Utilizing 3D Printing to Assist the Blind

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Abstract: *The rapid advent of 3D printing technologies in recent years has far-reaching implications for individuals with disabilities in general and those with blindness in particular. This paper explores how 3D printing is being utilized for the blind as an affordable, easily accessible means of creating tactile representations of visual information and also expounds upon the possibilities which this technology opens up for blind people, their caregivers and accessibility designers and researchers in terms of enabling them to rapidly and cost-effectively design, create and share assistive tools and components.*

Keywords: 3D printing, assistive technologies, blind, visually impaired, tactile representation, accessibility.

1. Introduction

The rapid advent in 3D printing technologies over the past decade has resulted in tools capable of producing high quality three-dimensional objects with a variety of customization options in terms of textures, colors and materials (e.g., plastic, wood, metal). These printers are not only becoming available at increasingly affordable prices - due to advancements in technology, expiring patents and increasing competition [1] - but are also being provided with user-friendly interfaces enabling non-experts to easily create custom products to meet their needs. The proliferation of these technologies has far-reaching implications for people suffering from blindness for whom the high prices of assistive solutions – resulting from the increased financial costs involved in the industrial production of limited batches of products tailored to a small user group [2]- coupled with the lack of access to any affordable means of manufacturing customized implements themselves have traditionally been a major hurdle to the procurement of products to aid them in accessing information and performing daily tasks.

This paper aims to provide an overview of how 3D printing is currently being utilized to assist blind individuals from two perspectives: first, by providing them with tactile representations of visual information useful in domains such as education and navigation, and secondly, by enabling them to create and adapt their own assistive devices.

The rest of the paper is organized as follows: Section 2 describes how 3D printing is being utilized to convey visual information to the blind. Section 3 delineates the potential of this technology for allowing blind users, their caregivers and accessibility designers and researchers to inexpensively create customized assistive solutions. Section 4 points out some online resources currently available to support 3D printing for the blind. Section 5 concludes the paper and indicates some directions for future work.

2. 3D printing for conveying visual information

In the absence of the sense of sight, blind individuals mainly rely on their sense of touch and hearing to access information which is available to sighted people in visual form (such as the form, structure and texture of various entities in their environment). Unfortunately, in many cases, much of this information may not be amenable to the sense of touch either because it is presented in two-dimensional form (for example, as images or distant scenery) or because the entities are on a large scale (e.g., buildings) or physically inaccessible precluding tactual exploration. Though a sighted observer may provide verbal descriptions of these details but these are usually not sufficient for blind individuals to construct complete and accurate mental representations of physical entities [3].

Various assistive solutions have been developed to address these problems. Some of these systems decipher images, real-world objects and/or scenes and convey audio descriptions of these either in the form of speech [4-9] (e.g., screen readers [10, 11]) or via sonification (e.g., the vOIce system [12]). However, this kind of output may be quite slow, tedious and incomplete; also, a steep learning curve is required to learn to decipher the sonification output which may be impractical for many blind users [4, 13]. Other solutions relay the descriptions in tactile form either as Braille or by producing tactile images and models. However, Braille descriptions suffer from the limitations outlined for verbal speech descriptions above. Also, until recently, the hardware for producing tactile images and models was prohibitively expensive and not easily accessible to the target users [14, 15].

3D printing offers a cost-effective, accessible means of presenting visual information in tactile form. Two-dimensional images can be converted into computer-aided design (CAD) models of raised outline images or tactile graphics utilizing available and emerging software while three-dimensional objects can be directly scanned using a 3D scanner to generate their 3D CAD models. The CAD models can then be conveniently and inexpensively printed out in physical form using a 3D printer.

3D printing as a means of conveying visual information to the blind is being utilized in several application domains. A few of the most prominent areas in which this technology is being employed are highlighted below:

2.1 Navigation

3D printing is being used more and more as a convenient method to generate tactile maps for blind people, with multiple height layers representing various topographic objects (such as roads, paths, water bodies, etc.), to allow them to navigate in both indoor and outdoor spaces. For instance, Gotzelmann and Pavkovic [16] introduce an approach that automatically generates 2.1D tactile models – blind users can customize the level of detail that appears in the model - from the OpenStreetMap [17] data which can then be 3D printed. Schwarzbach [18] created a 3D model for visually impaired users representing the Slovalla recreation area in South Finland using data extracted from aerial photographs and a LIDAR (Light Detection and Ranging) system. Gual et al. [19, 20] conducted a study in Barcelona, Spain with blind and visually impaired individuals to analyze the use and efficacy of tactile maps produced by 3D printing and investigated how the range of tactile symbols used on such maps can be extended. It should be noted that the idea of tactile maps for the visually impaired is not new but the high cost of producing such maps and the inflexibility in terms of customizing them put them beyond the reach of most visually impaired users.

Voigt and Martens [21] propose that 3D printed tactile scale models of the interior architecture of buildings can be used to convey spatial information to blind individuals, thus, serving as an orientation aid for indoor navigation. They suggest placing such models in public buildings in locations that are spatially complex, such as in the vicinity of staircases.

2.2 Deciphering the content of digital and printed images

Digital and printed images are used to depict a wide variety of information, e.g., the appearance of objects, people and places, sceneries, graphs, diagrams, etc. Unfortunately, blind people have limited – if any – access to this information and that too, is usually in the form of brief verbal descriptions. However, several techniques are being proposed to convert these 2D images into 2.1D and 3D CAD models which can then be 3D printed to obtain tactile representations of these images. For example, Bajcsy et al. [22] introduce a method for translating web graph and map images into 3D printed models to give the blind and visually impaired access to voting and election data. The Tactile Books Project [23, 24] launched by researchers at The University of Colorado aims to convert basic children's picture books into 3D printed tactile books with 3D figures, sometimes along with Braille text, embedded in the pages (Figure 1). As discussed in the section on navigation, research is also underway on

Figure 1. An example of a 3D printed page from a tactile storybook (image courtesy of [25])

generating 3D printed tactile maps from digital images [16, 18].

Another area being actively explored is the development of methods for producing 3D printed tactile representations of paintings to facilitate the access of visually impaired people to artwork in museums. For example, Volpe et al. [26] propose four alternative computer-based methods for semi-automatic generation of tactile 3D models starting from RGB digital images of paintings. The Midas Touch project [27] at Harvard Innovation Lab also aims to convert paintings into tactile form by adding layers of texture to the 2D images of paintings.

2.3 Tactile exploration of remote, huge, miniscule and/or tactually inaccessible objects

Some objects cannot be explored via touch because of their size (they may be too large (e.g., buildings, sculptures, etc.), or too small (e.g., atoms molecules)), their distance (e.g., planets, remotely located objects) and/or their inaccessibility despite their physical proximity (e.g., internal body organs, museum artifacts, zoo animals, etc.). However, since these objects can be visually perceived - in some cases, by using tools like telescopes, microscopes and X-rays, their dimensions can be scanned and measured enabling their 3D CAD models to be produced and 3D printed.

A few examples of how 3D printing has been utilized in this manner are as follows:

2.3.1 Huge or miniscule objects: Celani et al. [14] have produced 3D printed tactile scale models of four buildings designed by a renowned architect to convey their architectural details to high school students. The Guide4Blind project [28] has utilized 3D printing to produce scale models of landmark buildings in the city of Soest, Germany. These models were then used to generate bronze models which are placed alongside the landmarks allowing visually impaired travelers to feel them and receive detailed impressions of the shapes and textures of the buildings. A library in Lithuania has also created 3D printed models of several historical buildings (such as the Taj Mahal and Reims Cathedral) and local landmarks for the same purpose out [29] (Figure 2). On the other hand, Teshima et al. [30] have created enlarged 3D printed skeleton models of micro-organisms for teaching blind pupils about their structure while Wedler et al. [31] have developed a system which allows visually impaired chemistry students to input computed molecular structures which are then printed out in physical form using a 3D printer enabling the students to tactually explore them.

Figure 2. A 3D printed model of the Reims Cathedral [29]

2.3.2 Remote objects: The 3D Astronomy Project at the Space Telescope Science Institute and NASA Goddard have created innovative education materials and 3D models of astronomical objects using Hubble data [32]. Since blind people cannot view photographs of celebrities and thus, cannot form an idea of what their faces look like, a library in Lithuania gathered several famous singers and actors, captured their face images from several angles, stitched them together to create 3D models and 3D printed them out [29]. The collection of 3D printed models has been exhibited in several cities.

2.3.4 Tactually inaccessible objects: Since blind parents are unable to view ultrasound images of their unborn baby, the Feto3D project [33] employs 3D prenatal imaging technology and 3D printing to produce physical replicas of a baby growing in the womb, allowing moms- and dads-to-be to hold a model of their unborn child in their hands. The same system can also produce 3D printed models of internal body organs and the skeletal system. Yahoo Japan's Hands On Search machine allows visually impaired children to verbally specify objects (e.g., "giraffe" or "Tokyo Skytree Building") [34]. It then searches Yahoo and upon finding the object, 3D prints out a miniaturized version of it for the child to tactually explore. Neumüller et al. [15] have expounded upon the potential of 3D printing as a means for making cultural artifacts in museums accessible to visually impaired people and have provided several examples of this [35, 36].

2.4 Education

Physical models are considered to be indispensable tools for teaching visually impaired children, especially those with congenital blindness, to help them form concepts of things that they have never seen [14, 15, 37]. However, the high expense of such models as well as the decreasing costs of simulation and visualization software and computer modelling have increasingly deterred educators from utilizing such models in their teaching [15]. 3D printing as a low cost option for producing physical models can turn that situation around. 3D printing for deciphering the contents of digital and printed images and the tactile exploration of remote, huge, miniscule and/or tactually inaccessible objects, as discussed in the preceding sections, has obvious applications in education, with several projects aimed specifically towards children's education, e.g., the Tactile Books Project [23, 24], Yahoo Japan's Hands On Search machine, NASA's 3D Astronomy Project [32], and the systems for teaching about molecular structures [31], microorganisms [30] and architecture [14] mentioned above. Some additional examples include the use of 3D printed models to convey chemistry and mathematics concepts to visually impaired students at Simon Fraser University, Canada [38], converging 3D printing and 3D surface thermal reflow treatment techniques to produce touchable objects with detailed lines and curves at the Korea Institute of Science and Technology [39] and having visually impaired pupils write code to produce accessible 3D printed tactile visualizations of data extracted from Twitter at the National Federation for the Blind's STEM-X camp [40].

3D printed models can also be incorporated into educational software for children. For example, we are currently implementing a system for teaching tactual shape perception and small scale space spatial relationships to visually impaired children which utilizes a tangible user interface consisting of 3D printed objects in various shapes and geometrics forms which can be identified and tracked by a computer vision based system as they are moved across a transparent surface [41].

It should be noted that 3D printed models can not only convey visual information to a student, they can also enable the student to relay information from his perspective to others in a form that is accessible to him as described in [31].

3. 3D printing for creating customized assistive devices

People with disabilities frequently rely on a variety of assistive devices to help them carry out daily activities. Though many such devices are commercially available, several studies have shown that about one third of all such devices are eventually abandoned by their users [42-44]. Some reasons identified for this high rejection rate include the following [45]: Assistive technologies (AT), which have generic designs, cannot meet the complex and ever-changing needs of people with disabilities who often suffer from multiple conditions [2, 46, 47]. The lack of user involvement in the selection of AT [42, 47, 48] and the often-observed proclivity of the disabled to purchase assistive devices just because they are easy to procure even though they do not meet their individual needs [42] have been cited as other significant factors leading to abandonment. Moreover, the high prices of AT, arising from the high development costs of producing small batches of products tailored for small user groups [2], put them beyond the financial reach of most disabled people and their caregivers.

3D printing offers a viable solution to all the above problems [2, 49, 50]. It allows blind users and their caregivers to design and print out their own assistive solutions customized to their unique needs and at a fraction of the price that it would cost to have the same solutions custom manufactured by a retailer. Moreover, if the user's needs change, the designs can be adapted and/or new tools can be created to meet the user's new requirements. With 3D printers becoming increasingly accessible and affordable, users can receive their assistive solutions at much faster speeds and with greater ease as compared to the often complex and lengthy procedures required to procure the same devices via referrals to multiple, often uncoordinated, organizations [49, 51, 52]. Furthermore, if a part gets broken or lost, it can be conveniently replaced.

Moreover, 3D printing allows researchers working in the area of assistive technologies for the blind to custom manufacture several of the hardware components for their prototypes. This offers two main advantages: 1. The CAD models of these components can be provided to the users enabling them to print these out and put together the prototype devices themselves. 2. It allows for the creation of a more aesthetically pleasing solution than one produced by clumsily attaching sensors and motors to existing products resulting in bulky, unwieldy, outlandish devices (this is especially significant since, as reported by several studies [53], the "cosmetic acceptability" of a device is perceived to be more important by visually impaired users than the actual functions it provides.).

A few examples of how 3D printing has been utilized for building assistive devices for the blind are as follows:

Several educational toys and games are being developed for VI children whose components can be 3D printed. For instance, Fittle [54] is a set of 3D printed puzzles where each puzzle consists of blocks imprinted with Braille letters which, when put together correctly, not only form a word but also the shape of the object that the word represents (e.g., blocks with letters "F", "I", "S" and "H" can be put together to form the shape of a fish (Figure 3)). This allows a child to learn both how to spell the word and also to visualize it. 3D printed objects can also be used to provide a tangible user interface to educational software. For instance, we proposed a solution which teaches Braille letter recognition to young blind children by allowing them to manipulate NFC-tag embedded blocks with Braille letters embossed on them [55]. The blocks can be 3D printed and customized according to individual needs. Children can interact with the system by providing input via the tangible interface and receive auditory feedback via a speech-based interface. Another system for teaching tactual shape perception and spatial relationships to blind children via a tangible user interface consisting of 3D printed geometric objects has already been described in section 2.4 [41].

Figure 3. Example of a Fittle puzzle [54].

Kane et al. [56] present touchplates, tactile guides which may be 3D printed, among other options, and overlaid on touchscreens as an aid for providing tactile feedback to blind users.

Nanayakkara et al. [57] introduce EyeRing, a 3D printed ring with an embedded camera, worn on the finger. The user can point the EyeRing towards an area of interest and press a button on the side of the ring to capture an image which is then transmitted via Bluetooth to a mobile phone application which analyzes the image and provides feedback to the user via a text-to-speech module. Some prototypical applications using this device for navigation, currency detection and color detection were tested. EyeRing has also been expanded to the FingerReader device [58] for reading printed text (Figure 4).

Figure 4. The FingerReader device [58] for reading printed text (image courtesy of [59])

Similarly, researchers at Oxford University [60] are developing glasses whose frames can be 3D printed and then equipped with various sensors and electronic components to enable people with severely impaired sight to use their remaining vision to detect obstacles (Figure 5).

Furthermore, several commercial assistive products for the blind are appearing in the market, such as the Braille phones developed by OwnFone [61], which are incorporating 3D printed components to keep their cost down.

Figure 5. Experimental prototype of 'smart glasses' to enhance vision for poorly sighted individuals. This system has a see-through display and a special type of camera that can detect and highlight nearby objects [60].

4. 3D printing resources for the blind

It should be noted that a number of resources are available online to support 3D printing for the blind. For instance, the Accessibility Metadata Project [62], aims to add metadata tags to the digital files for 3D printing available on MakerBot's Thingsverse website [63], to enable search engines to pick out only objects which are tactile. Individual users (e.g., [64], [65]) have also uploaded their designs for 3Dprintable products for blind individuals in various online communities.

Various user friendly tools for converting 2D data into 3D models are also being developed. Some have already been mentioned in section 2.2. Another example is VizTouch [66], a software, developed through a user-centered approach involving visually impaired users. It allows a user to input an equation or an excel file for the information which he would like to visualize and automatically generates an STL file ready to be printed on a 3D printer. VizTouch has been equipped with a screen reader to allow visually impaired users to access it.

Tools like the Easy Make Oven [49] allow users with little or no 3D modelling experience to scan, alter and combine physical objects and then export them in a format ready for fabrication on a 3D printer or laser cutter.

In addition, there are several libraries of 3D models available online which, while not specifically targeted towards blind users, can be 3D printed to offer tactile representations of various kinds of physical objects and visual information [63] [37].

4. Conclusion

This paper explored how 3D printing is being utilized for the blind as an affordable, easily accessible means of creating tactile representations of visual information. It also expounded upon the possibilities which this technology opens up for blind people, their caregivers and accessibility designers and researchers in terms of enabling them to rapidly and cost-effectively design, create and share assistive tools and components. Moreover, it listed some online resources currently available for this purpose.

The continuing proliferation of 3D printers with decreasing prices and increasing functionalities and options, and the ensuing development of more user-friendly 3D modelling software tools coupled with the online global sharing of ideas and resources indicate that the potential of this technology will continue to expand. We are eager to see how this potential will be harnessed in innovative ways to assist blind people in their everyday lives.

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