.

Keywords: Haptic visualization; constrained visualization; tour visualization; line graphs; charts

1. INTRODUCTION/MOTIVATION

The main aim of this research is to explore the different possibilities of haptic visualization of line graphs and charts and how we may improve the methods that will allow greater understanding of what the user is feeling via the haptic device. The goal of this is to hopefully allow the user to understand the actual underlying data rather than understanding the shape of the graph.

Motivation for this research comes from accessibility challenges especially generating visual representations that allow users who have partial or no sight to perceive and control the given information. Indeed, we believe in an inclusive definition of visualization that provides tools to allow users to perceive and understand the underlying aspects of the data, whether this is via graphics and vision based techniques, touch or sound methods. In visual terms it is often better to display the information in many representations giving the user different perspectives of the same information such as Yagel et al¹ and Roberts.^{2,3} Likewise, multimodal representations may make visualizations more accessible. Although this paper focusses on haptic representations we are interested in multimodal aspects of such representations, indeed, we believe much research is required in multimodal interfaces especially for accessible exploratory visualizations.

Many methods have been used in the search for the answer to how line graphs can be represented haptically to the user, (described in more detail in section 2). But, we feel that these current methods do not take into account that most current haptic technologies as only allow the user to view a small window or single point of the line graph(s) at once. We as a research team have often discussed about the brilliant PHANToM device, by SensAble technologies,⁴ saying the exploration does not implicitly provide synoptic information, and that the investigation may be likened to a form of tunnel vision phenomenon. Indeed, when a user sees any graphic image they make saccadic movements: visually searching the image, making eye scan movements from fixation to fixation. When the user reads and understands the information at the point of fixation they also take in the overall shape of the larger pattern of information.⁵ The metaphor here is one of a searchlight, with the wider focus of the beam representing the useful field of view. By using a haptic device, such as the PHANToM, the user may miss out on the richness of the data presentation by not gaining an implicit general view of the whole. Ramloll et al⁶ in their implementation of haptic line graphs supports this view, saying, "The single point contact constraint that our design faces makes a tactile overview of the graph difficult to achieve".

E-mail: {j.c.roberts,kmf1,jac22}@ukc.ac.uk <http://www.cs.ukc.ac.uk/people/staff/jcr/>

Thus, there are many challenges in appropriately representing the information by haptic displays. Such challenges include: the user not innately seeing or scanning the whole view, but having to build up a mental understanding of the representation through explicit browsing or haptic saccade. Many haptic devices provide only point based representations, thus, perhaps providing views that allow the user to miss out on the richness the data; Relationships and difference operations may be difficult, as they would have to rely on short-term memory and physical distance measurements, so reading off exact values of a graph may be difficult; Such graph forms may not be understandable or at least may need to be learnt by the user. This is not to say that this approach is invalid for a particular type of users such as people that have become visually impaired during their life, which would imply that they have an understanding of the normal visualization of line graphs. In the case that the users was visually impaired from birth then the user might not mentally draw the same picture and hence a different approach is needed.

We are interested in generating appropriate haptic representations, looking at equivalences between graphical visualization and haptic representation styles. We are interested in learning how we can achieve certain visual effects in haptic representations; for example, how can we best implement preattentive processing, equivalent to that in visual representations, where the information (or at least features of interest) pop-out to the user; In this paper, we are specifically interested in looking at the different types of exploration that can be used to allow the user to explore graphs haptically using the PHANToM device, by SensAble technologies.

We propose that there are three useful styles of exploring haptic graph information in such a way as to allow the user comprehend the information. Unguided exploration: Where the user may freely explore the haptic visualization in their own time. Techniques here are to (say) use a raised or a grooved texture mapped to individual lines of the graph. Constrained exploration: Where the user's pointer is constrained to a particular path, but the user can still explore within these constraints any areas that are of interest to them. Tour: Where the user is completely guided round a predefined path with set amount of time at every point and the user has no or little control over the tour once it has started.

We state that each exploration occurs on a Haptic work surface: the main panel, which is used to stop the pointer from falling past the representing graph geometry. This panel is often in 'xy' plane.

Second, we propose that the information needs to be displayed in an appropriate form. In graphical presentation of results there may be one effective way to represent the information, so in haptic visualization we seek to find an effective representation method: such that the haptic user understands the given information, by browsing and exploration mechanisms. Thus, an effective touch based strategy may, or may not, be a direct equivalence to the visual form. For example, the information in a line graph may be more effectively presented in some other abstract form, appropriate for the haptic device.

2. BACKGROUND AND CURRENT METHODS

There are many senses that may be useful to allow users to feel words, graphs and charts. These human senses include touch, pressure, vibration, thermo-receptive (hot, cold), and proprioceptive sensations of muscle movement and position of limbs. Indeed, these have been used to develop different tactile displays. These can be organized as tactile methods pertaining to the sense of touch (which are mainly two dimensional output devices) and a wider haptic definition that includes touch with the sense of position, force and movement⁷:

Static tactile graphics, a hardcopy form. There are different production methods, from Braille graphics, embossed paper, to using microcapsule paper, where the raised form is created when the paper is fed through the tactile image enhancer; the microcapsules beneath the black lines of the diagram absorb more heat and expand in diameter, thus, raising that part of the drawing.⁷

Dynamic tactile displays. These devices usually stimulate the skin sensations, such as high frequency vibrations, pressure and thermal properties.⁸ Research systems include single pin mice, 64 pin fingertip displays to polymer gels and electrocutaneous stimulators such as electrical shocks and air jet stimulators.⁷

Haptic interfaces. These can represent three or more dimensions and reproduce the sense of space. For example, the PHANToM (SenSable technologies⁴) provides force feedback in six degrees of freedom.

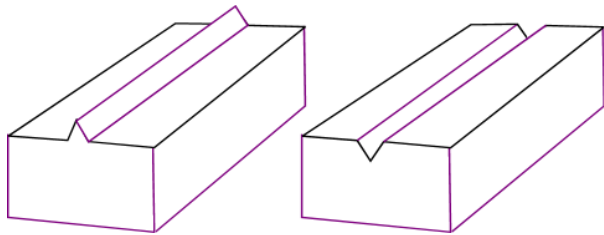


Figure 1: Graphs may be felt using ridges and grooves.

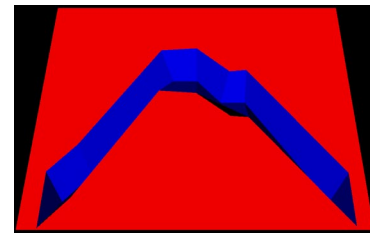


Figure 2. Screen shot of the constrained exploration view of one graph.

There are two main methods that have been used to allow a user to feel a graph, such that visually impaired people can work with graphs in the computer environment: (1) by a raised surface, equivalent to Braille and (2) an engraved line (Figure 1 left and right, respectively).

The first uses an object such as a cylinder or ridge that is protruding from the haptic work surface. This is similar to gluing a section of rope to a haptic work surface, for example. This method is an unguided exploration method in which the user is allowed to move about the 3D environment with no constraints. The user can feel the bumps and therefore the extent of the graph. If the graph is translated directly from a two-dimensional image then appropriate image filtering operations need to be applied, to *clean* up the tactile image.⁹

As noted in,¹⁰ when the user is presented with a raised surface to move the pointer along which is sloped, they find it difficult to keep the pointer on the geometry due to the nature of the sloping surface. This can lead to confusion about the actual shape of the graph.

The second method is to create an engraved surface, a 'V' shaped groove instead of a raised object; this allows the user to explore the work surface by putting their 'pointer' into the groove and following it around. With this solution, the user had problems when graphs intersected, when multiple line-graphs were depicted.⁶

The main problem was that at an intersection point between two or more graphs the user might follow the incorrect path out, without the knowledge that they had changed graph that they were tracing out. The second problem was that at the point of intersection they might not realise that it is an intersection point between two graphs due to the fact that there is no clear force to indicate it. Lastly, the user may be confused as to which line of the graph they are currently tracing, especially when the users switch between graphs.

We postulate that multimodal interfaces may be beneficially used, where, for example, a sound or motif may be associated with a particular graph to notify which graph is being viewed; or that sound may be used to designate, and make the user aware, of a cross-over point; or that the rise and fall of the graph and other attributes may be sonified appropriately. Sound has been used to generate appropriate visualizations¹¹; such sonification methods may be used to depict data, feedback or notify important events, and to support haptic visualizations^{6,12}

3. METHODOLOGIES

Ben Shneiderman in 1996¹³ presented the visual information seeking mantra: Overview first, zoom and filter, then details-on-demand. Although this is to do with visualization, the idea of producing a general overview first and then specific information is reinforced in by other work. Indeed, Way and Barner,⁹ say, "The exploration by a blind person of a tactile graphic generally is performed in two stages. First the entire image is explored as a whole, providing a general tactile overview. Second, the details of the tactile image are explored".

We believe that it is useful to allow the users to explore the whole graph, and then explore specific aspects, perhaps through a zoom or equivalent operation. Thus, we believe it is important to provide simplified and different views of the same information that allow the user to gain a specific understanding of certain aspects of the underlying information. For example, a user may initially browse the structure of the graph, by feeling a bumped depiction of the graph, then the user

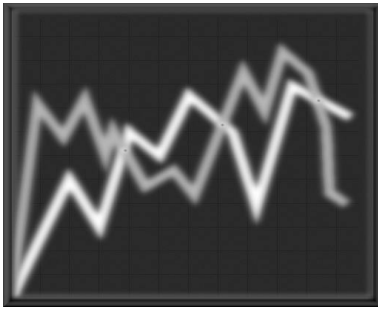


Figure 3. A greyscale image that is used to create a bump-map feel.

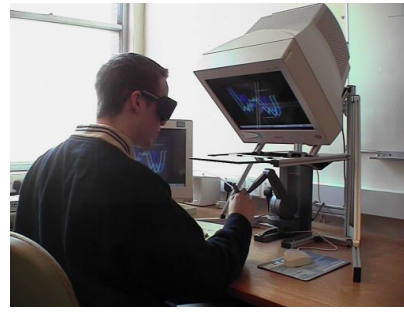


Figure 4. The example shows a haptic graph being visualized in the ReachIn system.¹⁴ One image defines the bump-map and another provides the appearance for sighted viewers.

may view specific representations – simplifications – that provide details-on-demand, such as a view that solely depicts, in a simplified graph, the maximum or the minimum of the data values, or position line intersections.

This idea is illustrated in our three-stage methodology. First the user may freely explore; then they may zoom in to look at specific aspects and finally the information is re-inforced by a guided tour of pertinent features of the visualization. In the following sections we expand upon the methodology, provide some examples and discuss their relative merits.

3.1. Unguided Exploration

This is a more traditional approach to the haptic visualization of graph(s) in which the actual graphical visualization is directly converted into a haptic version of (say) bumps and ridges. The user then moves the pointer freely around the screen to experience the haptic representation of the graph. When they come across the structure that has been created by (say) a bump map then they can simply follow it around to get an understanding of the shape of the graph.

3.1.1. Examples: bump-map model

The bumpmap model is an unguided exploration of the graph that has been programmed into the system. The bumpmap surface is defined by a greyscale image, the different grey-values in the image describe the height of the final bump. Ideally, this requires some image processing to be performed on the image to *clean* it up and emphasise the lines rather than the background, for example.⁹ These images are often generated by a sighted user.

We have developed our demonstrations using the ReachIn Magma¹⁴ software that interprets Portable Network Graphic (PNG) images into a bumpmap by assigning different values in the ‘z’ direction depending on the grey value in the file (Figure 4).

If multiple graphs are represented at the same time then at interesting points such as the intersection then the depth can be changed to represent this to the user, or an audio *signal* could be played. Indeed, we have experimented with different scenarios; Figure 4 shows different depths for each line of the graph.

3.1.2. Discussion: bump-map model

The flexibility of this model allows the creator of the representation freedom to express particular points that they wish to convey to the user. Such points of interest could be the normal turning points or the points of intersection when multiple lines are being displayed on the same graph. These points of interest may be easily *highlighted* haptically by adjusting the colour level and hence adjusting the depth so to outline individual features and aid a particular investigation task. But, at present this imposes an implication on this model that the creator is a person and not an automated process.

The other issue with this model is not to do with the model but with Magma. Magma at present does not allow us to easily add another layer of haptic cues, such as frictional forces, directly onto the imagemap layer at the same time. This would allow additional parameters to be perceived. However, we have introduced different granularity of *random noise* texture to the bump-map to provide additional information, of say another variable.

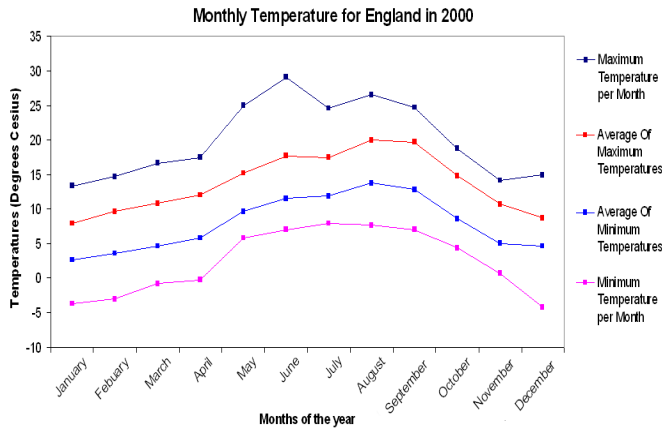


Figure 5. Temperature Graph for England in 2000 showing maximum and minimum temperatures for each month, and their respective averages. Data courtesy of the UK Met Office.

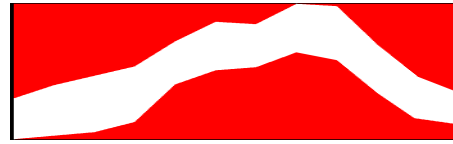


Figure 6. Screen shot of the Friction & Zoom View showing the representation of the average maximum and average minimum information displayed in Figure 5.

3.1.3. Example: Friction & Zoom View

Most of the haptic representations solely display the lines of the graph; although, often in a visualization it is the space in between the graph that provides the most information to the user. Not only should the chartjunk be removed, but the remaining space and layout should be designed appropriately.¹⁵ Moreover, a user may calculate implicitly or explicitly the area under the graph. Thus, we have developed some views that allow the user to move their pointer over the graph to feel above and below the lines.

The first example allows the user to explore the area under a line of the graph. We assign different haptic textures to various parts of the graph. Whilst the user is in the area under the graph they will just feel a smooth hard surface, which the pointer can move over. When the user moves above the graph then they will feel a friction force indicating that they are above the graph. If at any time they move the pointer up to the maximum value that the graph reaches then they will find a solid object that they cannot push past. This constrains the users to the range of ‘y’ values that the line graph uses, and hence they will be able to find the relationship between the points they are currently at with that of the maximum ‘y’ value that the graph uses.

The second example is designed for the use with more complex data such as temperature graphs and acoustic wave graphs. These graphs often have four values indicating the maximum and minimum, and the maximum and minimum averages for a particular variable; such as the temperature graph in Figure 5. First only the inner two lines of the graph are shown (the most often view of this data), in that the user will feel a frictionless hard surface between these two lines that indicate the averages of the maximum and minimum points in the data set. Then the representation can change (zoom out) to depict the maximum and minimum graph values, using the same friction method. Additionally, the inner average values could be also depicted by a small raised bump to give a perception of the average values.

We postulate a third example, where the user may press a button to generate a more detailed version of the graph. The user can then freely explore the small zoomed higher resolution area. This allows the user to generate an understanding of the overview of the information, and then drill down to feel finer-grain detail from a small window. This provides a focus+context view.¹⁶

3.1.4. Discussion: Friction & Zoom

This model of unguided exploration is based on the more traditional approach of using the graphical visualization of the data. This means that it is slightly easier to understand by people who know what a graph is from previous experience. However this system differs from current methods by adding extra constraints, like limiting the amount of movement

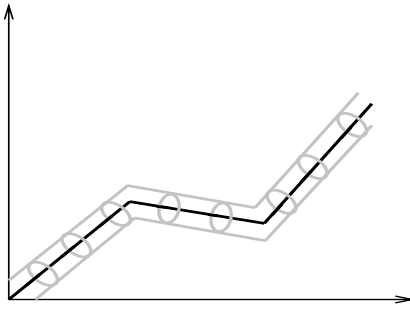


Figure 7. Constrained exploration: The constrain could be along tunnels as used by Fritz and Barner.¹⁸

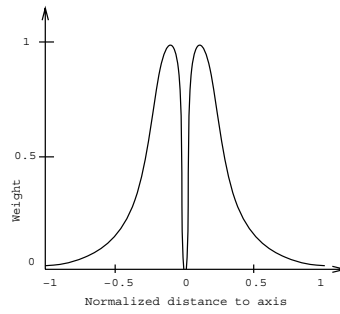


Figure 8. Graphical version of the weighting function used by Fritz and Barner¹⁸ to snap the stylus to the line of the graphic.

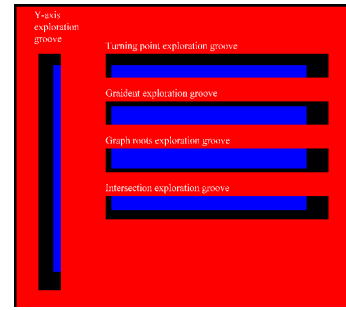


Figure 9. The figure shows a work surface with four grooves. Different information about the graph is stored within each. This is a divide and conquer approach, where specific information is depicted in separate views.

in the 'y' direction to that of the maximum and minimum values that the whole graph contains. This allows the user to compare values of any arbitrary point with any other point i.e. peaks and turning points to find out which have the greatest 'y' value. However, the first two examples suffer from the scenario that large scale graphs have to be reduced and scaled down in size. But, in the case of a graph like the temperature graph then averages of the maximum could be taken separately from the average of the minimums, to allow the user to gain a better understanding of the information.

3.2. Constrained Exploration View

Constraint exploration allows the user to freely explore the information within certain constraints. In essence, forces are applied to constrain the user to features such as the line of the graph that they are trying to follow. The constrain could be by using grooves as used by Yu et al¹⁷ (Figure 2), magnets or tunnels (Figure 7). Indeed, Fritz and Barner¹⁸ use a weighting function, that allows a snap-to-grid force which pulls the stylus to the cylinder axis and then allows the user to move freely along the graph line; a cross-section of the force over the cylinder is shown in Figure 8. Challenges exist with multiple lines on the graph especially when the paths of the graphs intersect.

3.2.1. Examples: Independent graphs

Our approach to multiple line graphs is to use separate haptic work surfaces depicting individual paths of the graph; we use a 'V' shaped groove method to constrain the user navigation, like Ramloll et al¹⁷ and seen in (Figure 2).

This means that the user is constrained to one particular graph shape that they can trace out and hence does not suffer the ambiguity previously found. The user is informed at an intersection point by a simple tactile force that is sent to the PHANToM device. To allow the user to experience the different graph lines, a swapping function has been mapped to a key on the keyboard. When the user presses the key the geometry is switched to display the alternate or next graph.

3.2.2. Discussion: Independent graphs

One of the advantages that we feel this approach has over the approach adopted by¹⁷ is that the user does not have think about the frictional forces that are being imposed on the pointer. This means the user is spending less time on working out if they are currently following the correct graph by comparing the frictional forces they are currently experiencing to what they experienced a few moments ago. This becomes a greater factor the more variables are introduced to the system at once. Moreover, each graph would have its own friction legend; but, it is a challenge to assign unique forces because of the perceptual limitation of such kinesthetic forces.

Within this model we have also removed the issue of the ambiguity of which graph to follow at the point of intersection. The only challenge that we currently have with the model is in the process of changing the geometries that they wish to

feel. At present when a user wishes to move to the next graph that they wish to feel they currently have to raise the pointer out of the groove and then change the geometry unless they are at the point of intersection between the two graphs. Then once the geometries have switched the user has to roam about the work surface until they find the groove. This means that the user may stray to either side of their current position and thus not give them an accurate relation between the two graphs at a particular point. One solution we are investigating is to animate the stylus and move it within the groove of the next geometry.

3.2.3. Example: Exploded Data View

Synoptic information is often difficult to obtain using a haptic device, thus, we propose a ‘divide and conquer’ approach that specifically depicts certain aspects of the information in specialized sub-realizations; making an ‘exploded data view’.

Indeed, Yu et al¹⁰ noted that due to the current single point of contact between the user and the virtual world that current haptic devices like the PHANToM Desktop, the bandwidth of information is hugely reduced hence the reason for separating the information into different grooves. As well as the bandwidth being reduced due to the single point of contact and the limitation of the human hand in respect to the nerves that respond to the force feedback information as noted by.¹⁹ It would seem that a separated view of individual aspects of the information would allow the user to understand the graph with greater ease and less likely to produce erroneous errors.

The Exploded Data View constrains the user to view simplified information from the underlying data. The work surface is made up of a number of grooves, which allow the user to feel different interesting features of the graph that they are currently tracing out. By adopting this approach the user may understand information in a more manageable way instead of being overloaded with too much detail as often the case in more traditional approaches.

3.2.4. Discussion: Exploded Data View

Figure 9 shows a work surface with four grooves. Different information about the graph is stored within each. The user is informed when they enter each different groove as to the information that will be presented to them. This enables the user to learn the different location of the grooves in relation to each other.

Groove 1 – Vertical Exploration. This first groove allows the user to first find out what the maximum and minimum values are of the graph that has been entered. The user can find this information out by pushing the pointer against the end wall of the groove and pressing the button on the stylus. Within the floor of the groove is a dip, which indicates the point of intersection with the ‘y’ axis. This is reinforced with an audio cue when they are in the dip.

Groove 2 – Turning Points Exploration. This groove allows the user to explore the relationship between the turning points. For each maximum and minimum turning point, there is either a raised or lowered section of the floor to represent them respectively. The user then can move the pointer along the groove to find out where each type of turning point is and where they are in relation to each other.

Groove 3 – Gradient Exploration. Within this groove the user can feel how the gradient changes as they move back and forth along the ‘x’ axis. The floor of the groove is sloped to represent the sign on the gradient i.e. when a positive gradient the floor will slope upwards and when negative then the floor will slope downwards. Work on the perception of gradients in the virtual environment has been shown to be very successful, see Riedel.²⁰

Groove 4 – Intersection with other graphs. This groove is only used when graphs are being compared with each other. This is normally the case when the user is seeking information about where two graphs intersect.

This separation of information is useful, because, by the nature of the model the amount of information that the user has to understand at any one time has been reduced to a more manageable amount. However the model is not without its own challenges. At present the most prominent challenge is that of comparison of the turning points, for example the information that is presented to the user within the grooves gives no indication to which is the largest of a particular type of turning point. The user therefore cannot compare maximum turning points to find out which of them is the larger of the two.

The last point is if the scale of the graph is very large then the effect of the slope on the base of the graph becomes less effective due to the fact that the floor of the groove always moves to the z value of 1 over the ‘x’ distance that has a

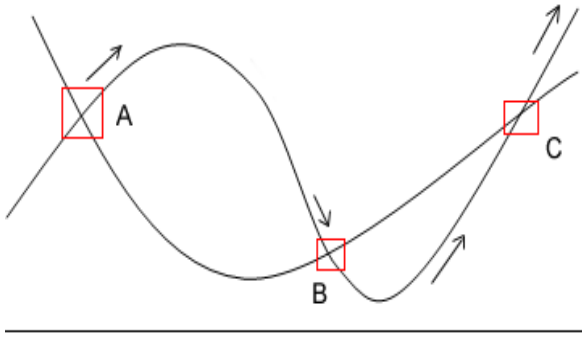


Figure 10. The image depicts a graphical version of the Museum tour, where the client on the tour is shown around points of interest; they are taken from one point of interest to another and allowed to roam around the certain rooms or within a small proximity of the guide (shown by the rectangles A,B,C on the image).

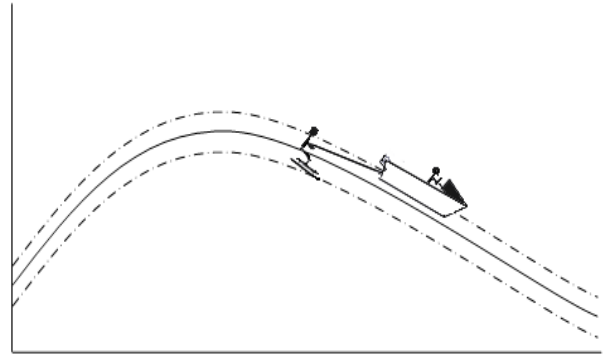


Figure 11. The image depicts a graphical version of the water skier guided tour version. The water skier is pulled in the direction of the boat but can move from side to side. A similar action is given to explore haptic worlds, where the users stylus is pulled in a certain, but the user can still explore within certain constraints.

continually positive gradient this was noted in²⁰ which they state that the perception of gradient was successful until a certain angle was achieved, after which users became confused and misunderstood the gradient.

3.3. Guided Exploration: guided tour

The tour guide model is an approach that allows the system complete control to guide and direct the user round the graph or to important features of interest. When the system takes control it moves the haptic device; in this case the PHANTOM device from SenSable. We are investigating three different approaches. These are based on three metaphors that allow different experiences of exploration.

3.3.1. Example: Bus Tour

The metaphor of a bus tour has been used to indicate the freedom that the user has whilst using this tour function. The person boards the bus and sits down in their seat. The bus then moves around the pre-designed route showing them points of interest. In the case of the haptic representation, the system moves the haptic device around producing forces that the user can feel and experience. However at no point in time can the user stop the tour if they wish to spend more time feeling a certain area of interest or change the speed of the tour.

3.3.2. Example: Museum Tour

Our second version of a tour is that of a tour that one would experience whilst going around a museum. The client on the museum tour is shown around areas of interest, they are taken from one point of interest to another. When the guide has finished talking about the next point of interest, the client is free to roam around the near proximity (normally within the same room as the guide) and ask questions of the guide. When a certain amount of time has passed then the guide will move onto the next stage.

In our case the guide stops at pre-designated points of interest such as intersection points. The user may then freely roam around the close area to where they stopped (Figure 10 shows the close area that the user can move around at the intersection point whilst on the tour). This can give them a feel for details such as how the other graph crosses the current graph i.e. is its gradient positive or negative or is it experiencing a turning point which just touches this graph.

We currently plan to implement this system based on a window idea in which the system stops at the per-defined points and the user can move around a set area. If a resolution change is also made, then this is similar in design to the focus+context example in section 3.1.3.

3.3.3. Example: Water Skier

The last example is that of a water skier. The water skier is experiencing a pulling force that moves them along a route much like the bus tour metaphor we looked at earlier. However this time the water skier has some freedom to move from side to side as they are being pulled along and thus, experience different forces and sensations. This means that within this model of the tour the program pulls the user along a pre-defined route, but the user can move within a certain angle to that of the route (Figure 11 shows dotted lines which indicate the area the user can move between).

We currently purpose to implement this using an approach that connect the pointer (representing the water skier) to an object (representing the boat pulling the skier) by a set of springs which would allow the user to move from side to side within some constraints.

3.3.4. Discussion

By comparing all three approaches to the tour method we can see that each has their own set of strengths and weakness. First of all the bus tour does not allow the user to get any impression of the information around the outside of the tour. This means that they currently only know when points of interest happen like intersection and turning points. With the turning points the user can gain all the require information just for the tour, however this method does not allow for the user gain knowledge about how the other graphs depicted on the same work surface interact with each other. Yet the approach is simple enough not to confuse the user by moving them at a constant speed which makes comparisons easier and the building of mental images on the same scale. The water skier model expands on the bus tour by allowing the user to experience items outside of the fixed tour, whilst keeping them moving at a constant rate. With both of these approaches it is noted that if some complex interaction between the graphs is happening then the user might need more time to understand this. This is where the museum tour offers the ability for the user to explore the interaction in more detail and hence allow more complex interactions to be understood. The draw back with this is that when the tour moves on the user might not be exactly on the same spot as they stopped which may confuse the user.

4. CONCLUSIONS

We have presented three methodologies for haptic exploration of graphs. There is still much work to do. Indeed, we plan to extend our work particularly with the Friction and Zoom techniques and the guided tour methods. We also plan to explore the area using other tactile, haptic devices and software that might allow us to convey the information to the user with a more accessible method that does not require expensive equipment such as the PHANToM.

We believe that each of the methodologies are useful. Indeed, it may be beneficial to use multiple techniques together, enabling the user to perceive the information from different perspectives. Research challenges then exist as to how the information is presented to the user, because in visualization the multiple views may be coincidentally displayed and the user can achieve side-by-side comparison, but, naively it is not possible to use such methods in haptic representations.

Visualization is about representing information effectively, indeed, it is not the graph that the user is trying to understand, but, the underlying data. Moreover, it may be better to represent the information haptically in ways that are different to the visual equivalence. For example, the visual graph display may not be the best way to represent that information to a non-sighted user, but, an ‘exploded data view’ method that provides similar information in specialized views, may generate a better understanding of the underlying information.

REFERENCES

1. R. Yagel, D. S. Ebert, J. N. Scott, and Y. Kurzion, “Grouping volume renderers for enhanced visualization in computational fluid dynamics,” *IEEE Transactions on Visualization and Computer Graphics* **1**, pp. 117–132, June 1995.
2. J. C. Roberts, “Multiple-View and Multiform Visualization,” in *Visual Data Exploration and Analysis VII, Proceedings of SPIE*, R. F. Erbacher, P. Chen, J. C. Roberts, and C. Wittenbrink, eds., **3960**, IS&T and SPIE, January 2000.
3. J. C. Roberts, “On Encouraging Coupled Views for Visualization Exploration,” in *Visual Data Exploration and Analysis VI, Proceedings of SPIE*, R. F. Erbacher, P. Chen, and C. Wittenbrink, eds., **3643**, pp. 14–24, IS&T and SPIE, January 1999.

4. "SenSable." <http://www.sensable.com>, 2001.
5. C. Ware, *Information Visualization: Perception for Design*, Morgan Kaufman, 1999.
6. R. Ramloll, W. Yu, S. Brewster, B. Riedel, A. Burton, and G. Dimigen, "Constructing Sonified Haptic Line Graphs for the Blind Student: First Steps," in *Proceedings of ACM Assets 2000 (Arlington, VA)*, pp. 17–25, 2000.
7. T. P. Way and K. E. Barner, "Automatic Visual to Tactile Translation, Part II: Evaluation of the TACTile Image Creation System," *IEEE Transactions on Rehabilitation Engineering*, March 1997.
8. "Introduction to Haptic Display." <http://haptic.mech.nwu.edu/intro/haptic>, 2001.
9. T. Way and K. Barner, "Automatic visual to tactile translation, Parts I: Human Factors, Access Methods and Image Manipulation," *IEEE Transactions on Rehabilitation Engineering*, 1997.
10. W. Yu, R. Ramloll, and S. Brewster, "Haptic Graphs for Blind Computer Users," in *Proceedings of the First Workshop on Haptic Human-Computer Interaction, Glasgow University*, pp. 102–107, 2000.
11. R. Minghim and A. Forrest, "An Illustrated Analysis of Sonification for Scientific Visualization," *Proceedings of '95 Visualization*, 1995.
12. R. D. Jacobson, "Navigating maps with little or no sight: An audio-tactile approach," *Proceedings of Content Visualization and Intermedia Representation. University of Montreal, Montreal*, 1998.
13. B. Shneiderman, "The eyes have it: A task by data type taxonomy for information visualizations," in *Proceedings of the IEEE Symposium on Visual Languages*, pp. 336–343, IEEE Computer Society Press, (Washington), Sept. 3–6 1996.
14. "ReachIn desktop system." <http://www.reachin.se/>, 2001.
15. E. R. Tufte, *The Visual Display of Quantitative Information*, Graphics Press, 1983.
16. S. Card, J. MacKinlay, and B. Shneiderman, *Readings in Information Visualization: Using Vision to Think*, Morgan Kaufman, 1999.
17. W. Yu, R. R., S. Brewster, and B. Riedel, "Exploring computer-generated line graphs through virtual touch," in *Proceedings of IEEE ISSPA 2001*, pp. 72–75, 2001.
18. J. P. Fritz and K. E. Barner, "Design of a Haptic Graphing System," *Proceedings of RESNA '96*, 1996.
19. C. M. Smith, "Human Factors in Haptic Interfaces," *ACM Crossroads: Special edition on Human Computer Interaction* **3**, Spring 1997.
20. B. Riedel and A. Burton, "Perception of Gradient in Haptic Graphs: a Comparison of Virtual and Physical Stimuli," in *Eurohaptics conference proceedings Birmingham UK*, pp. 90–92, 2001.