Domínguez-Reyes, R., Moreno, L., Muñoz-Sanchez, A., Ruiz, B., & Savoini, B. (2023). Modular 3-D-Printed Education Tool for blind and visually impaired students oriented to net structures. *IEEE Transactions on Education*, 66(1), 55-61.

DOI: 10.1109/te.2022.3183244

Modular 3-D-Printed Education Tool for Blind and Visually Impaired Students Oriented to Net Structures

R. Domínguez-Reyes, L. Moreno, A. Muñoz-Sánchez, B. Ruiz Mezcua, and B. Savoini

***Abstract*—*Contribution:* This article presents the design, creation, testing, and results after the use of a 3-D-printed educational tool that helped a blind student learning electric circuits theory in higher education.**

***Background:* Educational tools oriented to visually impaired and blind students in higher education are limited or even nonexistent in the STEM area. Previous developments on the field present in the literature, including other 3-D printing solutions, have been revised and compared to the proposed educational tool.**

***Intended Outcomes:* The tool was tested by a blind student in order to test the potential of the design to achieve a better understanding of the topology and performance of electric circuits. The main purpose of the tool described in this work is helping to increase the resources available in the field of teaching students with visual impairments.**

***Application Design:* 3-D technology has the potential to be used to create accessibility tools for visually impaired and blind individuals. Modular systems can be used to create complex structures using simple elements. A modular 3-D-printed tool was fabricated to help blind and visually impaired students to learn net structures.**

***Findings:* The 3-D tool has allowed the blind student to work autonomously in the study of simple electric circuits and supplies the teacher with a resource to communicate with the student in an easy and fast way. Updated design can be used to describe more complex net structures that can be applied to most electric circuits despite their complexity. The use of the modular system provided the blind student with a direct representation of the whole subject, even when it involved a great amount of graphical information and manipulation.**

***Index Terms*—3-D printing, blindness, computer engineering, design, higher education, prototyping, rapid prototyping (RP), students with disabilities.**

I. Introduction

ONE OF the first challenges a teacher faces when teaching a student who is blind is adapting the teaching material with the aim of making it accessible. This process is far from being a guided process following a set of established steps but an effort for finding the best way to approach the knowledge to the student with disabilities in the same quality and quantity as to the students without disabilities.

Adapting text-based materials has evolved since the very first braille texts made by hand [1] or braille writing machines [2] to the current digital texts that can be directly read in a “loud voice” by a software [3]. However, adapting graphical materials or the graphical content of a text-based material is a different and complex matter.

II. Literature Review

Along time many methods have been used to adapt pictures or plots for academic purposes. Most of these methods rely on reproducing the picture in relief in acetate or any other surface or making volume models in plastic, wood, or any other material [4]. These methods also evolved using computers resulting in relief printing or model 3-D printing [5]–[7]. Additive manufacturing (AM) techniques [8] have spread due to their variety and utility in the last decades. One of their best applications is rapid prototyping (RP) [9] that has been widely used both in the office environment and industrial mass production [10], [11]. The possibility to test variations in the design of any piece within a day, or even minutes, makes any RP tool a valuable method to improve the design, test, and redesign cycle that accelerates and improves the creation of new models and applications [12], [13]. 3-D printing is one of the best RP methods for low-scale design and production, making it the perfect technique to create prototypes from initial designs, not only in the industry but even in the education field [14]. This makes 3-D printing the perfect technique to design new modular system tools consisting of a wide variety of different elements. Furthermore, this fabrication technique allows to modify the prototype quickly after continuous feedback until its functionality is optimized. Related works on 3-D-printed models used in the field of accessibility and education can be found in the literature: in [15], 3-D-printed arrays and cylinders are used to represent data. In [16] and [17], real objects and 3-D-printed models are marked in order to use a specially designed app to provide audio feedback (including

---

Manuscript received October 20, 2021; revised February 28, 2022; accepted June 12, 2022. This work was supported in part by the “Programa de Atención a Estudiantes con Discapacidad” from Universidad Carlos III de Madrid under Grant 2012/00119/005. *(Corresponding author: R. Domínguez-Reyes.)*

AQ1

This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

R. Domínguez-Reyes and B. Savoini are with the Physics Department, Universidad Carlos III de Madrid, 28911 Leganés, Spain (e-mail: rdomingu@fis.uc3m.es; bsavoi@fis.uc3m.es).

L. Moreno and B. Ruiz Mezcua are with the Computer Science Department, Universidad Carlos III de Madrid, 28911 Leganés, Spain (e-mail: lmoreno@inf.uc3m.es; bruiz@inf.uc3m.es).

A. Muñoz-Sánchez is with the Mechanical Engineering Department, Universidad Carlos III de Madrid, 28911 Leganés, Spain (e-mail: amsanche@ing.uc3m.es).

Digital Object Identifier 10.1109/TE.2022.3183244

tutorial and descriptions) when the marked parts are touched. These tools were tested with visually impaired and blind students in order to improve design guidelines. Reference [17] presents the combination of a series of quick response (QR) codes-based labels and a device with audio that can be used by visually impaired and blind users to work with a 3-D-printed representation of several items providing audio guidance during the manipulation. Research works on 3-D-printed models with haptic interaction have also been reported. Reference [18] uses Android phones to enhance the tactile interaction on phones' touchscreens. This is achieved by the use of an application that maps the interactions with a previously printed hardware. Reference [19] describes the learning process of visually impaired students to analyze Twitter data by the use of 3-D-printed representations of the data based on the output of their software.

Although the use of these 3-D printing technologies represents a major advance in communication with blind persons, they present a drawback with respect to previous methods such as computing applied to text-based materials. 3-D printing solutions are still single-direction methods because blind persons would not be able (or, at least, would be very hard) to design a picture to print it in relief or design a 3-D model to print. Also, 3-D models are typically limited by their design if the models are unchangeable after being created. In that case, they are noninteractive, as changes cannot be made directly in an already-existing version, and any change in the picture requires the creation of a new design or model and printing it again. This implies that using these methods, any communication that requires a graphical item will never be at the same level of efficiency in the case of blind students compared to nonblind students. Due to the variety of levels of study of electric circuits based on the kind of elements that it includes, from simple circuits with batteries and resistances to more complex circuits with diodes or operational amplifiers, the system must have the capability to be able to cover all. Besides, this approach should allow being used by a blind and nonblind person under the same conditions regardless of their access characteristics. In this way, the communication channel would be entirely bidirectional, as in the case of the text-based materials, which allows a learning interaction between students with disabilities and nondisabled teachers. With this motivation, a modular tool based on 3-D-printed models that represent net structures allowing to teach electric circuits to blind and visually impaired persons is presented.

III. Research Purpose and Questions

Minimizing or even eliminating the graphical content from teaching material could be a solution for this problem when the pictures are just supporting the information and can be replaced by text describing the items. Still, there are cases where the graphical approach is the best or even the only option; this is the case, for instance, the teaching of electric circuits. While most, if not all, the methods and techniques applied to solve, treat, or simplify electric circuits can be verbally described, they all require the knowledge of the topology of the circuit.

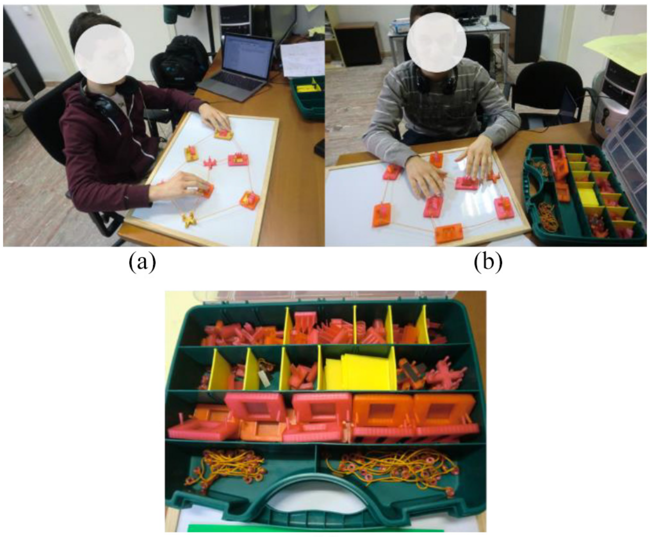

(a) (b) (c)

Fig. 1. (a) and (b) Photograph of the student using the educational tool. (c) Storage suitcase.

When going behind the graphical environment of any circuit analysis software, or just check any code-line-based computer language, it could be noticed when doing a design and abstraction process that this topology can be described in terms of its nodes, elements, connections, and values in text format. However, this description would require keeping in mind a lot of data, which is easy for a computer but hard for a person. This indicates that the graphical description of electric circuits is an advantage with respect to nongraphical approaches providing information and interacting with them. Because of this, it is necessary to design a model that adapts the topology of any net structure, such as electric circuits. The question is, it is possible to fully replace the graphical content in this field, including its flexibility in the communication, without losing information, or restraining to limited cases? In order to solve this question, a modular 3-D tool has been designed to explore its potential to be used as a communication method to teach and study electric circuits.

IV. Methods

A. Participants

The modular 3-D tool has been tested by a Computer Engineering student with 100% blindness in the subject Principles of Computer Engineering (see Fig. 1). The main content of the subject is the design, study, and characterization of direct and alternating current circuits (dc and ac circuits). This implies the use of passive elements, such as resistances, capacitors, and inductances; sources, such as dc batteries, ac voltage supplies, and intensity sources; and other elements, such as general impedances, capacitors, and switches. The content of the subject also requires the student to learn to identify series and parallel element association, simplification of circuits by equivalence (equivalent resistance, capacitance or inductance, and Thévenin and Norton equivalents). The common teaching process of these topics involves a lot of graphical content for describing and manipulating structures and information, making it less accessible to students with visual impairments. The student's previous knowledge about electric circuits was the corresponding to Secondary School, that is limited to the application of Ohm's law to isolated elements or to the resolution of single-loop circuits by resistance simplifications.

In addition to the student, the working group has been composed of five teachers. Two of them (from the Physics Department) were the regular teachers of the subject (with several years of experience in the subject) which are the same as for the rest of the students. One of these two teachers was in charge of the theoretical sessions of the subject while the other was in charge of the practice (exercises) sessions. In order to improve the learning rate in the use of the modular tool, a single teacher (theoretical session's teacher) was assigned to the tutorial sessions corresponding to the usage of the modular tool. Two other teachers (from the Computer Science Department) were in charge of the communication between the student and the university in terms of any special need it could appear, such as extra or special material that might be needed or to ease any logistic issue. Finally, another teacher (from the Mechanical Engineering Department) was in charge of the 3-D designing and printing and any other technical issues about the modular tool. There was continuous feedback between the teachers of the subject, the student, and the teacher responsible for the 3-D printing in order to improve the design of the tool.

B. Materials and Parameters

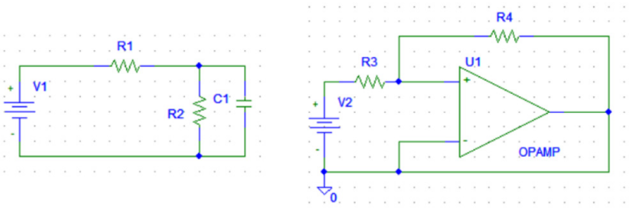
All the prototypes and the final pieces that form the educational tool have been designed and modeled using Solid Edge 2019, a 3-D computer-aided design (CAD) software. The parts have been printed using Creality Ender-3, which is an open-source fused deposition modeling (FDM) extrusion 3-D printer that can use 1.75-mm polylactic acid or polylactide (PLA), thermoplastic polyurethane (TPU), or acrylonitrile butadiene styrene (ABS) filament. FDM printers are the most used for RP [20].

The maximum printing size, 220 × 220 × 250 mm, has allowed us to exclude any limitation printing size for the printed parts, as easy manipulation of the size modules requires significantly lower sizes. The nozzle characteristics (0.4-mm diameter and 255 °C temperature), the layer thickness (0.1–0.4 mm), and the printing accuracy (0.1 mm) provided enough resolution to make the parts fit perfectly with almost no polishing after the creation of the parts. 3-D printing slicer Ultimaker Cura software [21] has been used to print the designs. Several printing parameters were varied until the printing time was optimized, while the consistency of the elements avoided them from being curved on cooling. Printing parameters can be seen in Table I.

With these settings, the printing time varies between 30–40 min (smaller parts) and 90 min (larger and thicker parts). The smaller parts correspond to the removable and exchangeable parts. They are more susceptible to break or loose during the use or manipulation, so it is important to be able to reprint them in a limited time to replace them or even to create new units in case the produced amount is not enough for certain use.

TABLE I
PRINTING PARAMETERS

Parameter	Value
Material	PLA
Layer height	0.15 mm
Material bed temperature	45 ºC
Material bed temperature layer 0	60 ºC
Infill pattern	Zigzag
Material print temperature	200 ºC
Speed print	50 mm/s
Support bottom enable	True
Support infill rate	12%
Support pattern	Triangles
Wall thickness	1.2 mm



(a) (b)

Fig. 2. (a) Example of a simple circuit with two poles elements and (b) more complex circuits.

C. Initial Design

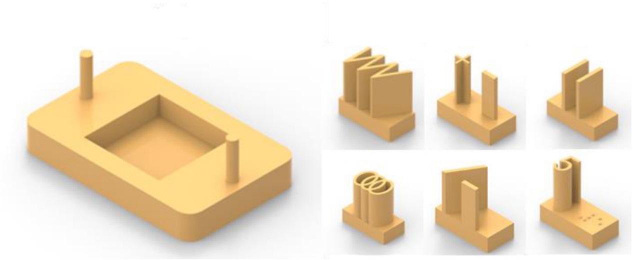
Electric circuits extend from simple circuits with batteries and resistances [net structure formed by elements with two nodes, see Fig. 2(a)] to more complex circuits with diodes or operational amplifiers [net structure formed by elements with more than two nodes, see Fig. 2(b)].

Following this abstraction process, two design phases have been followed: a first phase using a metamodel to address simple electric circuits and a more advanced one with an extended metamodel for complex electric circuits. Using this metamodel, a modular 3-D tool based on 3-D-printed models has been created as a proof of concept of the desired approach at a concrete level.

To design simple electric circuits, a metamodel with three constructors or design primitives has been defined: 1) frame; 2) element; and 3) connector. Each constructor includes different characteristics and constraints in order to design different electric circuits designs.

D. Metamodel: Frame Constructor

Frame constructor is the main component of the design. It is designed to contain the element constructor instances and to connect themselves with the connector constructor instances. The frame constructor instance is a 3-D-printed piece that



(a) (b)

Fig. 3. (a) Frame constructor and (b) examples of element constructor corresponding to resistance, battery, capacitor, inductance, switch, and number label.

consists of a square-shaped cavity that can hold the elements at any of the 90° orientations with respect to the direction of the connection [see Fig. 3(a)]. The designs will be more or less simple according to their connectivity or the number of connector instances it includes. In the case of simple circuits with simple elements, such as resistances, capacitors, batteries, inductances, and so on, that only have two sides to be connected, the most basic design for the frame presents two connections, one on each side. If the frames need to be used in the context where the elements can have more than two elements, a design of a frame with more connections by the side can be used. The general shape of the frame has been determined to be a rectangle shape in order to allow easy orientation recognition by touching it.

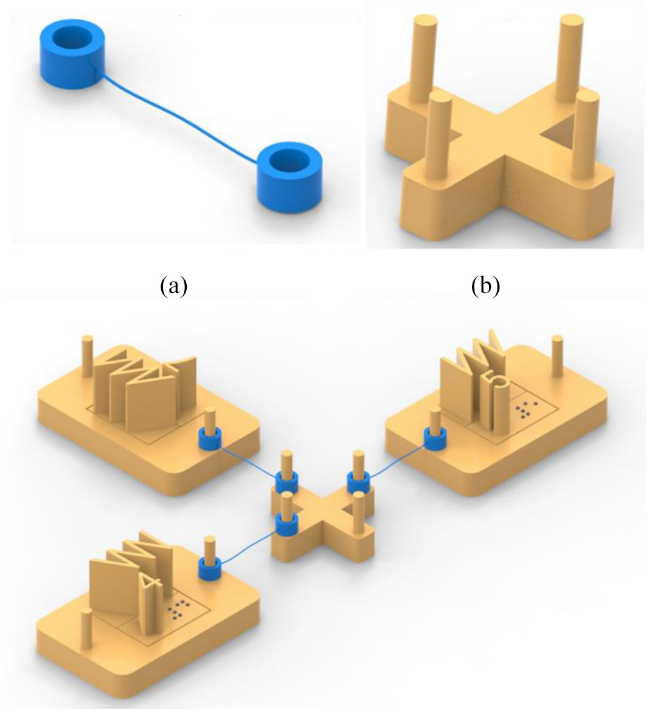
E. Metamodel: Element Constructor

Element constructor is designed to contain information or semantics about the type of electric element in the circuit (resistance, battery, capacitor, etc.). An instance of the element constructor corresponds with a 3-D-printed piece with electric symbols in relief and braille included (following dimensions and proportions according to Spanish Braille Commission [22]), allowing the recognition by touch for students who are blind [see Fig. 3(b)]. The 3-D-printed piece has a specific shape that allows the combination of any two of them (regardless of nature) on a frame constructor instance, allowing the user to combine any item with any label with symbols.

F. Metamodel: Connector Constructor

The connector constructor specializes in two kinds: 1) line connector constructor and 2) node constructor. Fig. 4(a) and (b) shows 3-D-printed pieces corresponding to the connector constructors.

Line connector constructor [Fig. 4(a)] instance allows connecting two frames of constructor instances directly. The line connector constructor symbolizes the cables in an electric circuit. Its design is simple; two 3-D-printed washers connected by a soft line material. This kind of connection allows an intuitive and easy electric connection of two elements in series or parallel. Circle-shaped washers have the advantage of enabling the rotation of the connection with the frame, which improves the handling of the elements. Square-shaped washers can be designed if the orientation needs to be locked.



(a) (b)

(c)

Fig. 4. (a) Line connector module. (b) Node connector module. (c) Example of the representation of three identified resistances (R4, R5, and R7) connected to each other by a node using line connectors.

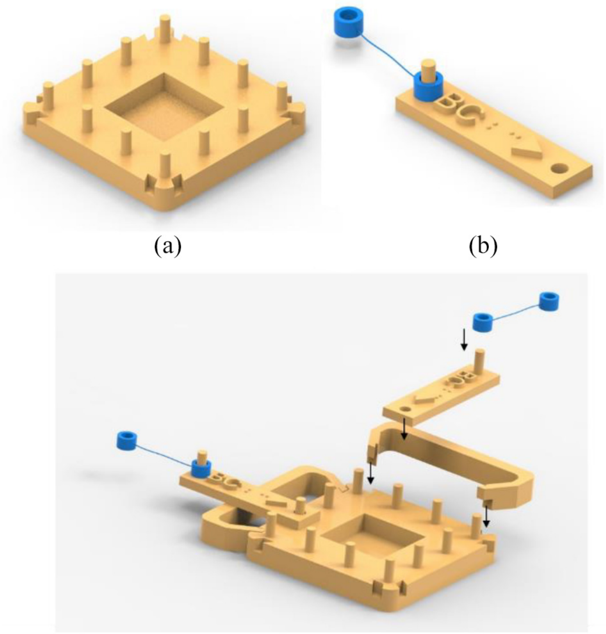
Node connectors constructor allows connecting more than two frames of constructor instances to each other. Node connectors constructor represents a typical node in a circuit where three or more cables meet at the same point [see Fig. 4(b)]. This connection allows an intuitive and easy electric connection of two or more elements with any configuration [Fig. 4(c)].

With the aim to cover any circuit, that is, that requires more than two nodes, the metamodel has been extended to provide models that allow for building more complex topologies.

G. Metamodel: Updated Constructors—Design Extension to Complex Electric Circuits

Common elements in complex circuits, such as operational amplifiers or transistors, usually have three to five poles. New elements can be easily represented by the same type of element constructor creating new shapes based on the standard electric circuit symbols.

The higher number of poles can be represented by improving the design of the frame constructor increasing the number of pins. Some electric elements have connections not only in their sides but also on its top or bottom, because of this, the position of the pins on the frame constructor needs to reflect this fact causing that the new design requires a square shape rather than a rectangle shape in order to simplify its use. The total number of pins can be based on the number of connections of the most common electric circuits resulting. The higher number of pins in the frame also implies a small increase in the size of the design allowing the student to easily manipulate the modules. In order to reproduce schemes with



(a) (b)

(c)

Fig. 5. (a) Updated frame constructor 12 pins case, (b) connector constructor with label and direction arrow, and (c) label assembled to frame constructor supported by the removable support, and same parts showing the assembling process.

a greater number of possible connections with the frame constructor, increasing the number of pins to 12 [Fig. 5(a)] was considered.

Some electric diagrams include arrows in the connections indicating the flow of the information. This can be included in the modular system updating the connector module, replacing one of the washers with a pierced label that will include both an arrow and a tag [Fig. 5(b)]. The increase of the size of this connection might cause the pins to break by lever effect while manipulating, as the connector now goes out of the border of the frame module. To prevent this, the size of the border of the frame constructor should be increased.

A simple increase of the border would require more printing time to produce the modules and would also result in a less comfortable general use, because of that it was decided to perform the increase of border size in terms of a removable part [see Fig. 5(c)]. The fact that the extension of the border is removable allows to increase the size only in the required cases and in the needed sides of the basic frame module and allows using the same frame modules for all the cases (i.e., the main purpose of the modular system). A simple redesign of the basic frame (adding indentations on each side) is enough to keep all the previous properties of the frame constructor and the possibility of attaching the extensions [see Fig. 5(c)].

H. Procedure

As expected for any new educational tool, testing the initial design and defining the operating procedure was the starting point. Determining the operating procedure consisted of the recognition of the modules followed by matching each element constructor with its respective electric element, and finally learning to attach each element to the others and connecting them together to build a complex structure. This process took the student around an hour.

A preliminary version of the modular system was provided to the student in advance (prior to the start of the subject) to use in simple cases, which served to identify the best approach to the common situations present in the subject. With this trial-and-error process, the student and the teachers were able to understand the operation of the tool, which resulted in the development of a basic procedure for use, i.e., to get used to represent acetate's drawings with the 3-D-printed elements. The initial usage of the modules by the student also resulted in design changes of some constructors, such as increasing the size of the frame constructors or decreasing the length of line connectors modules. Another relevant improvement was the placement of adhesive magnetic bands below the frame constructors to provide a soft fixation when used over a conventional magnetic board (horizontally). This allowed keeping the shape of the circuits while manipulation.

The final version of the modular system was provided to the student at the beginning of the subject along with an adapted digital version of the same exercise lists the rest of the class had and a copy in relief acetate of all the figures on those lists. One of the best characteristics shown by the 3-D-printed modular system is the independence it gives to the student. A full set of parts was provided to the student in a storage suitcase [see Fig. 1(b)] that enabled easy sorting and access to the elements. The possibility of easy transportation of the modular system made it easier for the student to work with it in several places (classroom, library, and residence) indistinctly. The storage suitcase allows a customizable and comfortable way of arranging all the items, so the student could access them in an easy and fast way. The combination of all these elements resulted in a complete set of materials that provided the student with the same information and resources the rest of the students had. Using the modular 3-D tool allowed the student to design the circuits, work with them, replace or simplify elements, and expand or create circuits as required. The student carried out all these actions without any assistance and in a complete autonomous way.

Another complete set of the tool was used during the weekly tutorial sessions with the student. In these tutorial sessions (around 90-min duration), the modular system allowed a fast bidirectional communication regarding the shape, design, or change of any part of the circuit, which would have been impossible using any other nondynamic medium, such as relief acetate.

As the basic operating procedure was already determined, in order to start working with the modular tool in applied cases, specific procedures should be found in order to use it to learn the basic principles of the subject (same as the rest of the students). This included building and recognizing structures, such as nodes, or element series and parallel association. These are the first basic concepts that must be recognized when working with electric circuits. This improvement of the operating procedure allowed the learning of the subject and the educational tool to be simultaneous and complementary since the specific needs of each topic were reflected directly on the requirement to define new recognition of structures methods using the modular system. Each new topic that required the definition of new procedures was covered in a weekly tutorial session (such as applying Kirchhoff's laws or determining Thevenin and Norton equivalents). Typically, the procedure was defined, tested, and debugged in a single 90-min session. The time required to fully learn the use of the tool in the subject can be estimated in roughly 8 h (five tutorials sessions). The rest of the tutorial sessions (around ten additional sessions) were used just to support the content of the classes and to check the progress of the student.

V. RESULTS AND DISCUSSION

The use of the modular system provided the student with a direct representation of the whole content and exams of the subject, even when it involved a great amount of graphical information and manipulation. Because of this, during the course, the student was able to keep up the pace of the rest of the students with a short time delay caused by the tool learning process. This implied the student was able to face the assessment elements with the rest of the students. Exercises, practices, midterm exams, and final exams were electronically adapted to be read by the student's computer, and the figures were converted to relief acetates, but no changes in the content were performed. This was possible because the communication between student and teacher using the modular system was fast, intuitive, and dynamic. This dynamic communication is one of the properties that must be highlighted as it is one of the main weak points that other physical media, like rigid predefined bodies or relief acetates, present. As those elements are not interactive, the communicated information is limited, as it is determined in the very instant of the creation of the elements and cannot be changed as the situation demands. Consequently, they cannot be used to work efficiently with systems like electric circuits, since their analysis requires continuous modifications of the arrangement of their elements by both teachers and students. This efficiency and dynamicity provide the student with high independence when working, allowing him to autonomously work and requiring small supervision during the tutorials (comparable to the attention a nonblind student could have in a tutorial).

As the subject progressed the need to define new procedures, or to debug the existing ones, decreased to the point where all the existing methods covered the new needs of the topics at the end of the subject. This proved that the operation procedures were coherent and formed a complete set of rules that covered all the existing cases that could appear in the subject, so the tutorials were progressively oriented to the study of the subject's content, decreasing the need to learn to use the modular system as the use of it became natural. At that point, the tutorial sessions with the student did not differ in content or nature from the tutorial sessions provided to the rest of the students.

Although the 3-D-printed modular system has been only tested for one student who is blind and the experience of more students would be necessary to obtain conclusions and define a definitive operating procedure and design, the excellent results obtained by the blind student indicate that this educational tool has a great potential that can be explored and improved. It must be highlighted that the modular tool was able to easily represent the 100% of the content of the subject including 3 and 4 mesh circuits with up to 15 electric elements both in direct current (dc) and alternating current (ac). Upon use, the educational tool hinted at the capacity of being used not only by blind students but also by students with other disabilities or without them. Even when initially designed to replace the graphical content of net structures when teaching a blind student, it could be used to support some other communication channels that might appear when teaching other students. In order to explore this possibility, a new more numerous and well-designed population of study should be considered and new approach to the tool should be defined. This is out of the current studied case and will be addressed in future research.

Despite the numerous and evident advantages of the modular tool, some drawbacks were identified during its use. The main feature that hinders its use is the need to carry the system to the usage place considering its size and weight (i.e., usually the main drawback in material for blind students). Even when two fool sets of the tool were created, one for the student's use and another for the teacher–student use in the tutorial sessions, it was still necessary for the student to carry it from his residence to the classroom (or any other studying place). Even when the suitcase and the magnetic board were a convenient way to transport and use the system, their size and weight (around 50 × 40 cm and total 3 kg) were not easy to carry along for a whole day. The size of the magnetic board was another issue as its size would limit the size of the circuits that could be represented by the modular tool (the used size, 50 × 40 cm, was just enough for the studied cases, but more complex circuits would require bigger boards). These could be easily avoided if the modular 3-D tool and boards were already present in all the educational places (such as classrooms).

VI. CONCLUSION

In this article, a modular 3-D tool based on 3-D-printed models is presented providing an accessible and universal teaching mechanism for visually impaired and blind students in net structures subjects as electric circuits. The proposal has been made concrete for a Principles of Computer Engineering subject and the resulting 3-D tool has been tested by a blind student. The 3-D tool has allowed the student to work autonomously in the analysis of simple electric circuits and supplies the teacher with a resource to communicate with the student in a dynamic, easy, and fast way. As future work, an extension of the metamodel should be carried out to address fields that share the topology, which will allow us to improve the model and test it with additional students and subjects. Other subjects, such as Logic and Discrete Mathematics, can be represented with this metamodel. For example, in the case of Logic, the addition of the new element constructors, such as OR, AND, or NOR gates would be an initial point to extend the current approach. In addition, a completely different approach to the use of the modular tool can be explored if used by students with different disabilities or without them to support their teaching.

ACKNOWLEDGMENT

Special thanks to Juan Francisco Pérez Carrasco.

REFERENCES

[1] R. S. Clark, *Books and Reading for the Blind* (Library Association Pamphlet #1). London, U.K.: Library Assoc., 1950.

[2] P. Golding, *Design Study on a Braille Type-Writer*, Curtin Univ. Technol., Bentley, WA, USA, 1998.

[3] L. Barbara and P. Fabio, "Increasing usability when interacting through screen readers," *Univers. Access Inf. Soc.*, vol. 3, pp. 57–70, Feb. 2004, doi: 10.1007/s10209-003-0076-4.

AQ2 [4] J. A. Gardner, "Tactile graphics, an overview and resource guide," *Inf. Technol. Disabil. J.*, vol. 3, no. 4, 1996. [Online]. Available: http://itd.athenpro.org/volume3/number4/article2.html (Accessed: Jun. 13, 2022).

[5] A. Agarwal, S. Jeeawoody, and M. Yamane. "3D-Printed Teaching Aids for Students with Visual Impairments." 2014. [Online]. Available: http://diagramcenter.org/wp-content/uploads/2014/06/E110-Final-Report-Team-Walrus.docx (Accessed: Jun. 13, 2022).

[6] M. A. Kolitsky, "3D printed tactile learning objects: Proof of concept," *J. Blind. Innov. Res.*, vol. 4, no. 1, pp. 4–51, 2014, doi: 10.5241/4-51.

[7] C. F. Karbowski, "See3D: 3D printing for people who are blind," *J. Sci. Educ. Students Disabil.*, vol. 23, no. 1, p. 6, Feb. 2020, doi: 10.14448/jsesd.12.0006.

AQ3 [8] K. V. Ashley and A. Hernandez, "A review of additive manufacturing," *Int. Scholarly Res. Notices*, vol. 2012, Aug. 2012, Art. no. 208760, doi: 10.5402/2012/208760.

[9] S. Yan, "Rapid prototyping systems," *Comput. Mech. Eng.*, vol. 113, no. 4, p. 34, 1991.

[10] X. Yan and P. Gu, "A review of rapid prototyping technologies and systems," *Comput.-Aided Design*, vol. 28, no. 4, pp. 307–318, Apr. 1996, doi: 10.1016/0010-4485(95)00035-6.

[11] D. T. Pham and R. S. Gault, "A comparison of rapid prototyping technologies," *Int. J. Mach. Tools Manuf.*, vol. 38, nos. 10–11, pp. 1257–1287, Oct. 1998, doi: 10.1016/S0890-6955(97)00137-5.

[12] W. L. Neeley, Jr., K. Lim, A. Zhu, and M. C. Yang, "Building fast to think faster: Exploiting rapid prototyping to accelerate ideation during early stage design," in *Proc. Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf. 25th Int. Conf. Design Theory Methodol. Power Transm. Gearing Conf.*, vol. 5. Portland, OR, USA, Aug. 2013, Art. no. V005T06A022, doi: 10.1115/DETC2013-12635.

[13] J. Wonjin *et al.*, "Introduction of 3D printing technology in the classroom for visually impaired students," *J. Vis. Impair. Blind.*, vol. 110, no. 2, pp. 115–121, Mar. 2016, doi: 10.1177/0145482X1611000205.

[14] S. Greenhalgh, "The effects of 3D printing in design thinking and design education," *J. Eng. Design Technol.*, vol. 14, no. 4, pp. 752–769, Oct. 2016, doi: 10.1108/JEDT-02-2014-0005.

[15] N. Papazafiropulos, L. Fanucci, B. Leporini, S. Pelagatti, and R. Roncella, "Haptic models of arrays through 3D printing for computer science education," in *Proc. ICCHP*, Jul. 2016, pp. 491–498, doi: 10.1007/978-3-319-41264-1_67.

[16] L. Shi, Y. Zhao, and S. Azenkot, "Designing interactions for 3D printed models with blind people," in *Proc. 19th Int. ACM SIGACCESS Conf.*, Oct. 2017, pp. 200–209, doi: 10.1145/3132525.3132549.

[17] L. Shi, H. Lawson, Z. Zhuohao, and S. Azenkot, "Designing interactive 3D printed models with teachers of the visually impaired," in *Proc. Conf. Human Factors Comput. Syst.*, May 2019, pp. 1–14, doi: 10.1145/3290605.3300427.

[18] X. Zhang *et al.*, "Interactiles: 3D Printed tactile interfaces to enhance mobile touchscreen accessibility," in *Proc. 20th Int. ACM SIGACCESS Conf.*, Oct. 2018, pp. 131–142, doi: 10.1145/3234695.3236349.

[19] S. K. Kane and J. P. Bigham, "Tracking @stemxcomet: Teaching programming to blind students via 3D printing, crisis management, and Twitter," in *Proc. SIGCSE*, New York, NY, USA, Mar. 2014, pp. 247–252, doi: 10.1145/2538862.2538975.

[20] C. K. Chua, K. F. Leong, and C. S. Lim, *Rapid Prototyping: Principles and Applications*. Singapore: World Sci. Publ. Company, Jan. 2010, doi: 10.1142/6665.

[21] B. V. Ultimaker. "Ultimaker Cura Software." Geldermalsen. 2018. [Online]. Available: https://ultimaker.com/software/ultimaker-cura (Accessed: Jun. 13, 2022).

[22] "Documento Técnico B1 de la Comisión Braille Española. Parámetros Dimensionales del Braille." Spanish Braille Commission. 2013. [Online]. Available: https://www.once.es/servicios-sociales/braille/documentos-tecnicos/documentos-tecnicos-relacionados-con-el-braille/documentos/b1-parametros-dimensionales-del-braille-2/download (Accessed: Jun. 13, 2022).