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Literature Survey of How Students with Visual Impairments Interact with Engineering Course Materials

Dr. Adrian Rodriguez, zyBooks, a Wiley brand

Adrian Rodriguez is an Engineering Content Developer for zyBooks, a Wiley brand and a Lecturer in Mechanical Engineering at The University of Texas at Austin. His research interests include engineering education, multibody dynamics, contact and impact with friction, electro-mechanical systems, and non-linear dynamics. He earned his B.S. degree in Mechanical Engineering from The University of Texas at Austin and his M.S. and Ph.D. degrees in Mechanical Engineering from The University of Texas at Arlington.

Lauren Fogg, zyBooks, a Wiley Brand

Lauren Fogg obtained her Bachelor's degree in Mechanical Engineering in 2021 and her Master's degree in Mechanical Engineering in 2022 from Louisiana Tech University. She is currently working on her Ph.D. in Engineering with a concentration in Engineering Education from Louisiana Tech University. She is currently an Associate Engineering Content Developer with zyBooks, a Wiley Brand. Her research interests are diversity, gender equity, retention, project-based learning, cognitive models of problem-solving, and making engineering textbooks more accessible and innovative for students.

Dr. Alicia Clark, zyBooks, A Wiley Brand

Alicia Clark obtained her BS Degree in Mechanical Engineering from Lafayette College, and her MS and PhD degrees in Mechanical Engineering from the University of Washington. Her research interests include engineering education, fluid mechanics, and medical ultrasound. She is currently an Engineering Content Developer for zyBooks, a Wiley Brand. At zyBooks, she creates digital content for engineering textbooks to help make textbooks more engaging and accessible for students.

Jennifer L. Welter

Jennifer ”Jenny” Welter has been a publishing professional for more than two decades, specifically focused on engineering publications and courseware during the majority of her tenure. She is passionate about supporting engineering education, specifically focused on content and assessment development for more effective student learning. She earned her BA in English from The University of Iowa.

Dr. Gergely Sirokman, zyBooks, A Wiley Brand

Gergely (Greg) Sirokman is an engineering content developer at zyBooks, a Wiley brand. He earned a BS in chemistry from Brandeis University, and a Ph.D. in Inorganic Chemistry from MIT. He was a Professor at Wentworth Institute of Technology for 14 years, with particular interests in renewable energy and gamification of education. He now works on creating and improving statistics and engineering content for zyBooks' online interactive textbooks, and has developed a keen interest in increasing accessibility for learning media.

Dr. Ryan Barlow, zyBooks, A Wiley Brand

Ryan Barlow obtained his Bachelor's Degree in Mechanical Engineering from the University of Utah in 2012, his Master's Degree in Science Education from the University of Maryland in 2016 and his PhD in Engineering Education from Utah State University in 2020. He currently works for zyBooks, A Wiley Brand creating interactive content for online mechanical engineering textbooks. His current research focuses on online engineering assessment, accessibility in online textbooks, and studying the effectiveness of online textbooks in engineering courses.

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Abstract

There has been an increase in overall accessibility (a11y) for students with blind/visual impairments (BVI) at colleges and universities across the country. However, there is a lack of details in content that is made accessible, which can help inform accessibility compliance guidelines for specialized areas of study. While the general a11y guidelines are helpful for many students at a baseline, creating accessible content in many engineering disciplines is difficult and a desire still exists to do more to support students with BVI. Ideally, accessible content should help a student learn the material so that the student can use those skills in other courses or in the workforce. However, it is entirely possible that accessible content can pass the minimum requirements to be compliant with ADA requirements, but remain non-functional for effective student learning. The current paper outlines what barriers exist for students with BVI in engineering despite baseline accessibility compliance and performs a short literature review of the current assistive technologies that exist to overcome these barriers. The paper discusses some conclusions and possible future steps towards specialized guidelines for engineering course materials that are better suited for the discipline as a whole.

Introduction

The National Federation of the Blind (NFB) defines a person to be blind "if their sight is bad enough--even with corrective lenses--that they must use alternative methods to engage in any activity that people with normal vision would do using their eyes" [1]. While the NFB recognizes that a generally accepted definition for "visually impaired," "low vision," or "vision loss" does not exist, the fact remains that people with any level of blindness/visual impairments (BVI) must have a fair opportunity to understand the world with which they interact. This is especially true for students with BVI given their need to interact with educational course materials that are often inaccessible. Students with BVI face a difficult path in education, where lack of accessibility resources can hinder their desire and ability to pursue higher education. According to a 2019 study, only 16.5% of adults in the U.S. aged 21-64 with a visual impairment attained a Bachelor's degree or higher [2]. To put this percentage in context, 34.1% of adults in the U.S. aged 21-64 without visual impairments have attained a Bachelor's degree or higher [2]. The percentage of students with BVI that pursued a STEM degree is likely even smaller since these fields involve complex equations, diagrams, charts, and schematics filled with contextual details. Student persistence will decrease unless students with BVI are supported and offered sufficient accessible content using assistive technologies [3].

A systematic literature survey was conducted in January 2023 using Compendex, which comprises more than 3,600 journals and 4,100 conference publications and trade magazines. The search terms were: "accessibility" or "assistive technology", "visually impaired" or "low vision" or "blind" or "BVI", "engineering", and "materials" or "content". The search yielded a total of 463 unique publications, which were evaluated for relevance based on the following criteria: relevance to STEM disciplines, relevance to auditory, tactile, and multi-modal types of assistive technology, and deduplication of assistive technology. This methodology narrowed the initial list to approximately 50 publications, from which additional forward and backward reference searching was performed and expanded the list to 67 relevant articles. The 40 references cited in this paper were a result of repeating the deduplication process and including references with the most recent improvements to predecessors of an assistive technology. These publications helped define the landscape around available assistive technologies for engineering course materials, while also exposing the areas that need improvement.

Assistive technology can be defined as equipment, devices, and systems that are used to overcome the social, infrastructural, and other barriers experienced by people with disabilities that prevent their full and equal participation in all aspects of society [4]. More specifically, assistive technology for people with BVI can comprise three main types: auditory, tactile, and multi-modal. Auditory assistive technology can consist of delivering speech (e.g., screen readers) or non-speech (e.g., sound) cues. For example, text-to-speech synthesis technology first became available in the late 1970s to programmers with BVI [5]-[6]. It was not until 1992 that screen readers were developed, which enabled people with BVI to access most of the commercially available text-based packages using either speech or braille technology [7]-[9]. A small-scale study in 2021 compared 36 screen reader users to 36 non-screen reader users. The results showed that due to the inaccessibility of online data visualizations, screen-reader users extract information 61.48% less accurately and spend 210.96% more time interacting with online data visualizations compared to non-screen-reader users [10]. While alternative text descriptions are seemingly the easiest approach towards making online engineering content and circuit diagrams more accessible, a good balance is still needed between effective and concise descriptions, as noted by Barlow et al. [11].

Braille is a type of tactile assistive technology that can include haptics (e.g., force feedback and tactile feedback) or physical objects (e.g., braille paper or 3D printing). Computer-controlled braille devices appeared in the late 1970s and conveyed a computer system's output to users [12]-[15]. The third type is multi-modal assistive technology, which combines both audio and tactile solutions into a system that delivers accessible content. The first appearance of a multi-modal device was in the mid-1970s with a system called Optacon. This system uses a small camera to read information and convert it into tactile stimulation of a user's finger through a vibrotactile matrix [16].

The sections that follow detail and compare the newer assistive technologies that have emerged as they relate to the field of engineering and the diverse content the discipline covers. This engineering content can comprise diagrams and schematics (in electrical, mechanical, and architectural engineering), graphs and charts (in materials science and computer science), or molecules and chemical structures (in physics and chemical engineering). These assistive technologies rely on auditory, tactile, and multi-modal approaches to translate complex engineering content into an accessible format that will support learning for students with BVI. While BVI students stand to benefit primarily from these accessible materials, the landscape defined in the present paper would also be useful to accessibility stakeholders including, but not limited to: digital content developers, assistive technology designers, accessibility coordinators, and disability and access offices.

Auditory assistive technologies

Currently, there are numerous auditory assistive technologies that exist to help students with visual impairments interact with engineering course materials. A semi-automatic tool was developed called BOOK4all to help adapt e-books for visually impaired students [17]. The BOOK4all tool is used to generate an audio format of engineering textbooks in a quicker and more efficient way since several of the tasks can be performed semi-automatically.

Batanero et al. [13] developed an adapted platform and adapted learning outcomes (LOs) to help blind and deaf students in computer engineering. The adapted platform creates a new version of each video tutorial in a lesson with the following auditory adaptations: an audio description, a long description of the images that can be converted to audio by a screen reader, and a long description of both images and audio. These accessible descriptions are manually created, unlike the semi-automatic process in Book4All [17]. The adapted platform also has a screen reader and a braille device that translates the text to braille for deaf-blind students. Results suggest that the learning performance of students with blindness and deafness in telecommunications and computer engineering improved noticeably using the adaptable platform. The results can be extended to other domains, including disciplines that are particularly challenging to students with specific accessibility needs, like mathematics or linguistics, since these courses require more detailed adaptations of the LOs.

To create accessible circuit diagrams, Pender and Healy [18] proposed a software-based solution that produces alternative text descriptions of analog and digital elements that are converted from netlists. This alternative text is then read by a screen reader similar to the output by Batanero et al.'s platform [13]. A different approach towards circuit diagrams is the work by Zapirain et al. [19], which presents an open source algorithm integrated in a tool compatible with Open Office. This algorithm applies digital image processing and computer vision techniques to any schematic circuit included in the document. The algorithm also provides an intelligent and automatic textual description of both the sequence of electronic components and their position in the schematic in order to make it accessible to students with BVI. The work was done for electronics engineering, but this device could be used for any engineering student taking a circuits course.

Graphs are an essential part of computer science and materials science education. A system called exPLoring graphs at UMB (PLUMB) displays a drawn graph on a tablet PC and uses auditory cues to help a blind user navigate the graph [20]. Preliminary trials were mainly intended to verify that non-sighted computer users could easily understand and interact with an audio-feedback interface of PLUMB. The results showed that blind users had an easy time mastering the interface and exploring small graphs. Beyond computer science and materials science, PLUMB has applications to assist blind individuals in navigation, map manipulation, and other applications that require graph visualization.

Kekul'e is another software solution, like Pender and Healy's [18], but applied to chemical structures in the areas of chemical engineering and chemistry. Kekul'e allows visually impaired users to explore the structures of chemical molecules using a speech-based presentation [21]. An evaluation compared a fully functional version of Kekul'e with a simpler version and showed that participants found it easier to explore molecules using the full version of Kekul'e than the simpler version. The development of suitable strategies was, however, harder in the full version, suggesting that more training or practice would yield significant improvements in performance. Similar improvements might also be achievable by improving the interface.

Tactile assistive technologies

Tactile diagrams, or tactile graphics, are a popular approach for converting a figure, graph, or other image to a form that is accessible to visually impaired users. The diagram is commonly printed on swell paper, braille paper, or thermoform and offers students with BVI a type of kinaesthetic learning. These print methods can have little control over the resolution of raised features, can lead to misinterpretation because of inconsistent printed textures, and have inaccuracies in the production methods used. The limitations of using print methods was overcome with a new innovative method that uses piezoelectric inkjet technology [22]. The technology in [22] has applications in electrical engineering, since a circuit diagram is a graphical representation of an electronic circuit usually in the form of an image consisting of wires and components. The technology can also be useful for other fields where flow diagrams are used, like in mechanical engineering. Alternatively, Pender and Healy [18] proposed a tactile-based solution. Unlike TangibleCircuits [23], which 3D prints all of the circuit schematics, Pender and Healy [18] used 3D printed tactile buttons with strings to represent analog and digital elements within circuit diagrams. Plus, dots and numbers were added on the sides of the 3D printed buttons to mark the element number in the schematic [18].

Dynamic tactile devices (DTD) are a refreshable braille and tactile graphics display on a single tactile surface [24]. DTDs are generally preferred in engineering because these disciplines usually encounter graphics that change, like videos, animations, and simulations. The Optacon [16] is a DTD used for basic letter recognition and composed of a tactile array of 6 by 24 pins that appear on the display [25]. The concept of having tactile feedback falls in the area of haptic technology. For example, in 2009 a relatively inexpensive force feedback device (i.e., haptics) called the Novint Falcon Force Feedback Game Controller was proposed by Pawluk et al. [26]. The controller is used within a virtual environment to allow students to compare nano-topologies and nano-forces to the macro-world. A student can move the controller handle to follow and sense the topology of hard surfaces, which is very difficult for students to understand otherwise in nanoscale science and nanotechnology [26]. Other examples of haptics can be found in the fields of physics, engineering statics, dynamics, and control systems for hands-on instruction [27]-[28].

In the area of chemistry, Mahnke [29] proposed a magnetic representation for chemical bonds since chemical formulas are represented with the help of Lewis structures. This representation uses a reduced set of magnetic symbols on a magnetic base that are different in color, shape, and size to represent atoms, electrons, and elements. The students were given tactile images of the structures in order to use the magnets to build the physical structure [29].

Multi-modal assistive technologies

The era of audio-tactile assistive technology for persons with BVI started with Nomad [30]. The device interfaces with a computer, while a touch-sensitive surface triggers pre-defined audio descriptions. Nomad was designed to make interactive maps accessible in non-educational settings. While Nomad was not developed for students with BVI, the technology laid the groundwork for the application of new audio-tactile devices for engineering content. For example, TouchMelody is a system that augments diagrams, graphs, and geometrical shapes using a motion tracker and 3D spatial audio [31]. The system allows a user to augment tactile diagrams (e.g., zoom, scroll) by tracking the positions of motion sensors on their index fingers and receiving auditory feedback. The TouchMelody system reduces the amount of "tactile clutter" by using a digital tactile diagram versus a physical tactile diagram, which produces a physical object. A digital tactile diagram allows the user to zoom in and focus more easily on a subset of the diagram. Physical tactile diagrams that are printed on braille paper, 3D printing, or swell paper continue to improve.

Audio, Braille paper

The IVEO by ViewPlus is a device that aims to address the shortcomings of the Nomad system by combining audio output and tactile graphics printed on braille paper [32]. Label descriptions that are stored within a scalable vector graphic (SVG) file can be read aloud to the user upon clicking on certain objects. This device generalized the accessibility of images to enable its application for scientific charts and graphs in science-related fields. Similarly, math and physics textbooks were converted into braille and combined with synthetic voice cues [12]. The technology uses mini-hyperbraille, which are interactive, dynamic tactile devices, unlike static tactile devices [32]. It also includes a nod ring for zoom to augment diagrams, similar to the method used in TouchMelody [31]. However, some hyperbraille devices, in general, do not have sufficient refresh rates and spatial resolutions for fast graphical renderings, like animations and videos. Also, braille is a linear writing system that poses a challenge when translating the nonlinear nature of equations and graphical information in engineering. So, other techniques for printing tactile diagrams have emerged, like 3D printing.

Audio, 3D printing

3D printing offers students with BVI the ability to interact with a physical object that can overcome the limitations of using braille, like its linear writing system. For example, 3D printed models were created for graphic visualizations in STEM [33], [34]. The CamIO [33] uses a Kinect camera combined with real-time text-to-speech audio feedback based on where a user touches the 3D model. Alternatively, the TPad System [34] creates a 3D printed frame as the tactile graphic, which is placed on a tablet screen. In the field of electrical engineering, TangibleCircuits [23] produces a 3D printed model of an electrical circuit, similar to Pender and Healy [18], from a Fritzing diagram. An audio interface is also extracted from the diagram to deliver audio feedback while a BVI user interacts with the model, as in the CamIO [33]. Other examples of audio-tactile devices that use 3D printing exist in the literature; see [35], [36], [37], [38]. Unfortunately, 3D printing can be cost prohibitive or students with BVI can have difficulty getting access to a printer.

Audio, swell paper

Swell tactile paper is an inexpensive medium, like braille paper. However, unlike braille paper, swell tactile paper is not restricted to a writing system. Swell paper allows for the creation of tactile diagrams from images, charts, graphs, or figures used in engineering. For example, Blenkhorn and Evans [39] developed talking tactile diagrams converted from images, schematic diagrams, and charts in software engineering and electrical engineering. A converted diagram becomes a tabular N-squared chart that is printed on swell tactile paper and read aloud as a speech message when a user moves around the diagram. Another "talking" device, known as the Talking Tactile Tablet [40] is used to interpret graphs and spatial math in the areas of science and engineering. A tactile graphic sheet is produced on swell paper and held against the touch-sensitive surface of a tablet, similar to the TPad System [34]. Audio responses provide students step-by-step instructions as the computer solves a problem. Additional examples of tactile graphics printed on swell paper can be found in STEM fields for making diagrams, charts, figures, and spatial maps accessible [41], [42]. The system described by Zeinullin and Hersh [41] is composed of three components: pre-labeled graphics using braille text, an interactive web tool, and an audio responsive phone application. Alternatively, the Tactile Graphics Helper [42] uses machine-vision technology to track a student's fingers on the tactile graphic and provide supporting audio information.

Conclusions and Future Work

This paper outlined the barriers that exist for students with BVI in engineering and conducted a review of the current assistive technologies that exist in the literature. STEM fields deal with complex equations and contextual, graphical visualizations, like diagrams, charts, and schematics. Assistive technologies that are auditory, tactile, and multi-modal help to convert these diverse course materials into accessible content for students with BVI. Auditory assistive technology uses speech or non-speech cues via a screen reader or synthesized sound. Tactile assistive technology uses haptics or physical objects to convey information, such as force/tactile feedback, braille paper, or 3D printed models. Multi-modal assistive technology combines both audio and tactile methods.

While the literature shows a large number of assistive technologies are available for STEM course materials, the fact remains that only 16.5% of adults in the U.S with a visual impairment are attaining a 4-year degree or higher [2]; likely lower for degrees in STEM fields. Thus, some key questions exist for researchers to consider in the area of assistive technology: Do students with BVI avoid engineering degrees? Does the problem arise from a lack of resources and support in their K-12 education? Are students with BVI more successful at an R1 university versus a community college because of the support for their disability? How will the recent rise of online courses and online programs in engineering affect student persistence and attainment for students with BVI? What assistive tools and technology will be available to students with BVI when they enter professional practice? The answers to these questions and others that arise from this research will help accessibility stakeholders, such as assistive technology designers and disability and access offices, establish new a11y guidelines and improve existing guidelines in support of engineering students with BVI.

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