Haptic models of arrays through 3D printing for computer science education

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Abstract. Computer science is taught as a regular subject in the school systems of many countries. Most tools used to teach main topics of computer science curricula, such as data structures and algorithms, are visually oriented. Our work aims to assist visually impaired students to understand fundamental data structures and algorithms through 3D printed haptic models. We developed a simple but general method that can be used by the teacher to introduce data structures and algorithmic thinking to both visual impaired and sighted students in inclusive classes. We evaluated our models for teaching one-dimensional arrays to both visual impaired and sighted students.

Keywords: Haptic models, blind users, visually impaired, inclusive education, accessibility, 3D printing, data structures, arrays

1 Introduction

Computer science is taught as a regular subject in the school systems of many countries. The Convention on the Rights of Persons with Disabilities demands that all states ensure inclusive education at all levels [25]. Even if computer science is a common subject for high school students with disabilities [9], most tools used to teach data structures, algorithmic thinking and basic programming are visually oriented and thus not suitable for blind students.

Assistive technologies allow visually impaired people to access information; however giving only the opportunity to access digital content might be not enough for a fully inclusive education. Paradoxically, students may perceive that assistive technologies place them in an atypical educational situation [22]. Therefore, their technical aids, special education teachers or different teaching concepts could cause them discomfort, by feeling different [6].

For this reason, any educational accessible tool that can be used with both sighted and visually impaired students merits to be investigated, since it can help them to fit in with their classmates and letting them feel “like everyone else”.

In computer science, data structures and algorithms are fundamental topics. Most teachers use diagrams, sketches, graphics or animations when introducing them to help students to “visualise” data structures and the behaviour of algorithms. Common assistive technologies, such as braille printers or screen readers, cannot reproduce the same effectiveness gained through the immediacy of an animation.

For these reasons, Capovilla et al. [7] proposed an inclusive teaching method using LEGO™ to introduce algorithmic thinking. They pointed out the importance of an inclusive approach and they developed an approach to teach visually impaired students basic algorithmic thinking that can also be used with sighted students, because it addresses yet another sense. Their haptic model, made of LEGO bricks, were used to teach algorithmic thinking, by recreating the initial situation and the steps leading to the solution. This can represent a first step as a haptic-based approach in computer science, which encourages to further investigate in this direction.

The contribution of our work is a general methodology to teach both data structures and algorithmic concepts to visual impaired students via haptic models. We propose representing data structures through three-dimensional geometrical objects, realized through 3D printing, that can model their most important characteristics. As stated by Hurst et al. [11] there is great potential in developing accessible tools through 3D printers and other rapid prototyping hardware. This happens not only because they are affordable and easy to learn but also for the possible interactions with online communities. Buehler et al. [4] uncovered that a minority population of designers with disabilities share their 3D printable assistive technologies through Internet.

Our solution intends to exploit 3D printing for reproducing haptic models in computer science. Teachers can use these proposed tactile models to introduce data structures and algorithmic thinking to both visually impaired and sighted students. As an example of our proposal, we present models for one-dimensional and two-dimensional arrays. Our case study is aimed at showing how 3D printing can be used for an inclusive education in computer science.

The structure of the paper is as follows: Section 2 describes the background and the related work in the field, section 3 introduces the proposed methodology, section 4 presents the design and the development of our haptic models and describes how they have been employed and evaluated, while section 5 concludes the paper and states the future works.

2 Background and Related Work

Several applications and plug-ins have been proposed for printing content into braille format [3], [27]. Unfortunately, when considering graphics and figures, specific skills are requested to prepare the content before printing it. In addition, figures may be too poor to be able to reproduce complex concepts via braille printers. For instance, Califf et al. [6] observed that even over-sized braille paper could accommodate only small trees and they were not a suitable solution for tree rotations and graphs. Also Braier et al. [2] found that use of braille-based output devices and printing concepts is limited, especially in the case of table-based data. Since, as previously stated, haptic perception allows to gather a fast overview of and deeper insight into the data, they developed a haptic 3D surface representation of classic diagrams and charts, such as bar graphs and pie charts. Finally, they proposed a model for German schools that includes a 3D printing approach to help integrate students with visual impairments.

There are several examples of using 3D printing in education for visually impaired students. 3D printing has been used by providing them with tactile representations of visual information, and by enabling them to create and adapt their own assistive devices [12]. 3D printing has been used as well as a way of meaningful communication among blind and non-blind students [15]. Buehler, Kane and Hurst found that 3D printing also encourages STEM engagement, besides supporting the creation of educational aids and customized adaptive devices [5].

Lumi Industries is releasing a software that translates text into braille code, creating the 3D model of a ‘solid braille label’ as a STL file [17], but in our experience, if the file is printed with low-cost fused filament fabrication 3D printers, the label may be unreadable.

LibraryLyna is a project that aims to host the largest collection of high quality educational 3D models to support learning by the blind and the visually impaired. This project provides printable 3D models for different disciplines: chemistry, biology and mathematics. Unfortunately, informatics and computer science are not included [16].

Kostakis et al. [15] examined how technological capabilities of open source 3D printing could serve as a tool for learning and communication. They created an experimental educational scenario focused on 3D design and printing in two high schools in Ioannina, Greece: 33 students were tasked to produce creative artefacts that carried messages in braille. Their experience was positive and led them to suppose that 3D printing can electrify various literacies and creative capacities and can be a way of communication and collaboration amongst blind and non-blind students.

Dickson presented three case studies in which three-dimensional models were used to teach mathematics to visually impaired and blind people [8]. 3D printing has been applied also in teaching mathematics and physics [20], astronomy [28], chemistry [13] [21] [23] [24], geoscience [10] and design concepts [19].

In computer science, however, to the best of our knowledge, approaches similar to ours were rarely proposed. Kane and Bigham [14] used, as we do, 3D printing to teach programming but in their work 3D printing was only a way to let visually impaired students to tactile-visualize the output of the Ruby programs they wrote. We used 3D printing to build assistive devices that teachers can exploit to explain concepts and students can use to reproduce algorithms for a better comprehension.

Indeed, given the excellent results of 3D printing in teaching other subjects, haptic models can be very promising also in computer science education. Furthermore, via 3D printing it is possible to create haptic models similar to those developed by other means and validated by other authors [7] [26]. 3D printing would made similar models replicable all over the world, without any manual or technical skill, just sharing STLs and using 3D printers to build them.

As stated by Másilko and Pecl [18], blind people often prefer reading graphs in a tactile form in relation of the spatial arrangement of nodes and edges, but they cannot modify them due to the limits of the current technologies. As described by Francioni and Smith [9] most haptic models allow only a static representation that cannot describe dynamic behaviour. In this perspective, we intend to consider this important aspect in our study. With 3D printing it is possible to overcome these issues by modelling structures that can be handled in a dynamic way.

3 Methodology

In this section we present a study proposed to model a haptic prototype designed for representing data arrays.

Some existing tools and toys can be used to create haptic models of abstract structures and to simulate algorithms and processes: magnetic toys, LEGO bricks, abacuses and similar. In fact, at many special schools for the blind, such tools have been used for many years to teach the blind mathematical concepts. As previously stated, we can find some examples of this in the literature.

Our goal is to use 3D printing to produce tangible visualizations of abstract data structures as arrays, following systematic rules that allows to model the most important characteristics of these data structures.

High school teachers often teach arrays by comparing them with a sort of container, in which data can be stored. We consider this case, by modelling arrays as flat parallelepipeds with holes that can hold three-dimensional structures that represent data. These parallelepipeds are 1 cm high, 4 cm wide and their length is variable, depending on the number of cells.

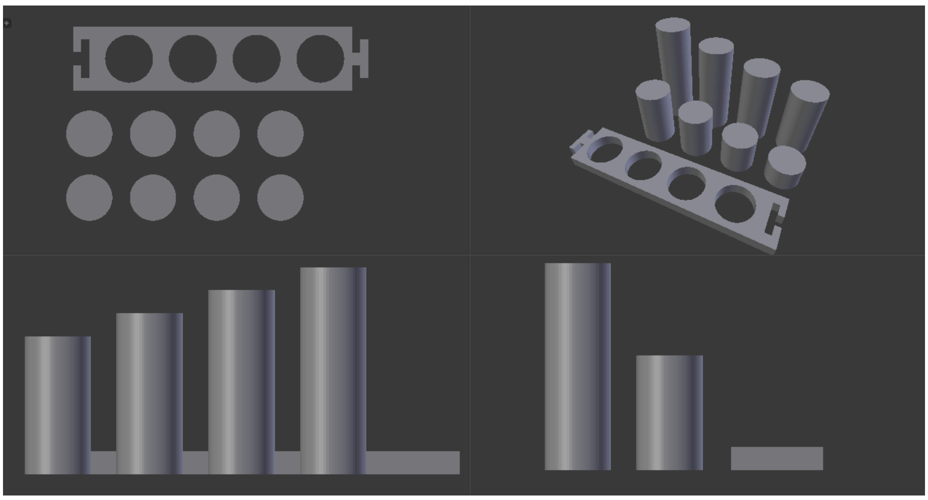

Fig. 1. - Blender model of a 4-cell array with four cells and 8 cylinders representing data.

In our case study we focused on arrays of basic numerical types. We chose to represent numeric data through cylinders with different heights proportional to the numerical value. Arrays have been modelled as flat parallelepipeds with circular holes in witch cylinders can fit (see figure 1).

The proposed model was used to explain, to both sighted and visually impaired students, sorting and searching algorithms working on arrays.

These haptic models are designed for being used in inclusive classes, both by blind and sighted students, as they can provide concrete examples to understand complex theoretical structures, since using hands can help students to think during interaction with computational objects [1]. Our 3D printed tools are supposed to support all students in understand the given problem: when the initial situation has been reproduced, each step of the algorithm can be explained by moving and switching the cylinders. When a student has understood the algorithm concepts, he should be able to apply them to the tool, by moving the cylinders and reproducing each step of the algorithms.

We use different shapes to model different types of data. In particular, we used different hole shapes (circular, triangle, square, etc.) in the parallelepipeds for different array types, which can be clearly detected by touch.

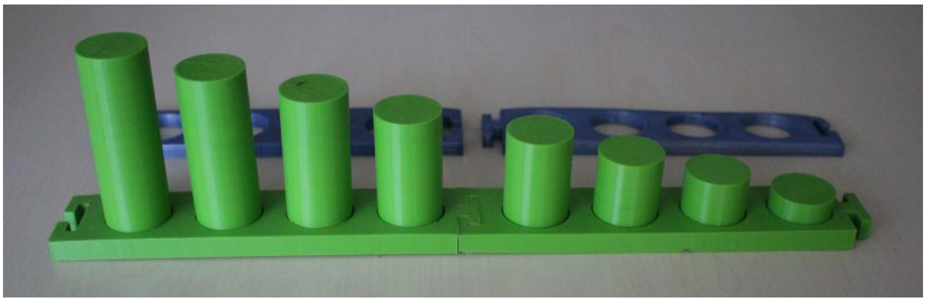

Fig. 2. 8-cell sorted array, obtained by joining two 3D printed bases

Commercial 3D printers have print area limitations. To build arrays longer than the printing area, we can link together several bases, by means of joints, thus obtaining arrays of different sizes (see figure 2).

Moreover, the same joints can be used to obtain 2D arrays, connecting in parallel two or more bases.

4 Development and Evaluation

The proposed models are so simple to allow even a high school students to develop them, just after a brief introduction of the main 3D printing concepts. Therefore, we involved some sighted students of I.S.I. Fermi, a high school set in Lucca. After a short course on the 3D modelling software Blender, the students of I.S.I. Fermi modelled and printed some of our models. This is an example of how students with a properly supervision can create by themselves the haptic models that will be used during the lessons, with significant benefits in terms of motivation and integration.

In order to understand if our proposal could be a potential solution for an inclusive lesson, we tested the haptic models with both visually impaired and sighted users. Three blind users took part in our study. Firstly, the blind author of this work had a key role in the design process regarding especially the usability of the 3D printed tools. Next, the haptic models have been evaluated with two other visually impaired users. To the first user, totally blind since birth, we presented the model explaining how it was built, what it is represent and how it have to be used. After that, we introduced a sorted array as an array in which cylinders are ordered from the shortest to the highest. Then we swapped the cylinders into a random order and we gave user the constraints: cylinders can only been swapped and cannot be put outside the array. User was asked to think how the cylinders could be moved in order to solve the sorting problem. We then present a simple sorting algorithm (bubble sort algorithm) and we asked the user to solve the sorting problem with a bigger array.

The second user was visually impaired and slightly intellectual developmentally delayed. He is a student of a vocational high school, in which computer science is not a study subject. Since he did not have any programming background, we just presented a brief introduction to basic algorithmic thinking without explaining data structures and IT topics. Also in this case, the user was able to work with the haptic model with no difficulty, and he was able to solve the given tasks. We taught him to sort cylinders with the bubble sort algorithm, by showing several times how the algorithm works on the haptic model. After some initial mistakes, user could follow perfectly all algorithm’s steps on an 8-cell array model.

Another possible application of our 3D printed models is in the "educational games" field, which can involve both sighted and visual impaired students. In order to test our model prototype, we evaluated an easy educational game with sighted students of I.S.I. Fermi that printed some models. The game was quite elementary: the teacher created an initial situation by randomly inserting cylinders in the array models. Then the students had to compute the minimum number of switching to reach the sorted situation. The first who claimed the right solution had to show the class how to order the cylinders step by step.

5 Conclusions

This paper describes a new approach in teaching computer science via haptic objects, based on the use of 3D printed models. In particular, we developed a simple but general way to represent data structures, i.e. haptic models for reproducing arrays and their application to algorithms. A short evaluation conducted with both visually impaired and sighted students was extremely successful and encouraged us to better investigate the benefits of using 3D printers in this field. Indeed, the blind users who participated to the experiment declared that haptic models made it easier the understanding of arrays and sorting algorithms much easier. Moreover, educational games tested with sighted students showed how our haptic models can be suitable to teach basic algorithmic thinking to both blind and sighted students: everyone was able to accomplish the given tasks and to repeat the algorithms steps by themselves. Thus, since this method can be used to teach both visually impaired and sighted students, it could be successfully used in inclusive classes as well.

The major limitation of our experiment is the small sample size of test groups. However, the focus of our research was to examine if the proposed teaching method could be feasible. Moreover, our method can be easily replicated, since it relies on a few very simple tools that can be built via 3D printing. Our haptic models are simple enough to be built by students and we suggest to let students to develop their tools: students of I.S.I. Fermi were highly motivating in using the tools they had made, even in elementary tasks, such as swapping cylinders. Anyway, STLs of our models could be shared in order to allow anybody to use them without the need of modelling them.

In the future, we plan to evaluate our method in a realistic case study with inclusive mainstream classes. We also plan to adapt it to other data structures, such as graphs and trees in order to cover all topics of high school computer science curriculum.

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