HAPTIC AND AURAL GRAPHS EXPLORATION FOR VISUALLY IMPAIRED USERS

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Abstract: Several web sites and e-learning platforms require the access to graphs that carry significant meanings. Understanding and perceiving the graph of a mathematical function is important but very hard for a blind user who studies mathematics. And the same happens if a cartographic representation has to be read learning geography. The paper presents an innovative solution that allows an haptic and aural exploration of the graphs of a mathematical function. The application starts from a Latex file that describes the function and its domain and uses a very cheap device connected to the audio output of the PC (AudioTact™). Preliminary experiments show that blind users can improve their graph exploration capability obtaining a better mental image of the graph. The proposed solution and the architecture of the described system allow the exploration of graph generated for other applicative domains (i.e. statistical or historical data).

Keywords: Multimodal graphs accessibility, vocal and haptic feedback, accessibility for visual impairments

1. Introduction

Several e-learning platforms or in general informative web sites have started to make their web site accessible, making them more navigable for (visually) impaired users. However, accessibility in the current conception mainly concerns navigation within the site, but does not help to effectively peruse the content in the site itself. For specific learning contexts, such as geography, math or statistics, access to graphics that carry significant meanings which are hardly translatable into words is barren to visually impaired users. In this case, providing a textual alternative like it is suggested in the accessibility guidelines may not prove sufficient, let alone satisfactory for the user. A solution to this problem is offering the image information in a multimodal way, enriching the graphical information with haptic (tactile) feedback and with aural (audio) cues.

In a multimodal version of a graph, it is possible to allow feature identification with a correlation to vibrational patterns, with corresponding voice annotations, so when for example the user hovers on a city in a map, the corresponding tactile cue is felt, and a voice reads the name of the city. Attempts using off-the-shelf haptic pointers like mice or joysticks proved that this approach is unfeasable for exploration. For this reason, it was necessary to create a new device (AudioTact™), which could be convenient and cheap, to let the blind user interact with web-based content in order to allow some sort of spatial exploration of graphs. The paper presents an innovative system which uses AudioTact™ and allows an haptic and aural exploration of the graphs of a mathematical function described in a

Latex file. The encouraging results of first experimental sessions and possible generalization and evolution of the methodology are discussed into the last part of the paper.

1.1 Learning math: dealing with formulas and graphs

Writing and reading formulas and perceiving the graph of a function stand in the way of a blind student for an efficient and complete study of the mathematics.

Writing and reading presents well known problems. The mathematical coding does not enjoy the linearity that belongs to natural language production: it is not only a succession of known characters, as it is a word and therefore a sentence, but it uses a set of symbols, extension of the common alphabet, whose meaning depends on the position and on the relative dimension in which a symbol appears (above, under, apex). The use of specific symbols and the absence of linearity make the writing of mathematical formulas very complex in Braille. But reading a formula it is possible to define where each symbol is located obtaining an unambiguous definition of its meaning. This operation (called formula linearization) describes the formula to a blind user allowing its understanding and can be obtained using a scientific editor like the Latex.

Looking at the graph of a function a student can easily perceive elements of primary importance as:

- where the function grows or decreases
- where the maximums, the minimums and the flexes are
- where the points of discontinuity are.

If the student knows the concepts that define the aforesaid elements, he can easily locate them on the graph of the function. In the same way, if he knows those concepts and where they are located, he can understand how the graph proceeds: after a maximum the graph decreases.
For the graph, that it is an image, an operation such as the formula linearization is obviously unthinkable. To give to a blind student the opportunity to build a mental map of the image, and therefore of the graph, we need a system that uses stimulus on alternative senses: we propose the contemporary use of aural and haptic feedbacks using a very cheap new device.

2. Overview of the System

The described system has been studied within a wide research project; it had the purpose to define a components architecture that allowed to a blind user to face the study of the mathematics in total autonomy, therefore that it allowed the insertion of mathematical formulas, their navigation and the exploration of their graphs. Only two components make up the system for the multimodal graph exploration:

- AudioTact™: is the transducer of the multimodal stimulus
- BlindGraph: is the software application that allows the graph exploration starting from a Latex file that describes the mathematical function.

The detailed description of the two components follows.

2.1 AudioTact™: a device for multimodal exploration

AudioTact™ is a device that allows a multimodal exploration of images. It is connected to the PC audio output and it is able to generate, at the same time, sonorous and tactile stimulus. The sounds are produced on the left audio channel; the vibrations are produced on the right audio channel and transmitted to the consumer applying a transducer to the user's finger, in the case of a touch screen, or to the graphic tablet pen.

The use of AudioTact™ requires that the image is opportunely enriched with the information about where the stimulus must be generated and their attributes, such as the frequency and the volume of the sound. Being the touch screens and the graphic tablets the only devices that exploit an absolute reference of the cursor position, they are the unique devices helpful to a blind user: using a mouse, the position of the cursor is defined by following and relative movements and those movements depend on the interaction with the visual stimulus. AudioTact™ has been designed for the interaction with a touch screen or a graphic tablet

Figure 1. Experimentation of the AudioTact™ device: a picture of a pen with the vibro-audio device attached.

The aim of an image exploration is that the user is able to understand where an object in the image is and what it is. In order to do this, in the case of exploration of an image through graphic tablet, the following strategy is proposed: the left hand is open and fixed on the graphic tablet; the right hand, that grasps the pen with the transducer, moves long of the ideal diagonals on the tablet maintaining a contact with the left hand; the relative position of the hands helps the consumer to hold some reference points during the navigation and so he can mentally reconstruct where a specific sound or vibration is positioned. The method also uses a swell paper over the tablet to allow the user to etch significant places, and add a usual tactile exploration to reinforce the multimodal exploration performed with the vibrating pen.

The innovation introduced by AudioTact™ is not simply relied to the combination of sonorous and tactile stimulus but also to the simplicity of the hardware, that means low cost and the facility to develop standalone or web applications able to use it.

2.2 BlindGraph: a graph editor

BlindGraph is the innovative application that receives as input a file that describes a 2D mathematical function, BlindGraph prepares, in automatic way, an image of the graph ready for the use with AudioTact™. At the moment BlindGraph assumes that the function is described by a Latex code but its architecture allows an easy extension to other formats. It can manage all the most common mathematical operators including, for instance, the trigonometric and hyperbolic functions and the radical sign of any index. There is no limit in the level in which the operator can be nested.

Figure 2. Experimentation of the AudioTact™ device: a visually impaired user explores the virtual image using the left hand for spatial references and the right hand for scanning for aural and vibrational cues.

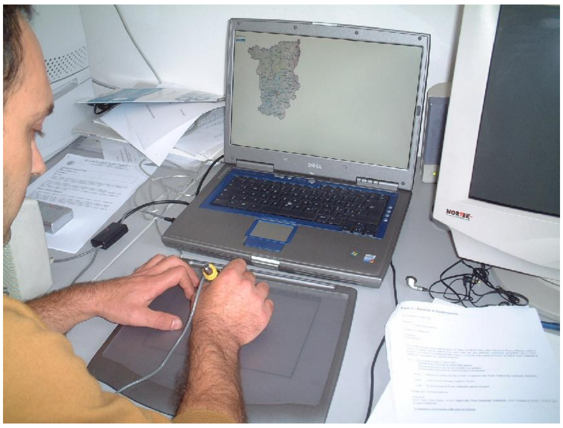

Figure 3. Experimentation of the AudioTact™ device: Exploration of a geographical map.

The file must define even the domain of the function. See, for instance, the following Latex code and the graph generated by BlindGraph in the
Figure 4.

```
\documentclass{article}
\begin{document}
$y=\sin(2x)$
$x\in (-7;7)$
\end{document}
```

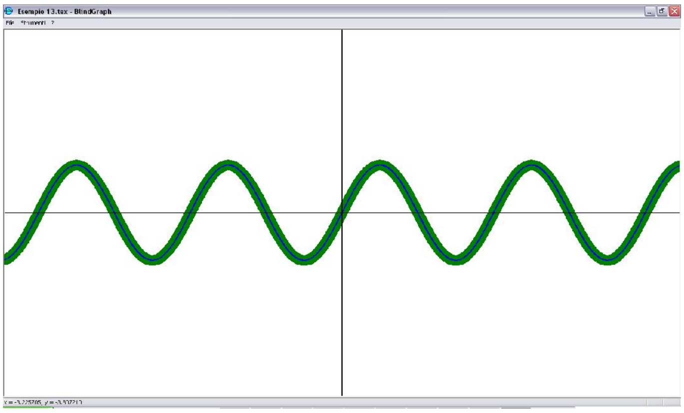

Figure 4. Example of a graph generated by BlindGraph

When the cursor is near to the graph, that is inside the green region, it is in charge of BlindGraph to send the right signals to AudioTact™ following the rules described in the following paragraph. The width of the green region can be defined for each user. Many other attributes can be defined by the user (i.e. the maximum volume), to easily adapt the system to his requirements.
During the exploration, whenever the user catches a significant point, such as a maximum, he is informed by an appropriate message. To send a "speech message" to the user, BlindGraph interacts with Jaws™, one of the most popular screen readers. In this way the user can both perceive the graph and get the most significant points of the function.

As the
Figure 5 shows, BlindGraph is made up from the following subcomponents:

- Acquisition: has the task of acquiring the definition of the function from the file;

- Study: using the structure generated by the Acquisition subcomponent, it calculates the function by points and determines the significant points;
- Visualization: displays the graph of the function and generates the signals for AudioTact™ depending on the user exploration;
- Interaction with AudioTact™: is a subcomponent to separate the signals generated by the Visualization subcomponent and how they are sent to AudioTact™ through the PC audio output;
- Message Manager: is a subcomponent to separate the messages generated by the Visualization subcomponent and how they are sent to the user;
- Monitor: both the audio signal for the exploration and the messages use the audio channel, so a monitor is required to manage the access to the same resource.

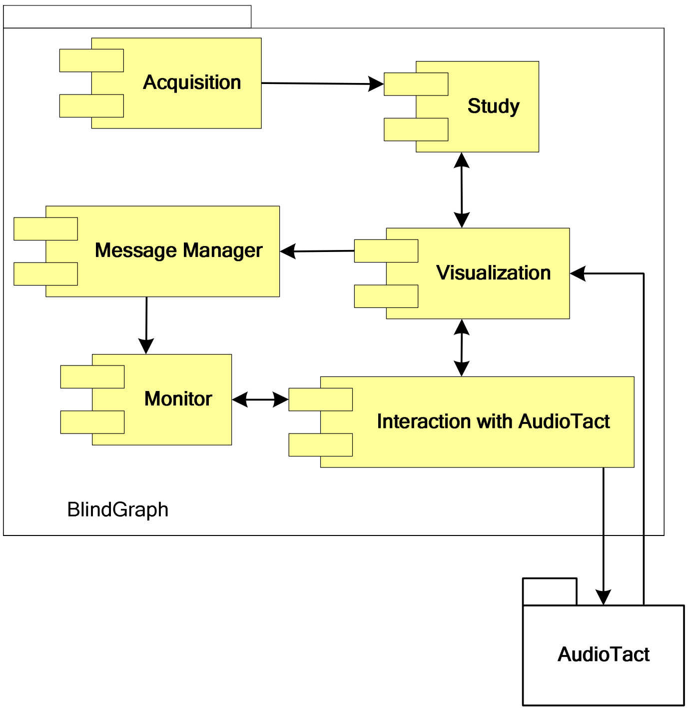

Figure 5. Architecture of the system

It is easy to understand that the Acquisition and the Study subcomponents are useful only to prepare the data for the Visualization: if the data are not generated by a function but, for instance, from the historical value of a share, the system allow the exploration of the graph that represents the state of the share.

2.3 Management of the multimodal stimulus

During the exploration BlindGraph must constantly provide to the user some reference points, so that he is able to orient and to have conscience of his own position in order to have an effective mental reconstruction of the image. The following paragraph describes the rules used by BlindGraph to allow the graph exploration in conjunction with AudioTact™.

2.3.1 Aural stimuli BlindGraph implements the sonification of the graph: an acoustic signal must be sent forth whose frequency is proportional to the ordinate. Obviously the relative value is meaningful and not the absolute one.

- when the user is to the least value of the codomain, the sound must have least frequency, independently from what the real value of the ordinate is;
- when the user is at the most value of the codomain, the sound must have the maximum frequency, independently from what the value of the ordinate is;

- only among 300 Hz and 3000 Hz the human ear perceives the increase of the frequencies in linear way and it is therefore only in this interval that the user succeeds in orienting in correct way; out of that interval a linear increase of the frequency would not be perceived as many linearly from the ear of the consumer and therefore a wrong information would be created to the ordinate of the position;
- the volume must also vary in proportion with the abscissa: increasing the abscissa, the volume increases;
- in case of the consumer incurs in one of the graph salient points, the user must be warns from a specific "speech message".

2.3.2 Haptic stimuli Vibrational stimuli are used for confirming to the user that he is on the graph: when the user is on the graph, vibrational stimulus must be issued.
Different vibrational signals will be produced:

- signal of weak width in the case of decreasing function;
- signal of great width in the case of increasing function;
- signal of maximum width in the case of "speech message" from the application.

Besides the further information transmitted via the vibrational stimuli, they allow to the user to immediately perceive that he is in a significant point: when he is, for instance, near a minimum he perceives a vibrational stimulus of maximum width so he can break the exploration and listening to the speeched message.

3. Learning Math: Experimentation and Results

The system has been tested involving four blind persons working at the Istituto dei Ciechi di Milano (the Institute of the Blind in Milan). All the users tested AudioTact™ in previous case studies relied to other applicative domains. Two tests were submitted to the user: the first one tries to verify if the consumer is able to recognize some common functions; the second one tries to verify if the consumer is able to recognize the differences between very similar function. The first test has been submitted to all the blind users; the second one has been submitted only to two of them.

The "speech messages" provided by BlindGraph result less useful and appreciated when the user has limited mathematical knowledge; otherwise they result fundamental and effective, in phase of exploration, when at least reasonable mathematical knowledge are available.

		User A	User B	User C	User D
Visual Disability		low-sighting	low-sighting	Blind	Blind
Mathematical knowledge		basic	basic	good	reasonable
Test 1	$y = x + 1$	10 min	7 min[1]	3 min	10 min
	$y = x^2$	4 min	7 min	6 min	failed[2]
	$y = \sin(x)$	7 min	12 min	4 min	5 min
Test 2	$y = x$	5 min	5 min		
	$y = x + 1$	5 min	3 min		
	$y = 3x + 5$	3 min	2 min		
	Differences	acknowledged	acknowledged		

Table 1. Result of the practical tests.

Also the methodology of exploration of the graph depends on the degree of mathematical knowledge of the consumer. In case of limited knowledge, the user performs an almost casual exploration while,

[1] After only 4 min, User B recognized that it was a straight line
[2] User D easily recognized and explored the part of parable with positive abscissas, but he did not explore the part with negative abscissas.

in case of at least reasonable mathematical knowledge, the consumer proceeds in the exploration hypothesizing that the function is continuous.
It is also interesting to notice the different use of the swell paper: when the visual impairments is more serious smaller results the use of the swell paper, but despite this the exploration results effective: this underlines the efficacy of the provided stimulus.

4. Generalization and Future Works

From the preliminary results of the described tests, it seems evident that the use of BlindGraph and AudioTact™ results extremely effective to allow the graph exploration and the success seems to be more meaningful when the user mathematical knowledge are deeper More experiments will be done with blind students involved in scientific programs during their secondary schools and academical activities

The described methodology will be generalized and tested referring to other applicative domains. Preliminary research activities have verified the efficacy of the AudioTact™ for the exploration of (manually annotated) cartographical representations. The test provided a training phase, in which the student could get confident with the method, and a second part in which it was required to use the system to extract new information from unknown images.

At the end of the training session, we required the students to extract autonomously information from two images, a simple shape of a triangle and another geographical map, representing a region of which they did not have any previous knowledge (the map of the Region of Perm, in the Russian Federation).

The results over 10 blind users show that all users were able to perform autonomous exploration of the map, and 90% of the users could extract fresh information from the image using this method. This figure moved up to 100% when we added the possibility to etch the swell paper together with the vibrating pen.

The good results obtained with AudioTact™ and BlindGraph encourage more studies to better support, for example, the automatic annotation of the cartographic images and the extraction of meaningful information directly from a Territorial Information System.

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