Audio Tactile for Accessible Teaching in STEM Disciplines: a Comparison of Two Low-Cost Production Chains

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***Abstract*—STEM education often relies on visual diagrams that are difficult for Blind and Low Vision students to access. This work presents an interactive audio-tactile solution that transforms 2D educational diagrams into accessible learning artifacts through two complementary scenarios: a tablet-based tactile overlay with a mobile app, and a tactile IoT board with NanoVNA-based sensing for larger diagrams. Both scenarios use a semi-automated pipeline to generate printable tactile artifacts enriched with audio feedback, aiming to reduce cost, production time, and technical effort for non-specialist producers.**

***Index Terms*—STEM education, Assistive Technologies, Blind and Low Vision, audio tactile interaction, tactile IoT.**

I. Introduction

STEM (Science, Technology, Engineering, and Mathematics) education relies heavily on visual representations to convey abstract concepts, spatial relationships, and procedural information. However, for Blind and Low-Vision (BLV) students, these materials remain difficult to access [1]. Assistive technologies such as screen readers, text-to-speech systems, and Braille displays are effective for linear text but often fail to convey topology, layout, directionality, and relationships among visual elements [2]. Recent research also shows that alternative descriptions, even when generated by multimodal Large Language Models (LLMs), may omit essential structural information or introduce inaccuracies in STEM diagrams [3], [4]. Tactile and manipulable representations provide BLV learners with direct access to spatial and relational information [5], and 3D printing enables affordable, customizable tactile learning materials [6]. However, static tactile artifacts are difficult to interpret when diagrams are dense, contain closely spaced or overlapping elements, or include multiple semantic components [7]. This is especially relevant for flowcharts, where labels, actions, and conditions are often embedded inside nodes; printing all this content in tactile form would require large artifacts and increase exploration complexity. Therefore, tactile access should be complemented with auditory feedback, as suggested by recent audio-tactile and haptic approaches for accessible mathematical and graphical content [8]. Additionally, the challenge extends to production: educational tactile materials should be sustainable in terms of cost, time, and required expertise, yet accessible STEM materials often rely on manual, labor-intensive workflows that are slow, expensive to produce, difficult to update, and dependent on specialized tools [7], [9]. Building on these needs, we propose an audio-tactile solution based on two complementary interaction scenarios with different trade-offs in cost, scalability, setup effort, and diagram complexity: a tablet-based setup combining a 3D-printed tactile overlay with a mobile application, and a tactile IoT board with NanoVNA-based sensing[1] for larger and denser diagrams. Both approaches are designed to be low-cost, time-efficient, and usable by non-specialist producers. They rely on a semi-automated pipeline based on our previous work on 3D-printed tactile graphs [10], now adapted and extended to support flowcharts and other diagrammatic STEM content and to integrate audio feedback.

II. Requirements and Method

Our work addresses five requirements: low cost, time-efficient production, usability by non-specialist producers, adaptability to varying levels of informational density, and accessibility for BLV students. Therefore, the process should use affordable fabrication technologies, reusable components, and commonly available devices; minimize the manual effort required to convert visual materials into tactile artifacts; be usable by teachers, tutors, or accessibility staff without expertise in 3D modeling, electronics, or assistive technology design; support diagrams with different levels of textual and semantic density; and preserve spatial and relational information while complementing tactile exploration with audio feedback. These requirements led us to design two complementary interaction scenarios for graphs and flowcharts: a tablet-based configuration for lightweight deployment, and a tactile IoT board for larger, denser diagrams. Both scenarios are generated through the same semi-automated pipeline. Starting from a 2D diagram image, a multimodal LLM extracts its logical structure and encodes it into a JSON representation containing elements such as nodes, connections, labels, and semantic descriptions. The JSON is processed by the Eclipse Layout Kernel (ELK) to

[1]NanoVNA official website: https://nanorfe.com/it/nanovna-v2.html

TABLE I
COMPARISON BETWEEN THE TWO SCENARIOS.

Criterion	Tablet overlay + app	Tactile IoT board
Target diagrams	Simple or moderately complex	Dense, large, or more complex
Hardware	Tablet and 3D-printed overlay and cover	3D-printed board, sensing circuit, NanoVNA
Setup effort	Lower; mainly software configuration	Higher; assembly and pairing required
Scalability	Limited by screen size	Scalable to larger physical boards
Interaction	Touch through overlay holes on the screen	Touch detection through sensing layer
Main trade-off	Low-cost and flexible, but screen-limited	More scalable, but hardware-dependent

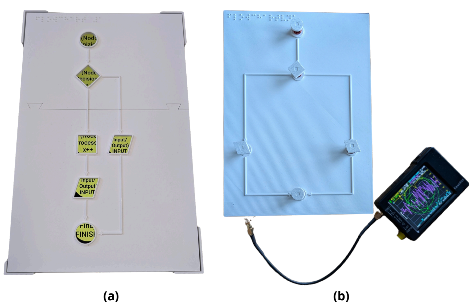

Fig. 1. Interaction scenarios: (a) tablet overlay and app; (b) tactile IoT board.

compute the spatial arrangement of the elements. The resulting coordinates are then converted by our Python script into a parametric 3D model, exported as a .scad file, and used for 3D printing. After this common phase, the workflow branches according to the selected scenario, as described in Sec. III.

III. SCENARIOS AND TRADE-OFF ANALYSIS

The two configurations address different educational and production constraints, enabling producers to select the most suitable solution based on diagram density, available hardware, and deployment context. Their main trade-offs are summarized in Table I, while Fig. 1 shows the two resulting interaction scenarios. In the **tablet-based scenario**, the generated 3D model serves as a tactile overlay placed on the user's tablet (Fig. 1a). Holes corresponding to diagram elements allow the BLV student to touch the underlying screen while maintaining a tactile reference to the diagram structure. The mobile application acts as a digital twin of the overlay, generating interactive regions from the same coordinates and associating each with an audio description. This solution is lightweight, flexible, and requires minimal additional hardware, but is limited by screen size and requires printing a tablet cover to ensure proper overlay alignment. In the **tactile IoT scenario**, the model is a standalone 3D-printed board (Fig. 1b). Holes enable reproducible assembly by hosting separately printed components, such as nodes, and facilitating circuit routing. A copper wire detects interaction through capacitive variations, while a NanoVNA-based setup reads the signal. During pairing, physical elements are linked to their digital descriptions; afterward, touching a node or component triggers the corresponding text-to-speech output. This configuration is better suited for larger and denser diagrams but requires additional hardware, circuit preparation, and an initial pairing procedure. Overall, the two scenarios are complementary: the tablet-based configuration prioritizes low cost and ease of deployment, while the tactile IoT board prioritizes physical scalability and interaction with denser diagrams. Thus, the same workflow can support various educational contexts, from individual lightweight use to structured accessibility services that require larger, reusable tactile materials.

IV. CONCLUSIONS

We presented an interactive audio-tactile solution to make STEM diagrams more accessible to BLV students through two complementary scenarios: a tablet-based overlay with a mobile application for lightweight deployment, and a tactile IoT board with NanoVNA-based sensing for larger, denser diagrams. Both use the same semi-automated pipeline, reducing the effort required to transform 2D educational images into tactile and audio-enhanced artifacts. By addressing both end-user accessibility and production sustainability, the approach enables non-specialist producers to create accessible STEM materials at low cost and with time efficiency. Future work will evaluate the two configurations with BLV students and producers, comparing usability, production effort, and learning support across diagrams of varying complexity.

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