Making Microsoft Excel™ Accessible: Multimodal Presentation of Charts

Iyad Abu Doush*, Enrico Pontelli*, Dominic Simon**, Son Tran Cao*, Ou Ma***
*Department of Computer Science, **Department of Psychology, ***Department of Mechanical Engineering,
New Mexico State University, Las Cruces, NM 88003, USA
[idoush,epontell,tson]@cs.nmsu.edu, domsimon@nmsu.edu, oma@nmsu.edu

ABSTRACT
Several solutions, based on aural and haptic feedback, have been developed to enable access to complex on-line information for people with visual impairments. Nevertheless, there are several components of widely used software applications that are still beyond the reach of screen readers and Braille displays. This paper investigates the non-visual accessibility issues associated with the graphing component of Microsoft Excel™. The goal is to provide flexible multi-modal navigation schemes which can help visually impaired users in comprehending Excel charts. The methodology identifies the need for 3 strategies used in interaction: *exploratory*, *guided*, and *summarization*. Switching between them supports the development of a mental model of a chart. Aural cues and commentaries are integrated in a haptic presentation to help understanding the presented chart. The methodology has been implemented using the Novint Falcon haptic device.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces & Presentation**]: User Interfaces

General Terms
Design, Human Factors

Keywords
Haptic, Assistive Technology, Accessible Graphs

1. INTRODUCTION
Statistics on usage of computers by individuals with visual disabilities are still depicting a bleak picture – the AFB reports a meager 7.3% of individuals with visual limitations being active computer users [1]. This has an impact on the ability of visually impaired individuals to gain opportunities to access rewarding careers in fields where the use of computers is unavoidable.

The research in the field of computers and accessibility has made giant steps in recent years, proposing solutions to enable non-visual access to information technology. Screen readers provide practical solutions to access text, while specialized tools offer access to specific data organizations, such as hyperlinked documents, mathematical formulae, and tabular structures.

The widespread use of Microsoft™ applications in the workplace (as much as 87.1% of 2,300 companies according to a recent survey by Forrester) poses the question of what steps can be taken to enhance accessibility of Windows-specific applications. Microsoft has embraced a model that acknowledges the needs of accessibility and offers solutions to both users and developers. In spite of this, the goal of making these applications fully accessible to visually impaired users is still unreached.

In this paper, we address the accessibility of Microsoft Excel™. Excel is a spreadsheet application. The spreadsheet can contain tabular (e.g., text, numbers) and non-tabular data (e.g., graphs). Excel is an interesting source of problems in terms of accessibility, as it integrates different data representations (e.g., text, numbers, formulae, tabular organizations, charts), within the same conceptual model, and in a deeply inter-related fashion.

The literature offers adequate solutions to some aspects of Excel's data representation. For example, the literature on accessibility of tabular data (e.g., [2; 3]) provides solutions for addressing access to tabular data in Excel. The literature on accessibility of mathematics [4] can also be applied to formulae in Excel.

Two main aspects in the use of Excel are, in our opinion, still out of the reach of existing technology. The first aspect is the lack of solutions for accessibility of charts that are suitable to meet the needs of Excel – as discussed in the rest of this paper.

The second aspect is the effective presentation of the *interconnected* nature of the information stored in an Excel worksheet. Furthermore, the amount of data present in a worksheet can be large. These aspects raise the issue of developing non-visual presentation schemes that **(i)** enable the seamless switch between modalities of presentations that are adequate for the different types of data, and **(ii)** offer a hierarchical organization of the presentation, reflecting the relationships between data items and enabling navigation of large data collections without overwhelming the user.

In this paper, we address the first of the two problems – while the second one is still a subject of exploration.

The role of charts in Excel is indisputably central to a majority of its uses. These pictorial representations can be used to give comprehensive information about the mathematical contents of a worksheet. Charts provide intuitive representations of extensional data, highlighting statistically relevant trends and features.

There is a rich literature about non-visual modalities for the presentation of graphs. Existing approaches span from the use of textual summarization techniques [5], to sonification of graphs [6], to tactile [7; 8] and haptic presentations [9; 10; 11].

In spite of these proposals, we feel that several of the proposed approaches are inadequate to meet the needs of making Excel charts accessible. Textual summarization techniques impose the requirement of a manual preprocessing and annotation, and they

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impose an excessive load on working memory. Tactile presentations are effective in handling several classes of charts, but they are costly to produce (e.g., using embossers or expensive tactile tablets) and static (e.g., do not allow zooming and repurposing). Research on sonification has made progress but provides low resolution and it is unsuitable for certain classes of charts (e.g., scatter plots). Haptic interaction offers an interesting alternative, but it has been plagued by the high cost of haptic devices, and it may also provide low resolution of presentation. The majority of the proposals have also limited the analysis to two basic types of graphs (bar and single-line charts), and it is unclear how to scale such results to other types of graphs.

In this paper, we investigate the problem of presenting the different types of charts (line, bar, pie, and scatter graphs) supported by Excel to visually impaired individuals. The novelties of the proposed approach are the following: **(a)** The proposed approach is multimodal and relies on a dynamic combination of haptic and aural cues; **(b)** The user has the benefit of both *passive* and *active* modalities. More precisely, the user is given the ability to dynamically switch between a (i) *guided* presentation mode (a passive scheme where the system guides the user in exploring the graph), (ii) *exploration* presentation mode (a dynamic scheme where the user is free of "navigating" the graph), and (iii) *summarization* mode (where the user is presented key statistical features of the graph). **(c)** The haptic presentation is designed to operate on affordable gaming devices (e.g., the Novint Falcon).

2. Related Work

We identify three main classes of approaches that have been proposed in the literature to address the problem of presenting charts and graphs without any visual aid. Due to lack of space, we will cite only some of the relevant works in this area.

Audio Presentation Schemes: An extensive literature exists on the use of audio for the presentation of graphs. Elaborate soundscapes models of 2-D graphs have been presented (e.g., [12; 13; 14]), combining features like mapping of graph to musical tones, sonification of graph trends, and other audio cues. The work of Walker et al. [14] explored several solutions for the creation of auditory displays of graphs, employing variations in different dimensions of sound (e.g., pitch, tempo) to capture different properties of the data in a graph. Similar principles have been explored by several other researchers (e.g., [15; 16]).

While suitable for line charts and single functions, sonification has limited applicability to other types of graphs (e.g., scatter graphs); sonification is effective in summarizing trends, but it is less effective in creating fine-grained presentations [14].

Textual Presentation: An interesting line of research aims at analyzing charts to produce either a textual summarization of the key aspects of the graph, or to enable a Q&A process. This line of work was pioneered by Kurze [17], who presented a tool to create verbal descriptions of business graphics. This direction of research was enhanced by Carberry and others (e.g., [5]), enabling the creation of effective summaries of a graph (e.g., hypothesize the message carried by the graph) and providing support for natural language question/answering. The work has, so far, concentrated on the analysis of bar chart graphs.

Tactile and Haptic Presentation: Tactile presentation of graphs requires either the use of a dedicated two-dimensional tactile tablet or the use of an embosser to produce printouts with raised surfaces. Traditional approaches to the production of tactile graphs require a significant amount of human intervention [18]. Various projects have intervened to provide automated mechanism to aid in the production of tactile representation of graphs (e.g., [8; 19]). Printed tactile presentations are static, potentially expensive, and do not provide any facilities for guiding the understanding of the graph or for scaling the graph.

The use of haptic devices – i.e., devices that provide force feedback along different dimensions – has gained momentum in addressing the needs of non-visually presentation of graphical content. Several researchers have developed presentation models for graphs on SensAble's PHANTOM device [9; 10; 20]. The work of Yu et al. [10] expands on these principles by introducing the use of textures to distinguish multiple lines in a graph. The system mostly focuses on simple line and bar charts

Several researchers have explored the use of custom-made devices to provide more effective haptic feedback in presenting graphs and charts. Iglesias et al. [21] proposed a haptic, dual finger haptic interface called GRAB. The system can be used for navigating line, bar, and pie charts.

Haptic cues can come in different forms of forces returned by the haptic device. Many researchers [11; 20; 22] use a magnetic force to pull the user towards the needed virtual object. In the work of Roth et al. [23], virtual fixture and vibrations are used to haptically render line graphs. Fritz et al. [22] use a light force to present axis's and gridlines. Several of the difficulties in handling haptic presentation of graphs (e.g., delimiting the graph space, maintaining contact with the graph) have been discussed in [10].

Multi-modal Presentations: Several researchers have leveraged on the benefits of both audio and haptic presentations, by enhancing one of the two methods with cues drawn from the other modality. In [23], the haptic presentation of graphs (using the Logitech WingMan mouse) is enhanced by speech cues, achieving a greater recognition rate. Aural cues can help the user in locating the position in the haptic space, when this cannot be identified by the touch sense alone. In the work of Grabowski et al. [9] sound is used to differentiate between gridlines and surfaces. Sound pitch is used to represent the surface height. Returning values of the graph using speech can help in building a more precise mental image of the trend of a graph. Yu and Brewster [24] use speech to give information about the graph values. Jay et al. [11] propose the use of different audio tones for different data types. Non-speech sounds can also help in providing the user with an outline of the graph. In the work of Roth et al. [23], sounds are used to warn the user if the cursor leaves the line.

3. Methodology

3.1 Design Principles

The overall organization of our proposed approach is illustrated in Fig. 1. Our focus is on the presentation of Excel™ charts using a combination of haptic and aural methods.

The *first principle* guiding the design of our approach is the need of customizing the algorithms used for chart presentation according to the specific class of charts considered. Different types of graphs are employed to highlight different features of a data set, and as such they suggest different modalities of presentation. We classify charts in the following categories: (i) Line charts; (ii) Bar charts; (iii) Pie charts; (iv) Scatter charts; (v) Radar charts; and (vi) Surface charts. In this work we consider categories (i)-(iv), being the most commonly used ones; (v) are rarely used, while (vi) is work in progress.

The *second principle* in our design is the use of multi-modality in the chart presentation. Aural (e.g., speech and non-speech) and haptic cues (e.g., vibration, stiff force, and gravity force) are used to help the user when exploring the chart. Sounds can be used to help the user in determining information about the chart (e.g., values at data points) and provide guidance in locating the chart. Haptic cues can be used (e.g., vibration) to delimit boundaries of the graph; gravity forces are used to pull the user to the graph.

The *third design principle* is the recognition that different modalities of presentation are required depending on the task the user is trying to accomplish. Following our previous investigation in the context of usage of tabular data [3], we can identify three major task-oriented approaches to accessing data: *question-answering* (data is used to seek a focused answer to a question), *knowledge synthesis* (data is used to synthesize new knowledge – e.g., as in a student writing a term paper), and *knowledge acquiring* (user wants to commit to long-term memory data for later retrieval – e.g., a student studying for an exam). Different modalities of presentation should be provided to match these distinct classes of tasks.

We classify modalities of presentation according to two criteria. The first criterion describes the role of the user in the exploration of the data space. **Passive navigation** means that the haptic device automatically moves along the chart or towards a specific piece of information. The user can use this navigation scheme to get summary information (e.g., the device handle will move to the minimum point of the graph) and to acquire knowledge about the shape of the chart. In **active navigation** the user can freely explore the graph haptically, by moving the haptic device on the representation of the chart. Haptic and aural feedback is employed to constrain the movement and provide information about the parts of the chart being navigated.

The second classification criterion refines the modalities of presentation depending on the task being accomplished. We identify three modalities: (i) *Guided presentation*, where the user is guided by the system in exploring the chart according to a predefined chart-specific strategy; (ii) *Exploratory presentation*, where the user is allowed to freely explore an haptic representation of the chart, posing questions wherever necessary (with speech feedback); (iii) *Summary presentation*, where chart-specific features (e.g., minimum, maximum, trend, clustering) are proposed in place of the chart. Observe that guided presentation responds to the need of knowledge acquisition, exploratory presentation is helpful in knowledge synthesis, and summary presentation responds to the needs of question-answering.

Finally, let us observe that the visual navigation of a chart containing multiple sets of data yields a comparison of the presented data. A non-visual navigation of such charts is more complex. The proposed system supports multi-series graphs for the case of *line and bar* graphs.

3.2 Pilot Study

In the rest of this paper, we discuss the different presentation modalities, distinguished according to the types of charts considered. The design of the methodologies has been derived from our previous work on accessibility of tabular data and the outcomes of pilot studies. The pilot studies have been conducted with 9 sighted students from an introductory psychology class at NMSU. During the study, several prototypes of aural and haptic interfaces have been used to present different types of charts. The presentations have been performed with the computer screen turned off. None of the students had previous experience with haptic devices. In each study, the students have been asked to complete chart recognition tasks using the haptic/sound interface.

Before the experiments took place, each student received training in using the haptic device, by performing simple recognition tasks – e.g., the student was asked to use the haptic device to touch different faces of a 3D cube and press a button on the device to know if s/he is touching the cube or not. During the preliminary studies, the users explored haptic representations of *line* and *bar* charts, providing feedback on the effectiveness of the solutions. The evaluation informed changes to the presentation strategies.

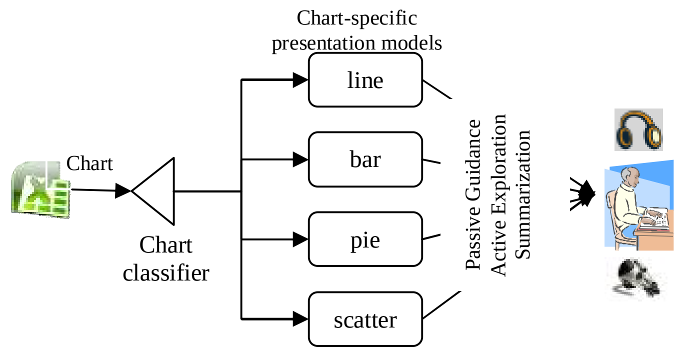

Figure 1: Overview

3.3 Presenting Line Charts

The line chart (Fig.2) is probably the most basic type of chart, typically developed by connecting a series of points, representing individual data items, by line segments. They are frequently used to describe time series or other variations of data over time or over a sequence of characters. Let us analyze the different modalities of presentation for line charts – note that the user can freely switch between them at any point during the presentation.

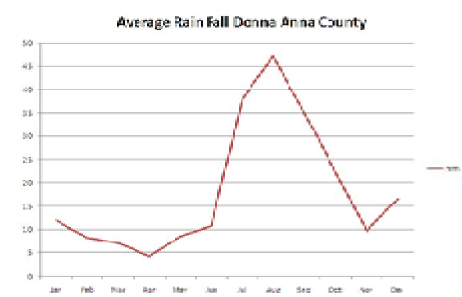

Figure 3: Line chart presented in Excel

3.3.1 *Exploratory presentation of line charts*

Design: In the exploratory presentation of a line chart, the handle of the haptic device is under the control of the user, who has the ability to explore the chart by freely moving along the graph space and detecting the position of the points and of the lines. The haptic exploration allows the user to discover the chart shape.

In order to facilitate locating the position of the line in the chart space, the haptic device asserts a gravity force, used to attract the haptic pointer to the nearest point on the line. Other types of haptic and sound cues are employed to help in the navigation. Vibrations are used to delimit the boundaries of the graph space (i.e., the 2D window that contains the chart). Speech cues can be requested to confirm whether the haptic pointer is located on the line, and to identify the value of the closest data point.

Another lighter gravity force from the current point to the next point is used to move the haptic device handle through the track of the graph. It is important for the user to easily locate the start point of the line. A gravity force can be requested (the “home” button) to pull the user towards the start point of the chart.

In order to address the issue of scalability – i.e., graphs with a large number of data points – the exploratory modality provides a zooming function. The function causes the graph space to be replaced by a window which includes the segment of the line chart with the current data point and a percentage (determined by the zooming factor) of the points preceding and following it. The segment is scaled to fill the complete navigation window. Zooming in and out is performed by repeatedly clicking one of the key on the handle of the haptic device.

Implementation: The forces applied to the handle of the haptic device are computed using well establish methods (e.g., [22]). Given a vector d along which we want to exercise a force, the intensity is determined by the formula

$$F(||d||) = C \cdot \left(1 - \frac{1}{1 + h1 \cdot ||d||^{h2}}\right) \cdot \frac{1}{1 + k1 \cdot ||d||^{k2}}$$

where C is a scaling factor; we selected h1=h2=0.5 to enable a smooth gravity effect and k1=k2=0.1 to avoid sharp force pulls. For all the forces calculated for the haptic device, we also weight the intensity by a stiffness factor (dependent on the presentation modality), i.e., *Force = Calculated Force * stiffness*.

Active navigation of line charts has three haptic parts: close to the line, far from the line, and end point of the line. If the haptic cursor is close to the line, a force will be generated to move the haptic device handle to the next point on the chart. If it is far from the line, gravity force will pull the user towards the start point on the line chart. Finally, if the user reaches an end point of the line chart, s/he will feel a vibration force feedback.

The closeness between the haptic cursor and the whole chart is tested by checking if the haptic cursor falls within a box that contains all the points of the graph – i.e., the box with opposite corners at (minX, minY) and (maxX, maxY). If there is closeness between the cursor and the line chart, a force is generated along a vector from the haptic cursor to the nearest point on the chart.

The test of whether the haptic cursor is on the line chart is realized by verifying whether the position of the cursor falls within a threshold distance from one of the line segments. If the original line segment is *Y=aX+b,* for X in the range [x1,x2], then the proximity box is the trapezoid delimited by the two lines *Y=aX+ (b+constant)* and *Y=aX+ (b-constant)* for X in [x1,x2]. The current value of the constant is 0.05. If the cursor is within the proximity box, then a force is applied to pull the haptic handle towards the next point on the line chart (i.e., (x2, a*x2+b)). If the cursor is considered close to the chart but not within the proximity box, then a force is applied perpendicularly towards the closest point of the proximity box.

In order to move the haptic pointer automatically from the current point to the next point on the line graph the force vector towards the next point (nextX,nextY) will be calculated. The vector formulas are: *vectorX=nextX-cursorX* and *vectorY=nextY-cursorY*. The force direction will be applied to the plane XY by applying these vector values to the force servo.

If the user is far from the line, a low intensity gravity force pulls the haptic cursor towards the start point of the line chart. The force is computed for a vector length (given (X_0,Y_0) coordinates of the first point in the line chart):

$$Vector\ Length = \sqrt{(X_0 - cursorX)^2 + (Y_0 - cursorY)^2}$$

The force feedback will be towards the negative z-axis.

To help the user in identifying the end of the line char, a vibration force is used. If it is the last point the calculated force vector will be in the direction of the previous point on the line graph.

3.3.2 Guided presentation of line charts

Design: The guided presentation of a line chart involves the use of attraction forces to guide the haptic pointer along the line of the line graph. The experience is that of a magnetic force successively pulling the handle of the haptic device from point to point. The buttons of the device can be used for two purposes – (i) activate audio feedback to obtain the actual data values of the points encountered along the line, and (ii) increase or decrease the speed of navigation. The latter feature was explicitly requested by the subjects in the pilot study – that complained about the excessive speed of the fixed-speed navigation introduced in the prototype.

The user has the ability to repeatedly perform the guided navigation; one of the buttons on the haptic device behaves as a "home" button, used to request the navigation to restart from the beginning (first point) of the chart. The navigation can be stopped and restarted at any point in time (using keyboard controls). Zooming functionalities are also in effect.

Implementation: This mode is divided into three stages: first, moving to the start point of the line chart. Second, a move from the current point to the next point is applied. Third, when the end point of the graph is reached, a force will keep moving towards that point, but the device handle will just stand still there.

To generate a force that will move towards the start point (X_0,Y_0) a vector will be calculated from the haptic cursor position (cursorX,cursorY) towards the start point. The calculated vectors are *vecctorX=*X_0*-cursorX* and *vectorY=*Y_0*-cursorY.* The force direction will be applied to the plane XY, by applying these vector values to the force servo. Some amount of stiffness (7) is used in order to make a decisive movement to the start of the line.

In order to move the device handle automatically from the current point (i.e., the current haptic cursor position) to the next point on the line chart, a haptic servo loop keeps calculating the force vector towards the next point (nextX,nextY). A small amount of stiffness (here we used 4) will be used in order to feel a smooth force. In order to stop on the end point of the graph, a continuous checking of the current point will be performed. If the end point is reached, a force towards such point is maintained, until the home button is pressed to restart the navigation from the starting point.

3.3.3 Summary modality

Design: In summary mode, the user can select several presentation options: chart title, average point, maximum point, minimum point, start point, end point, and trend of the graph points. In the case of maximum, minimum, average, start, and end point, the haptic device handle moves to the position of that point and the user can listen to the value of the corresponding data point. The chart title can be spoken by the speech synthesizer.

The trend option allows the user to replace the "jagged" graph, produced by simply connecting the data points with line segments, with a smooth line or curve that approximates the points in the chart. The curve is generated by interpolation (using least squares polynomials), and the user has the option of selecting the degree of the approximating polynomial. The navigation of the trend line is similar to the active navigation of the line graph.

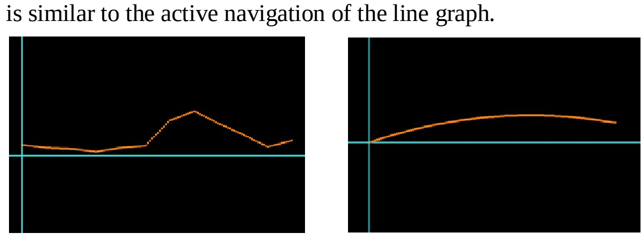

Figure 3: Original line and trend curve

The trend curve interpolates between points and focuses on the overall trend of the data set. Fig. 3 shows an example of the jagged line and a corresponding trend curve.

Implementation: For the point haptic navigation (i.e., minimum, maximum, average, start, and end point) a force vector towards that point will be generated, with gravity effect towards the xy plane. In the case of trend of points calculations, the least squares method is used to interpolate the points. We use a Spline C++ library to extract a smooth trend function from a set of data points. To explore the trend a force feedback implementation similar to the exploration of a line chart is used, with a fine grain resolution on the x-axis to generate a smooth curve.

3.3.4 Multiple line charts

Design: In the case of graphs containing multiple lines, the framework enables the selection of one particular line to be navigated (either in exploratory or guided mode). The selection is realized using an aural menus, which cycles through the names of the lines until one is selected. The framework allows also the selection of **two** lines for *comparative navigation*. The objective is to enable a presentation which compares the data points in the two lines. Important comparative features include the distance between the two lines at corresponding coordinates and identification of the points of intersection.

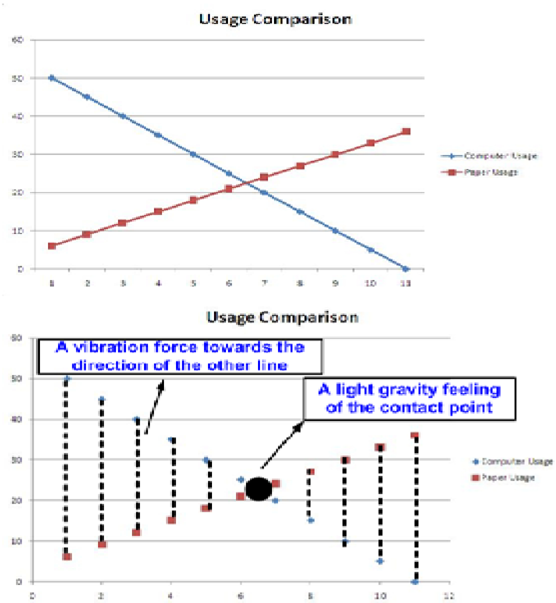

Figure 4: Comparing two lines (graph and haptic view)

The navigation is a step-wise navigation (Fig. 4) – i.e., the user can move the haptic cursor horizontally, and the cursor locks onto any of the x-coordinates from the data set; once a coordinate is locked, the user has the freedom of moving vertically, producing a stiff force each time one of the two lines is touched; speech messages can be requested to identify which line has been touched. At the points of intersections, the vibrations are replaced by a light gravity force.

Implementation: given three consecutive data points at X coordinates x1, x2, and x3, the locking effect on the x2 coordinate is realized by asserting a horizontal force towards x2 as long as the haptic cursor is within the X coordinates x1+(x2-x1)/2 and x3-(x3-x2)/2. A vibration force helps the user in determining the vertical position of the two lines being compared. It pushes the user from the current line graph to the other line graph. The calculations are similar to the ones used for line graphs, except that the force on the y vector will be towards the other line chart.

3.3.5 Evaluation

The line chart presentation has been evaluated with the same group of nine students. The students completed three tasks: exploring a single line graph (drawing it after completing the exploration), getting summary information about one line graph, and getting summary information about two line graphs. The measured parameters are: the student's ability to reproduce the graph, finding minimum or maximum values in the graph, usefulness of audio cues, similarity between the 2 line graphs, how suitable is the feeling of the force feedback, and the time needed to finish each task.

The study results show that 33% of the students were able to draw correctly the line graph using exploratory mode. On the other, hand 83% students correctly draw the line graph using the guided mode. The average time to navigate the line graph in exploration mode is 3.85 minutes and 0.4 minute in guided mode. Most of the students agreed that the guided navigation mode was more helpful in identifying the graph shape.

All the students quickly determined the minimum and maximum values through the summary mode.

In the case of comparison of two line charts, most of the users did not like to have vibration as a sign of touching the graph (used in a first prototype), while they preferred the use of stiff forces. Nevertheless, the results show that all the students were able to identify the points where the two lines intersect. 66% of the students were able to draw correctly the 2 line graphs being compared. The average time taken in this task is 2.8 minutes.

3.4 Presenting a Bar Graphs

Bar graphs (and column graphs) are composed of rectangular bars, with length proportional to the data points being represented (Fig.5). It is a form of visual display more commonly used to highlight differences between independent variables. A bar graph has the advantage of concurrently conveying both absolute (i.e., height of the bar) and relative information (i.e., differences in heights across bars).

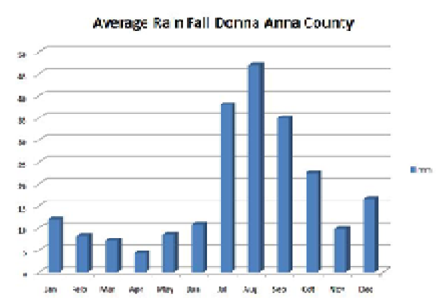

Figure 5: Bar graph presented in Excel

3.4.1 Guided and Exploratory Navigation

Design: In the case of a bar chart, we opted to combine exploratory and guided navigation into a single, hybrid form of navigation. The form is partially guided – in that it provides a mechanism to "lock" a user on each bar – and partially exploratory – in that the user decides whether to move left or right, from bar to bar. The navigation can be started from the first bar (by pressing the "home" button). Whenever the user reaches one of the bars, he/she is "locked" on it using a force that limits left/right movements. The user is instead free of moving vertically along the bar, to explore the height of the bar. The movement across columns is realized by the user by exercising a horizontal force, and it is allowed only from the top of each bar (moving to the top of one of the adjacent bars). Movement across bar tops enables comparison about relative heights of bars. As for line charts, speech output can be requested to obtain a description of the current bar (data point value, eventual labels).

Implementation: Active navigation of bar charts has two components: close to the graph and far from the graph. If the

haptic cursor is close to the graph a force will be generated to move the haptic device handle to the top of closest bar. On the other hand if the haptic cursor is far from the graph gravity force will pull the user towards the closest point on the bar chart.
The test for closeness is realized by creating a proximity box around each bar; whenever the haptic cursor is within a proximity box, a force towards the top of the bar is applied. The formulae and parameters are analogous to those used in the case of line chart; in particular, whenever the cursor is within a proximity box, the same horizontal locking mechanism described for comparison of multiple lines is employed.

3.4.2 *Summary modality*

Design: The summary mode includes all the options of summary navigation of line graphs, including the ability to generate a trend curve that flows over the top of the bars. Summary modality includes one additional case: it is possible to obtain a "differences" view of the graph, where each pair of adjacent bars is replaced by a vertical window describing the difference in height between the two bars. The top and bottom of the vertical window will be felt like a vibration force that pushes the user towards the other bar. As for the guided/exploratory navigation, the user needs to assert a horizontal force to move from one window (e.g., bars 1-2) to the next one (e.g., bars 2-3).
Implementation: the implementation is follows analogous principles as used for the comparison of two line graphs.

3.4.3 *Multiple bar charts*

Design: The proposed system allows the comparison of two data sets expressed as bar charts (where each bar from one data set is adjacent to the corresponding bar from the other data set). The haptic comparison is focused on the relative differences between the bars from the two data sets: a stiff force is exercised, indicating the vertical distance between the top points of two adjacent bars. The space feeling between the two stiff borders represents the difference between the two bars. The currently touched graph can be determined using speech feedback. If the Excel™ file contains more than two data sets, the user can select which two of them s/he wants to compare.
Implementation: the implementation reuses the principles described earlier: vibration forces are used to push the user from the top of one bar chart to the top of the other. The same x-axis locking mechanism is employed to move across different coordinates of the data set (and compare the next pair of bars).

3.4.4 *Evaluation*

The subjects in the pilot study were able to easily navigate a bar chart and reproduce the overall trend described by the bars (in less than 2 minutes). Most of the students found it difficult to navigate bar graphs using the haptic device before the introduction of the x-axis locking mechanism.

3.5 Presenting a Scatter Chart

Scatter charts (Fig.6) are 2-dimensional graphs displaying a collection of points, each representing a data point in a data set. The display of the points on a 2-D plane enables the visual recognition of trends or correlations between the data points.

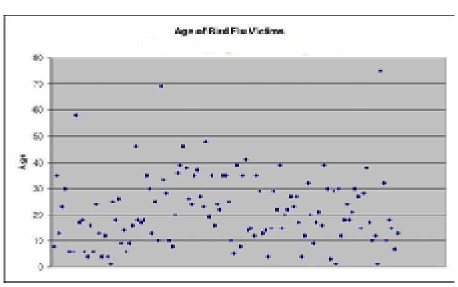

Figure 6: Scatter chart presented in Excel

3.5.1 *Guided presentation of scatter charts*

Design: In the guided navigation of scatter graphs, the user is taken automatically from point to point. The ordering of the navigation follows the values of the X coordinate of each data point. As in the case of the guided navigation for line graphs, the speed of movement can be controlled by the user. The intuition behind this approach is that small consecutive movements reflect points that are lying in small proximity, while extensive movements indicate lack of correlation.
Implementation: A force vector from the current position of the haptic cursor to the next point is computed and used to generate a force feedback towards the next point on the scatter chart.

3.5.2 *Exploratory presentation of scatter charts*

Design: Free exploration of the haptic space to find different points of the scatter chart is performed in this navigation scheme. If the user is near any of the points s/he will feel a vibration force. The user can also use speech to know the value of the touched point. Gravity force (similar to the one in exploring line charts) will be used to take the user to the start point of the scatter graph whenever the "home" button is pressed.
Implementation: The active navigation of scatter chart is realized using haptic feedback whenever a point is reached. A vibration force is used for that purpose. The localization of a data point is implemented as a small proximity circle around each data point; the vibration is in effect as long as the haptic cursor is within the proximity area; furthermore, the intensity of the vibration is increased if the multiple proximity areas have non-empty intersections.

3.5.3 *Summary modality*

Design: the summary modality for scatter charts includes several presentations of the summary modalities described earlier (e.g., minimum, maximum, average, and trend curve). In addition, the scatter chart can be navigated by *clusters*, where groups of points at a close distance from each others are collapsed into a single area. A hierarchical clustering method is used to group similar data points (Fig. 7).

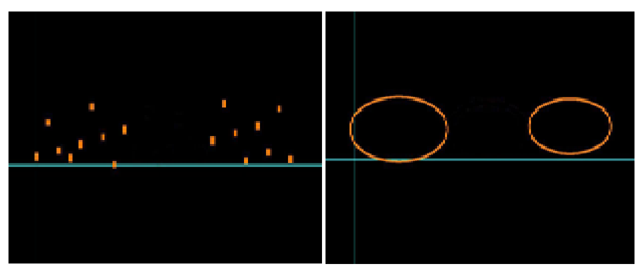
Figure 7: scattered points and clusters

The similarity metric used in the clustering is the distance between points. The points that are closed to each other within a specified threshold (0.4 by default, but can be increased or decreased at will by the user) will form one cluster. The number of clusters generated relies on the value of the distance. Each cluster can be felt as a gravity force towards weighted center of the cluster. The intensity of the force is proportional to the size of the cluster. In addition, a light vibration indicates the boundaries of the cluster – enabling the user of moving within each cluster and locating the individual points.To help the user in grasping the trend of data inside a cluster, the average of each cluster points can be known through speech.
Implementation: Each cluster is represented as an active force position in the haptic space. The gravity force is applied as a force

in the z-negative direction to the center of the cluster.

3.5.4 Evaluation

Providing the user with three navigation levels can help him/her in dynamic exploration of the scatter graph. The guided exploration can give the user an automatic way for finding the points in the graph. However this is not always the best way to navigate scatter graphs. For example, if there are many points in the graph the summary modality is a better navigation approach, as it gives the user a smaller number of points in the form of clusters.

3.6 Presenting Pie Charts

A pie chart (and similar charts, like doughnut charts) is typically a circular graph divided into sections (Fig.8); the relative sizes of the sections correspond to the relative magnitudes of a set of exclusive events or frequencies of possible values of a property. Pie charts are widely used to provide relative comparisons between values in a data set, especially to emphasize the relevance of certain data points (i.e., size of certain sectors) with respect to the "whole" (i.e., size of the whole pie chart).

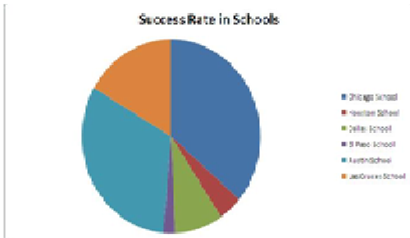

Figure 8: Pie chart presented in Excel

3.6.1 Active presentation of pie charts

Design: In the case of pie graph the circle of the graph is covering the complete workspace of the haptic device. The movements of the haptic handle are constrained to happen in a fixed radius circle (typically the perimeter of the chart). As the haptic pointer enters one of the sections of the chart, the user will experience a gravity force. The user is offered two concurrent mechanisms to understand the relative size of the section of the chart currently being visited: the span of the section (traversed by the haptic device before encountering the next section) and the intensity of the gravity force (which is proportional to the size of the section). Speech feedback can be requested to obtain the numeric value associated to the current section and its label.

Implementation: To explore a pie chart a force is needed to indicate different sections of the pie. The navigation has three phases: identifying if we are inside the pie chart circle, identifying in which section of the circle is the haptic cursor, and determining when the user moves from current section into a new section.To check if the haptic cursor is inside the circle of the pie chart, we test if the distance between the haptic cursor position and the circle center is less than or equal the circle radius.

For each section of the chart, we can calculate angles describing the section. Given the coordinate of the circle center (x0,y0) and the two boundary points of the section on the circle circumference (x1,y1) and (x2,y2), we obtain the two angles:

$$\Theta 1 = \tan^{-1} (y1\text{-}y0 / x1\text{-}x0) \text{ and } \Theta 2 = \tan^{-1} (y2\text{-}y0 / x2\text{-}x0)$$

The haptic cursor point (cursorX,cursorY) falls within this section if the angle $\Theta 3 = \tan^{-1} (cursorY\text{-}y0 / cursorX\text{-}x0)$ satisfies the condition $\Theta 2 \geq \Theta 3 \geq \Theta 1$.

The angle size that the haptic cursor falls in determines the amount of gravity force to be generated (i.e., force stiffness). The gravity force will be generated in a similar way as for the case of the line charts. The direction of the force will be towards the negative z-axis and the middle point of the section.

3.6.2 Summary modality

In the case of pie charts, the summary modality includes the traditional summary information (e.g., minimum, maximum, average), along with the ability to focus pair wise comparisons of sections of the chart. In this last modality, the user can select two sections (by moving the haptic cursor and clicking the space bar to select/deselect) and reorder the sections of the chart to make the two selected sections adjacent.

3.6.3 Evaluation

The experience with the navigation of pie charts suggests that the proposed scheme is quite effective when dealing with pie charts that have significant variations in the sizes of the different section (which are well reflected by the variations of gravity force intensity). On the other hand, minor variations in size are hard to perceive – this is a problem that even a sighted user has to address. An improvement we are considering is also the introduction of explicit speech sounds that are produced upon switching from one section to the other, to highlight either the absolute values associated to each section or automated generate percentages describing each section. We are also considering the use of haptic textures to render different sections of the pie chart.

4. Implementation

The implementation of the proposed system consists of five different components: the Open Office XML parser, the haptic renderer, the graphic renderer, the speech synthesizer, and the line equation generator.

The system uses the Novint Falcon device for haptic interaction. Novint Falcon is a haptic point interaction device with a 3 DOF. The cost of the Novint Falcon haptic device (around $150) makes it very affordable. The device provides the user with 4 different buttons available on the device circular handle. The haptic device buttons implement four functionalities: zooming, home, speak values, switch between modalities (explore, guided, and summary mode).

Open Office XML parser: the input file is collected from Microsoft Excel and parsed to identify instances of graphs. Since 2007, Excel documents are encoded using the Office Open XML (OOXML) format. This format provides explicit elements describing the types of charts being used, the parameters of the chart (e.g., data labels, scale, etc.), and the link between the chart structure and the tabular data used to generate the chart.

The information extracted from the OOXML file is used by our system to render the graphs both visually and using haptic/sound. In order to enable scaling and zooming, the graph data are normalized by the parser before being passed to the rendering modules. The implementation of this component has been realized using the TinyXML C++ library.

Haptic renderer: the haptic renderer implements the graph-specific haptic interactions discussed earlier. This module has been implemented using the HDAL SDK provided by the Novint Falcon platform. The haptic renderer is organized as layered architecture; the lowest layer implements a haptic servo loop which repeatedly checks for cursor position and haptic device buttons pressed. The middle layer provides graph-specific algorithms for collision detection, used to detect if the haptic cursor is near the graph. The top layers implement the modules which produce the force feedback required by the current graph and presentation modality.

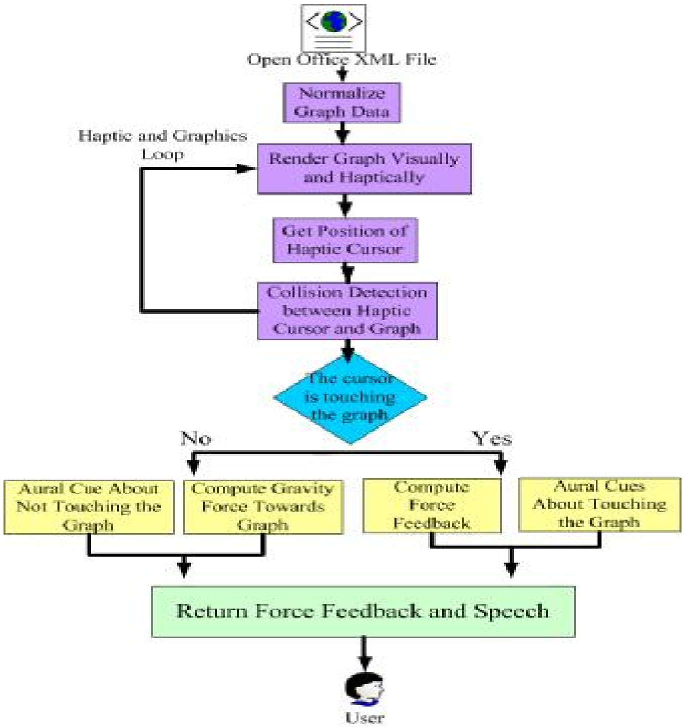

Figure 9: An Outline of the Proposed System

Graphic renderer: the system provides also a graphical rendering of the graph, implemented using OpenGL. Haptic device cursor movements are rendered on the screen as movements of a sphere.

Speech synthesizer: The speech synthesis has been realized using the Microsoft SAPI SDK. Audio cues will be used to help the users in getting different information about the graph. Also it will help the user in knowing his/her position in the haptic space.

Line equation generator: The line equation generator is used to check if the haptic cursor is touching the graph and to provide the graph-specific forms of interactions discussed earlier e.g., pulling across points, generation of a fitting curve.

5. Conclusion and Future Work

In this paper, we described a system designed to provide non-visual access to charts generated by Microsoft Excel™. The proposed solution coordinates the use of different communication channels to adapt the presentation to the specific type of chart and the specific user task. In particular, we investigated the combined use of haptic and aural feedback to provide non-visual accessible presentations of charts.

The results from the system evaluation show the importance of using guided navigation, which leads to a better recollection of simple graphs. The evaluation also pointed out the importance of using audio cues to separate the virtual areas of the graph.

The next step in this process will be the development of comprehensive user studies, to thoroughly evaluate all modalities and all types of graphs. We have already received preliminary indications of areas of improvement. For example, several users did not like the use of vibration forces as a signal in the case of comparison of distinct data sets – which could be replaced by the use of other types of force feedback or the use of non speech audio to indicate touching the graph. As future work, we also propose to expand the prototype by enabling the direct activation of the presentation tool from within Excel.

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