Converting Mathematics Textbook to Tactile Form: Process and Experiences

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Abstract

NCERT Mathematics textbook for Grade 9 was converted to a version complete with tactile diagrams. Lack of tactile diagrams hampers the education of mathematics for millions of visually impaired children. The diagrams were first simplified using appropriate guidelines drawing upon those formulated by BANA and RNIB. They were then converted using a mix of automatic, semi-automatic and manual techniques, and printed using a production process that uses 3D printed mold and theromoforming for cost-effective and bulk printing. The automated process ensures high accuracy and fidelity to the original diagram. User study has been conducted to check the efficacy of the diagrams and it was found that the inclusion of tactile diagrams significantly helped the students in understanding of mathematics.

1 Introduction

Education of mathematics is hampered by lack of diagrams that are critical for understanding key concepts. Mathematics books for visually impaired students in India comprise exclusively of Braille text, with all diagrams removed. The reason for the same is that there has been no cost-effective bulk production process for producing tactile diagrams. The availability of 3D printers and also the development of image processing techniques provide an opportunity to produce cost-effective tactile diagrams. Creating a cost-effective conversion and production process is a multi-disciplinary effort. We have found that fully automatic conversion is not feasible for all diagrams, and that a mix of automatic and semi-automatic techniques works best. The objective was to evolve the optimal blend of design and production techniques for achieving our overall criteria of seamless flow, cost-effectiveness of production line, affordability and accuracy of the tactile diagrams in reference to the original diagrams. Moreover, our focus was on diagrams for Mathematics only and this allowed us to tune our mix of techniques to that domain. We found that automatic diagram generation formed an important technique for Mathematics because of similarity of images and presence of a core set of geometric elements. We have converted an entire set of books for Grade 9 Mathematics to tactile diagrams using an innovative flow consisting of a mix of automatic and semi-automatic conversion techniques. The entire set of Grade 9 books originally consisted of 3 volumes of Braille text, which after addition of tactile diagrams and corresponding descriptions, increased to 6 volumes. In all, 432 diagrams were converted, and that resulted in creation of 265 master molds for 3D printing process.

Samples of the book were produced in our laboratory itself and user testing is being done at collaborating institutions for visually impaired. Our contribution to the state-of-art is the creation of end-to-end conversion and production flow that works seamlessly, is cost-effective to assemble, and produces an affordable and accurate tactile graphics product. This work is the first step in creating affordable tactile diagrams for mathematics education in India and as such requires further refinement that will come as a result of field use as well as user studies on perceptibility of the current set of diagrams.

In Section 2 we describe related work in this area. Section 3 describes the conversion and production flow that we used for conversion of the book. Section 4 describes the testing and validation of the diagrams. Section 5 describes the validation results.

2 Related Work

In this section we will look at related research done by various groups in the field of automatic conversion of diagrams to tactile diagrams. Richard Ladner's [1] group has worked on creating a flow using image processing and machine learning techniques and uses Photoshop for diagram simplification. The group used segmentation and simplification techniques as a generalized solution for all images including science, mathematics and computer science. These techniques were incorporated into a tool called Tactile Graphics Assistant (TGA). Chandrika Jayant et al [2] describe the trial of Tactile Graphics Assistant (TGA) in the field and is extension of earlier work with Ladner [1]. Takagi et al [3] have worked on recognition of broken line curves in graphs using clustering techniques. Here, we have to emphasize that focus of most of the research so far has been on fully automatic techniques of image processing like segmentation, simplification etc, and using machine learning classifiers to separate out text. While these techniques are definitely very useful and productive, especially for science, but for Mathematics, diagram generation techniques have proved to be very useful. The diagram generation is at higher level of abstraction than that provided by graphical editing tool like Photoshop or CorelDraw. Graphical editing tools provide objects like lines, circles, triangles etc, while our level of abstraction would consist of objects like axes, label arrows, bar charts etc. Segmentation techniques are productive in case of Science diagrams, but there too, some topics (e.g. wave motion) might benefit from automatic generation oriented tools than segmentation. There is another advantage of generation i.e. more predefined attributes can be attached to the generated objects, allowing better decision making on object placement and text placement.

3 Conversion Flow and Production Process

The conversion path we took consisted of a mix of automatic and semi-automatic techniques. In this section we will describe the flow and techniques used. The original diagram is evaluated for its complexity and checked if it can be automatically generated using our in-house automatic diagram generation tool EduTactile [3]. This is achieved by specifying the equations for the curves and shapes in the diagram, or whether the diagram is suitable for segmentation and classification based machine learning flow, or whether it requires manual techniques using tools like Photoshop or CorelDraw. The automatic conversion tools perform Braille conversion, but for manual process the Braille translation is done using Duxbury tool. The output of the conversion process is an SVG file. The SVG file is given to a 3D CAD modeling tool that generates an STL file. This STL file is used by the 3D printer to prepare the mold. A base is first created with Braille labels and the 3D printed mold is assembled on to this base. This assembled mold is used for Thermoforming process that can be used to create multiple copies on Braillon sheets.

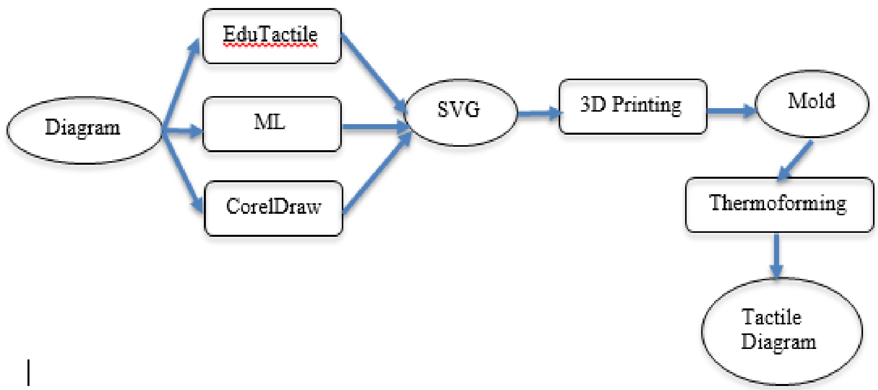

Figure 1 : Tactile graphics conversion flow

3.1 Diagram Elements in Grade 9 Mathematics

The diagrams in Grade 9 Mathematics consist of regular geometric shapes like lines, triangles, rectangles, circles etc. Graphs involve creation of axes and addition of Braille labels both for the axes and the shapes and curves. Topics that are covered are those related to subjects of coordinate geometry, areas and volumes, and statistics. In the diagrams we found several repetitive elements – for example in chapter on coordinate geometry, there were 8 instances which repeatedly used X-Y coordinate axis as shown in the samples in Fig 2 in the chapter on Coordinate Geometry and 12 instances in the chapter on Linear Equations. Therefore having an automatic axes generating feature is a very useful feature to have.

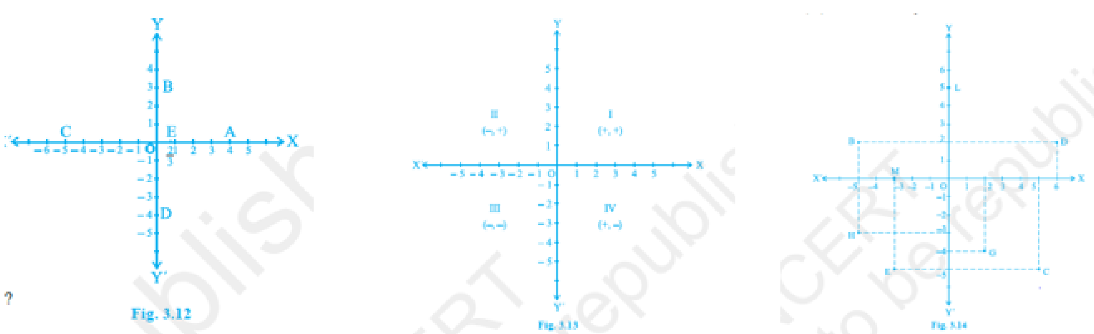

Figure 2 : Example of axes as a frequently occurring element in coordinate geometry

Similarly, the next couple of chapters involve properties of lines. For this we found that using Hough Transform for lines and circles is a better option. Hough transform is an image processing technique that basically uses a voting procedure – it passes several lines through all the non-background pixels in a neighborhood and then counts which line has maximum pixels associated with it. Hough transform works well even for dashed lines, because of the majority strategy. Figure 3 shows samples of diagrams that are line oriented.

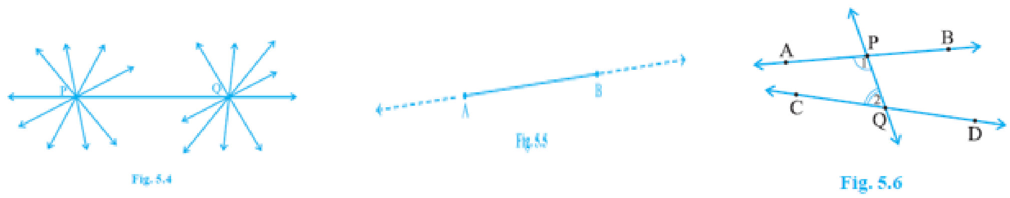

Figure 3 : Line oriented diagrams suitable for Hough line transform

The diagrams were classified into four categories – simple, medium complexity, high complexity, not directly translatable. Samples of the diagrams that are not directly translatable are shown in Figure 2. The complexity is due to 3D perspective that visually impaired students untrained in tactile graphics would find hard to understand.

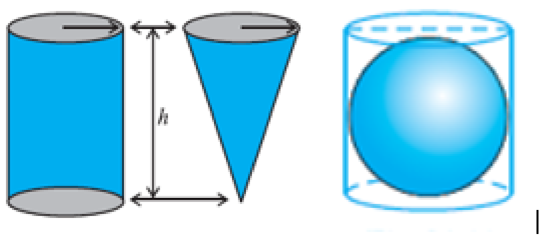

Figure 4 : Complex diagrammatic elements with 3D perspective

3.2 Use of EduTactile - Automatic Diagram Generation

Use of equations for generating the required shapes is a powerful tool in the toolbox for conversion of diagrams. This is especially true for Mathematical diagrams. EduTactile[3] is a software tool developed in-house that provides the capability to generate diagrams using equations. This tool has been written in Java. Equation entered is parsed and then the resulting graph is plotted. It provides hooks for specifying the range and also automatically labels the axes in Braille.

EduTactile provides several modules one of which is for generating statistics diagrams. Common diagrams like Pie charts, Bar charts and histograms can be automatically generated from EduTactile[3]. This tool can be used to produce statistics distribution curves like Normal and Uniform distribution. This module generates tactile graphs based on the data provided by the user through Excel/csv files. The software automatically allocates textures to the chapter on Statistics in the Grade 9 book used this module extensively to generate the diagrams.

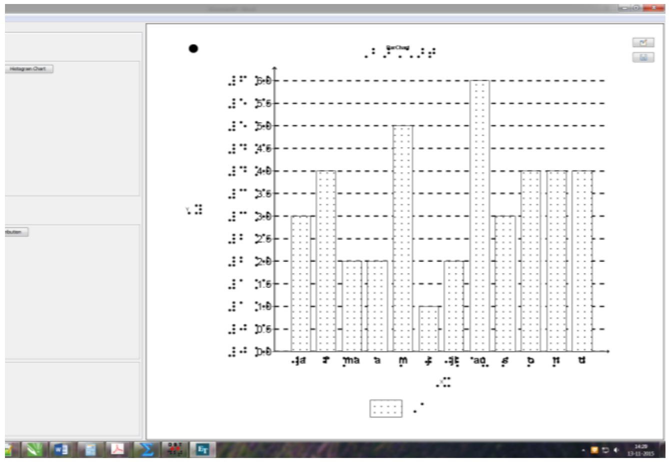

Figure 5 : Bar chart generation using statistics module of EduTactile

3.3 Separation of Text and Graphics using SVM Classifier

We have written a utility that automatically separates text and graphics using SVM classifier. The SVM is trained on the letters of the alphabet and numbers. First the image of the page is scanned and pre-filtered to remove noise. All connected components are then extracted. The connected components are then sent to an SVM classifier that classifies them as text character or graphics. The classified text is removed from the diagram. The rest of the graphics is sent to a Hough transform engine that detects lines and circles.

3.4 Lines and circles detection

Hough transform is then used to detect all the lines in the diagram. Hough transform draws lines between a point and all other points in the curve and then creates a histogram of the number of lines versus the slope. The line with the highest histogram value is the best fit for the line.

3.5 SVG Output

All the tools and utilities generate a Scalable Vector Graphics (SVG) file. Almost all the graphical drawing tools like Photoshop and CorelDraw support SVG output. The advantage of SVG is that image does not get distorted when it undergoes scaling or other such transformations. SVG files can be rendered on a normal browser also. SVG is also the input to 3D CAD Modeling tool.

3.6 3D CAD Model

A 3D CAD Modeling tool is used to convert the SVG output to a 3D CAD model. The 3D CAD Modelling tool raises the lines in the 3rd dimension depending on the width of the line. This technique allows different lines to be of different heights. Important lines could be given a larger height so that they could be perceived as important lines. The 3D CAD model generates an STL file that can be used to print the mold.

We used Blender and OpenSCAD for this task. Both the tools are easy to use and are free of cost. We used Blender when different geometry parts had different height and thickness in the same model. We used OpenSCAD when all parts of the diagram had same height and thickness.

3.7 Mold creation using 3D Printer

The STL file is used to print the mold on a 3D printer. The software used for this depends on the printer we use. Prominent ones in the printers we used were Replicator G and Cura. The final printer we selected used Cura as the operating software. ReplicatorG is an easy-to-use program in which you can load up 3D designs of the STL and DAE format. Cura also supports STL, DAE, OBJ and AMF formats.

3.8 Final mold assembly

Tactile diagram could have labels in Braille. Braille dots are hard to print on a mold. Therefore we print all the braille labels on a separate base and then stick the mold on the base. This final assembled mold is used for multiple thermoforming cycles.

4 Testing and Validation

Testing and validation was done at the National Association of the Blind, R.K.Puram Delhi. The testing team included 5 visually impaired students and a Special Educator whose role was to explain the context of the diagram. We also did a study of the response of 4 special educators. We took the same 10 concepts but taught them all the basics prior to starting our study. This ensured that they understood the topic itself. Also we provided them a few diagrams to make them acquainted with our technology.

After this the study group was given a questionnaire containing questions to measure the utility, efficacy and quality of tactile diagrams and measured on a scale of 1-5 where 5 was for "strongly agree" rating and 1 for "strongly disagree". Similarly, the four special educators were given a separate questionnaire to get their feedback on the ease as well as effectiveness of using the tactile diagrams for teaching mathematics.

5 Validation Results

The study indicates that tactile diagrams are very effective in education of mathematics. Note this was a student community that had not extensively used tactile material before – definitely not in this setting of learning text material and solving problems associated with it. Clearly, a student exposed to tactile material from the beginning would be much more benefitted. Even then, both the visually impaired students and special educators felt that tactile diagrams are very effective for teaching mathematics.

The diagrams were found by the visually impaired students to be well perceptible. Of course the purpose of the study was to test the perceptibility of the diagrams directly converted from the original textbook. It was not a set of focused study of elements of perceptibility. For example, we did not study what is the minimum size of an arc that can be perceived or whether a student could make out the difference between various types of triangles.

Results of testing on 10 concepts using 10 questions for all the five users are shown in figure 6. Left part of the figure is based on actual correct answers from the five students. Performance ranged from only 4 correct answers to all 10 correct answers. The right part draws the number of correct answers for the three distinct topics (Coordinate geometry, lines angles & triangles and Quadilaterals, circles and area) when the questions are considered in increasing level of complexity. Tenth question that related to reading bar graphs was left out in this analysis. It clearly establishes that as the complexity of the topic increases, performance is going down and that matches with the intuition one had on these questions and topics.

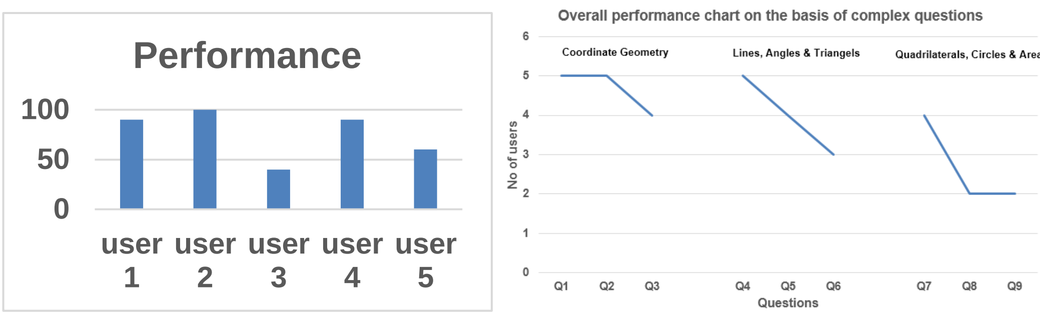

Figure 6: Results of testing 10 concepts on 5 visually impaired users

Table 1 describes the overall feedback from the users on the utility they feel for the tactile diagrams. Again the response is reasonably good with most students reporting positive experience with the use of tactile diagrams. However on the question whether this technology would enable to pursue Mathematics and/r Science there was still significant skepticism.

S.No	Attributes	Agree	Neutral	% of positive response
1	No simplification /decomposition required in diagrams	4	1	80%
2	No modification required in overall layout(placement of headings, diagrams, labels in the diagram)	5	-	100%
3	Placement and method of representing keynotes correct	5	-	100%
4	No problem in Braille text reading	5	-	100%
5	Labels easily locatable with use of connecting lines	5	-	100%
6	No problem in touch and feel of PVC sheet	5	-	100%
7	No difficulty in overall understanding of diagrams	5	-	100%
8	Promote self-learning	5	-	100%
9	Enable maths, science subjects in higher studies	3	2	60%

Table 1: Feedback from five visually impaired test subjects

Table 2 reports summary based on feedback taken from the special educators. There were four special educators and clearly their responses though reasonably positive – especially on reduction in teaching effort as well as on promotion of self-learning. On the other hand they felt that the diagram layout itself can be handled much better and that would improve comprehension as well.

S.No	Attributes	Agree	Neutral	Dis-agree	% of positive response
1	Reduction in effort of teaching	4	-	-	100%
2	No further simplification and decomposition is required?	2	2	-	50%
3	Layout of these diagrams are appropriate	2	1	1	50%
4	Will these diagrams promote self-learning?	4	-	-	100%
5	These tactile diagrams ease the explanation of concepts	4	-	-	100%

Table 2: Feedback from the four special educators

6 Conclusion and Further work

Our current work in addition to creating the first set of Grade 9 mathematics textbook with tactile diagrams, also creates a platform for further research on effectiveness of the diagrams and how they can be improved. This would require several focused studies. For example, how does a late stage student perceive tactile diagrams for the first time. We hope that with this work, more visually impaired students would be motivated to take up study of mathematics. Affordability of tactile graphics is a key factor and we feel that we have achieved that goal by selecting thermoforming as the core process. Front-end conversion process was made efficient and guidelines compliant by using a mix of automated, generative and manual techniques. Thermoforming has the additional advantage that height can be varied. Further research needs to be conducted to see how this height variation could be exploited.

Study was conducted with 5 visually impaired students as well as 4 special educators. Results of this study are reported in section 5. It is clear from the study results that the generated tactile diagrams were not only effective as study material but also elicited positive response from the students as a tool. The special educators were also overall positive but felt that the composition needs improvement. Perceptibility of tactile graphics is something that grows over time. We will need to create similar books with tactile diagrams for lower grades as well so that late stage perceptibility problem goes away.

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