Technique-aware Digital Embroidery Simulator with Gaze and Voice Interaction

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Abstract. This paper deals with problems related to craft software development oriented to handmade embroidery, created as a simulation of the stitching process by following the needle movement path. The paper focuses on human-computer interaction of the application involving gaze- and voice-based interaction to ensure hands-free control of the embroidery process. This approach allows users with physical disabilities to apply the software on the one side; on the other it speeds up the workflow for users without disabilities. Gaze and voice-based interactions are part of whole system architecture. The presented work demonstrates that interaction technologies can be combined with technique-aware embroidery simulation to support inclusive participation in digital craft environments and to facilitate the preservation and sharing of traditional embroidery knowledge.

Keywords: Cross-stitch Pattern Software, Craft Software, Computer-aided Design (CAD), Gaze-based and Voice-based Interaction, Human-Computer Interaction (HCI), Domestic Handicrafts, Digital Preservation, Cultural Heritage.

1 Introduction

Embroidery, along with knitting and crocheting, is part of the traditional textile home crafts which are still practiced today. Passed down over the centuries, these home crafts and occupations are part of cultural heritage safeguarding knowledge and skills for manufacturing embroidery, knitwear and laces, which are part of traditional national costumes. Although craftsmen keep on with traditions, they often use modern digital technologies to facilitate their work. Such examples are software applications known as Craft Software (FlossCross-Designer, 2026; Pattern Keeper, 2026; Pixel-Stitch, 2026; StitchFiddle, n.d.; Cross Stitch Saga, 2025), intended for computer aided design of future craft projects using a short video with explanations to provide some specific technological information; information and knowledge are exchanged via Internet forums, social networks, sites and blogs (Nasledstvoto, 2026; Dimitrova, 2022; Victoria and Albert Museum, 2024).

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Cross-stitch software is a kind of Craft software that helps users create, edit and manage embroidery patterns. It serves as a cross-stitch patterns representation in a digital way. Usually, Cross-stitch applications are equipped with graphical based editor which allows the development of embroidery patterns. They provide a grid-based interface where users can fill in cells with symbols and colors, corresponding to embroidery threads (FlossCross-Designer, 2026; StitchFiddle, n.d.). Practically, this type of software copies the embroidery pattern representation in printed books and magazines used by embroidery designers for decades(Nasledstvoto, 2026; Dimitrova, 2022). These applications are suitable to show embroidery charts digitally, but they give too insufficient an idea for embroidery techniques realizing a particular embroidery pattern. Furthermore, just some of them support different stitch types and none covers all known embroidery stitches. In this regard, these applications have limited capabilities.

The paper presents Cross-stitch software development based on different strategies for embroidery pattern design and description. The application is created as a simulator that represents a whole embroidery process following the needle movement path (Zaharieva-Stoyanova & Bozov, 2025). The user interface is developed as a dual-view; the approach allows the user to track (keep an eye on) both embroidery front and back side (Bozov & Zaharieva-Stoyanova, 2025a). This approach enables a graphic representation of different stitch types and embroidery techniques in a digital way. Practically, the application is developed as a digital embroidery simulator.

As a software solution, compared with the other "traditional" applications, the presented software has its own advantages, but it has also shortcomings. Experienced craftsmen would find it annoying to design a digital embroidery chart step by step as a real embroidery process. That way, the patterns design has to include other system control methods except mouse click and finger tap. Opportunities for more efficient work with the system are provided with gaze and voice control.

To address these limitations, the present work explores alternative interaction methods that allow users to control the embroidery simulator without relying on traditional manual input. In particular, the system introduces gaze-based interaction and voice commands as hands-free mechanisms for interacting with the embroidery canvas. Both interaction methods allow the user to move the cursor across the embroidery grid and to initiate an action equivalent to a mouse click, which represents the insertion of the needle through the fabric. Through a sequence of such actions, the user can construct stitches and simulate the embroidery process digitally. Handsfree interaction is particularly important for users who experience difficulties performing manual embroidery due to motor limitations, fatigue, or progressively degenerative conditions. By enabling this functionality, the system allows users to re-engage with embroidery as a creative activity while at the same time to present the procedural authenticity of the craft. Furthermore, the technique-aware simulation permits users to record and share the execution traces of stitching techniques, which is very important for the preservation of embroidery craft technologies as a part of intangible cultural heritage.

2 Technique-aware Embroidery Simulation

The accessible interaction system presented in this paper is built on a digital embroidery simulator designed to represent embroidery as a procedural process rather than a static chart. Traditional Cross-stitch applications typically describe embroidery patterns only as visual grids filled with symbols and colors representing the final appearance of the embroidery. In contrast, the proposed approach models embroidery by following the path of the needle as it moves through the fabric, allowing the system to capture not only the visual structure of the pattern but also the underlying embroidery technique (Zaharieva-Stoyanova & Bozov, 2025).

In the simulator, embroidery patterns are represented as ordered sequences of needle puncture points arranged on a logical grid corresponding to the woven structure of the embroidery fabric. Each puncture point represents a location where the needle can enter or exit the fabric according to the embroidery technology. By connecting these points sequentially, the system reconstructs the path of the thread and forms the corresponding stitches. This representation makes it possible to digitally reproduce a wide range of embroidery stitches without relying on predefined stitch palettes and it allows users to define their own stitch palettes, too. In essence, the approach adheres to the following principle: instead of selecting stitches by name or symbol, the embroidery structure emerges from the actual movement of the needle across the fabric.

The underlying representation is based on a stitch-agnostic, technique-aware data model in which embroidery patterns are encoded as sequences of grid coordinates describing the needle path (Bozov & Zaharieva-Stoyanova, 2025b). This model captures the execution of the stitching process rather than only the resulting visual pattern. As a consequence, the system preserves the full procedural structure of embroidery, including the order of stitches and the movement of the thread across the fabric.

As previously mentioned, to better reflect the physical behavior of embroidery, the simulator visualizes both sides of the fabric simultaneously. The user interface is implemented as a dual-view canvas that displays the front and the back sides of the embroidery in real time (Bozov & Zaharieva-Stoyanova, 2025a).

An example of an embroidery pattern represented in the simulator is given in Fig. 1, where the pattern is constructed by connecting successive needle puncture points on the fabric grid. The left part of the screen represents the decorative structure on the front side of the embroidery (the visible segments of the thread form), while the right part shows the reverse side, which reveals the path of the thread between successive stitches. The dual-side representation allows the user to observe not only the visual appearance of the pattern but the technique used to construct it as well.

The simulator also provides dynamic visualization of the stitching process. During pattern creation or playback, the needle and thread are animated step by step, illustrating how stitches are formed and how the thread travels across the fabric. The current needle position is represented by a marker on the canvas, while lines connecting successive puncture points represent the thread segments created during stitching. Through this animation, the simulator communicates the procedural structure of embroidery and allows users to observe different stitching techniques in detail.

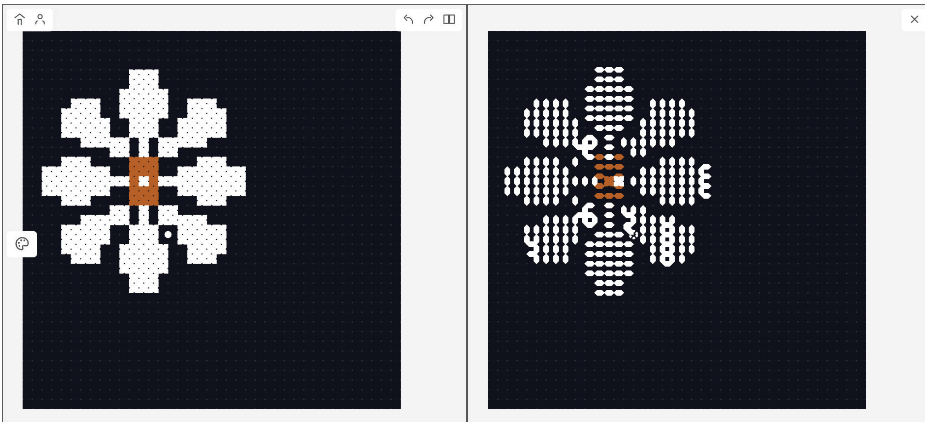

Fig. 1. Side by side front and back views of the embroidery pattern.

Because the embroidery process is encoded as a sequence of needle movements, the simulator preserves the complete execution trace of the stitching process. This representation forms the basis for additional functionalities such as animated playback of stitching sequences, analysis of embroidery techniques, and sharing of technique-preserving patterns. In the context of the present work, this procedural representation also enables the embroidery simulator to be controlled through alternative interaction modalities, including gaze- and voice-based interaction.

Gaze- and voice-based interaction has been the subject of research for many decades. A number of researchers rely on this type of interaction as part of Human-Computer Interaction (HCI) to ensure hands-free control of computing environments for users with physical impairments especially (Ghani et al., 2014; Khan et al., 2022; Zhao et al., 2020; Yamini et al., 2025; Bashar et al., 2026). Involving gaze- and voice-based commands in the application enriches its functionality by enabling people with temporary or permanent disabilities to use the software. It is worth noting that many embroidery practitioners are older adults and some of them have diseases that prevent them from practicing handmade crafts. The simulator with hands-free control interaction can help them share their knowledge and skills. Besides people with physical disabilities, hands-free control can be equally convenient for the users, who want to accelerate the embroidery process design.

3 Gaze and Voice Interaction Model for Digital Embroidery

The proposed embroidery simulator introduces an interaction model that enables users to control the embroidery process without manual input. Instead of relying on a mouse or touch interface, the system allows users to operate the simulator using eye tracking and speech recognition. Both input modalities generate the same logical interaction commands, enabling the embroidery process to be controlled entirely hands-free.

The proposed approach treats gaze tracking and voice commands are treated as interchangeable input modalities that trigger the same interaction events in the system. Whether the user positions the cursor and confirms an action using eye gaze or voice commands, the resulting operation in the simulator remains identical. This unified interaction model preserves the same logical workflow used in traditional pointer-based interfaces while enabling completely hands-free control of the embroidery process.

The architecture of the interaction model is illustrated in Figure 2. The system is organized into three main layers: input processing, simulation calculations, and rendering.

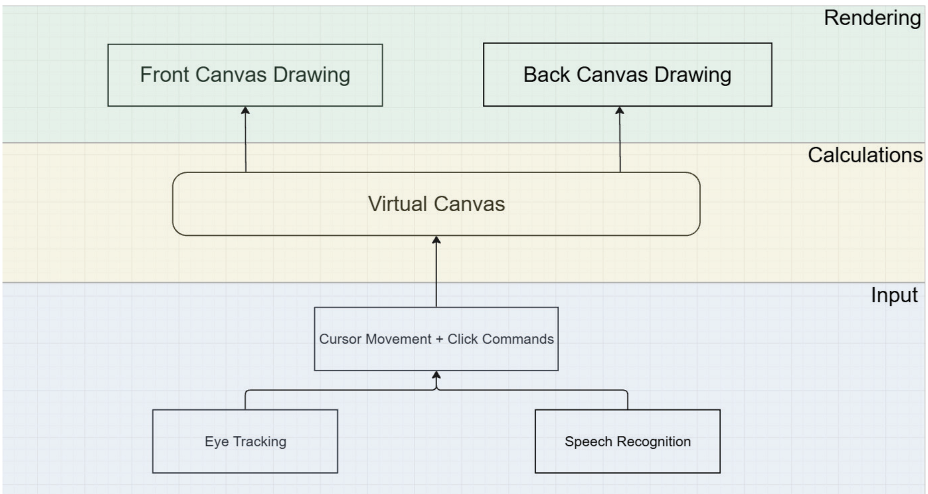

Fig. 2. Architecture of gaze and voice interaction model for digital embroidery simulation.

At the lowest level, the **input layer** captures user actions through eye tracking and speech recognition. Eye tracking determines the current gaze position on the embroidery canvas, allowing the user to move the cursor by looking at a specific location on the grid. If the user maintains their gaze on the same point for a predefined time (for example, approximately three seconds), the system interprets this dwell time as a confirmation action equivalent to a mouse click. In this way, the user can both position the cursor and initiate stitching actions using gaze alone. Speech recognition processes spoken commands that initiate actions within the system. Both input modalities ultimately produce the same logical operations: cursor movement and click commands. In the context of embroidery simulation, these commands correspond to positioning the virtual needle and initiating a needle insertion through the fabric.

The resulting interaction commands are processed by the **virtual canvas**, which represents the computational model of the embroidery state. The virtual canvas maintains the position of the needle, the current stitching state, and the sequence of puncture points that form the embroidery pattern. When a cursor movement or click command is received, the virtual canvas updates the internal representation of the embroidery process according to the technique-aware stitching model described in the previous section.

After the internal state is updated, the system proceeds to the **rendering stage**, where the embroidery pattern is visually updated on the screen. The rendering module produces two synchronized visualizations: the front canvas drawing and the back one drawing. These two views correspond to the embroidery visible front and back sides that show the thread path between the stitches. By updating both views simultaneously, the simulator allows users to observe how each stitching action affects the embroidery structure of both sides (front and back) together.

This layered architecture separates interaction, simulation, and rendering responsibilities, enabling flexible integration of different input modalities. Because eye tracking and speech recognition ultimately produce the same interaction commands, the embroidery simulator can support multiple accessibility scenarios while maintaining a consistent internal model of the embroidery process. As a result, users can construct stitches, simulate embroidery techniques, and observe their effects on both sides of the fabric using completely hands-free interaction.

4 Testing Gaze and Voice Interaction

In the implemented prototype, gaze tracking is used to control the position of the system cursor on the embroidery canvas. Instead of moving a mouse pointer, the user moves the cursor by directing their gaze toward a specific location on the screen. The gaze position is continuously tracked and mapped on the pointer location, allowing the user to select puncture points on the embroidery grid by simply looking at them. In the context of the embroidery simulator, the cursor position corresponds to the current position of the virtual needle on the working embroidery canvas.

To initiate stitching actions, a dwell-time activation mechanism is used. When the user maintains their gaze on a selected location for a predefined time period (approximately three seconds), the system interprets this dwell event as a confirmation action equivalent to a mouse click. In the embroidery simulator, this action corresponds to inserting the virtual needle into the fabric and creating a stitch segment between two selected puncture points.

For experimental evaluation, gaze-based cursor control was implemented using the **GazePointer** application, which provides webcam-based eye tracking and translates gaze direction into cursor movement (Ghani et al., 2014). Because GazePointer itself does not generate mouse-click events, a separate dwell-click utility was used to simulate click actions. In the presented setup, click generation was implemented using **Dwell Clicker 2**, a software tool that automatically performs mouse clicks when the cursor remains stationary for a predefined time interval. This configuration allows the user to move the cursor using gaze and initiate stitching actions without using a mouse or touch input.

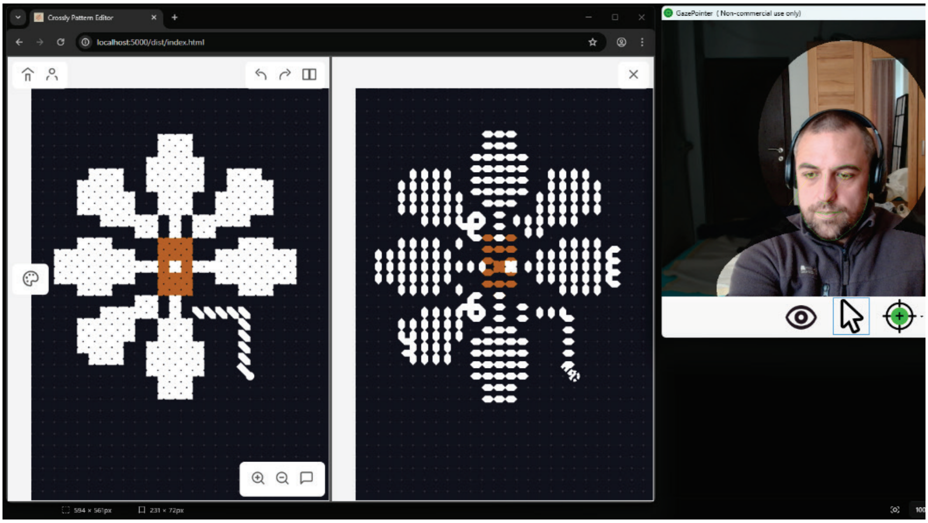

Fig. 3. Experimental setup for gaze-based control of the embroidery simulator using GazePointer and Dwell Clicker.

Figure 3 illustrates the experimental setup used in this work. The embroidery simulator runs in a web-based interface displaying the dual-view canvas with the front and back sides of the embroidery pattern. GazePointer controls the system cursor through webcam-based eye tracking, while **Dwell Clicker 2** generates click events when the cursor remains stationary. In this configuration, the user can select puncture points on the fabric grid and construct stitches step by step using gaze.

Voice interaction provides an additional method for controlling the embroidery simulator without relying on manual input devices. Instead of generating click actions through dwell-based gaze activation, the user can initiate interaction events through spoken commands.

This accessibility feature enables hands-free control of the operating system through spoken commands. One useful mechanism provided by Voice Access is the numbered grid interface which overlays the screen with numbered regions that can be selected by voicing the corresponding number. By successively narrowing the grid, the user can position the pointer with sufficient precision to select puncture points on the embroidery canvas.

The presented configuration relies entirely on **built-in Windows 11 voice control functionality**, demonstrating that hands-free interaction with the embroidery simulator can be achieved using readily available accessibility tools. This implementation shows that such interaction can be achieved using a low-cost research setup consisting of freely available tools, including webcam-based gaze tracking and built-in voice control functionality in OS Windows 11 and it also enables users to interact with the embroidery simulator while preserving the procedural structure of the embroidery process and the visualization of both sides of the fabric.

The adaptation of the simulator to use gaze and voice-based commands is done on the first stage. Only the authors of the paper have tested the system. The hardware and software requirements for testing necessitate the use of relatively expensive equipment, which makes it difficult to conduct tests involving more users. Testing the system with end users, some of whom with disabilities, is planned as future work.

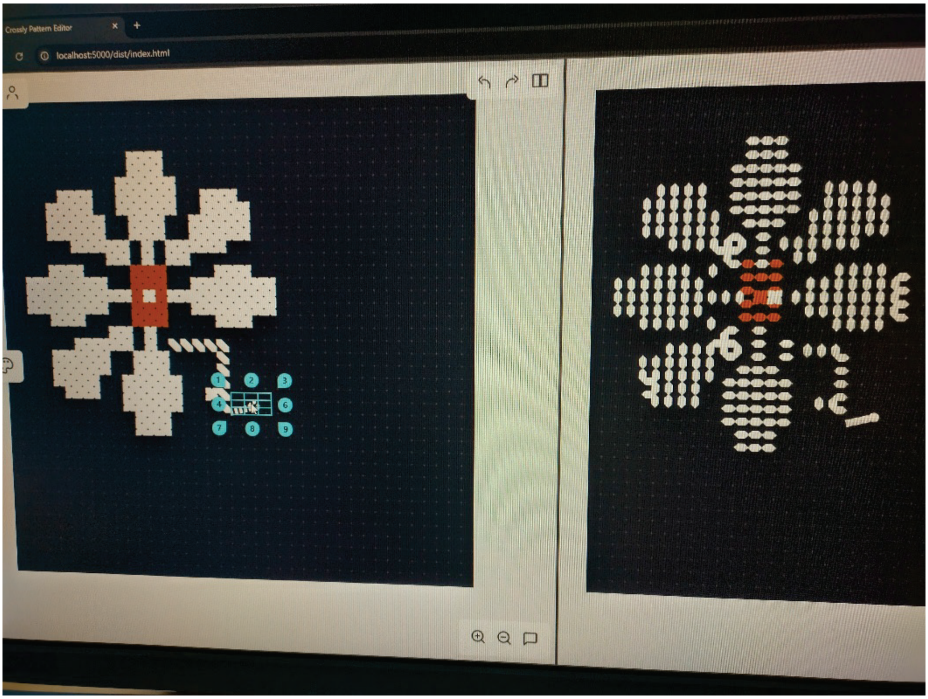

Fig. 4. Voice-based pointer selection using the Windows 11 Voice Access numbered grid in the embroidery simulator.

5 Conclusions

This paper presents an accessible interaction approach for a technique-aware digital embroidery simulator that enables hands-free control through gaze and voice commands. The proposed interaction model allows users to position the virtual needle, initiate stitching actions, and construct embroidery patterns without relying on traditional manual input devices. By combining gaze-based cursor positioning with dwell-based or voice-triggered commands, the system demonstrates how accessible input technologies can be integrated with a digital embroidery environment.

This craft software application is built as an embroidery process simulator unlike the existing Cross-stitch software. The aim is to develop an environment for digital representation of embroidery techniques. So, besides accessibility, the proposed approach contributes to the broader goal of preserving embroidery techniques in digital form. Because the application represents embroidery as a sequence of needle movements, it allows users to observe, reproduce, and share stitching techniques in a way that reflects the actual crafting process.

Compared with traditional Cross-stitch applications, the proposed simulator offers several advantages, but it also introduces certain challenges. Experienced craftsmen may find it inconvenient to design embroidery patterns step by step, following the same sequence as in real embroidery. To accelerate the design process, gaze- and voice-based interaction is integrated into software along with mouse and touch screen control. Involving hands-free human interaction in the application enriches its functionality by enabling people with temporary or permanent disabilities to use the software. Elderly people with various diseases belong to this target group. Gaze- and voice-based interaction allows all these people to share their knowledge and experience.

Although gaze and voice interaction can also be applied to other digital embroidery tools, these tools typically operate only on symbolic pattern charts where users fill grid cells with predefined stitch symbols. Such systems support visual pattern editing but do not represent the actual embroidery process. In contrast, the technique-aware simulator presented in this work allows users to perform digital embroidery itself, where stitches are constructed through simulated needle movements and the resulting thread structure can be observed on both sides of the fabric.

The presented work demonstrates that accessible interaction technologies can be combined with technique-aware embroidery simulation to support inclusive participation in digital craft environments and to facilitate the preservation and sharing of traditional embroidery knowledge.

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Generative AI is used for English editing only.

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