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Applying Paper Prototyping to Design an AR Teaching Tool for Novice Woodworkers Practicing Components Arrangement in Material Cutting

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ABSTRACT

This study focuses on Taiwanese university students in the field of vocational education. The research observed a woodworking product elective course in the Department of Industrial Design at National Cheng Kung University, where most students lack relevant experience and feel confused when learning about mechanical operations, physical applications, spatial concepts, and other aspects. The "components arrangement" stage is a crucial step from paper design to actual material processing, where students arrange the spare parts of their designs on the wood to be used in a manner suitable for machine sawing to achieve smooth, efficient processing, material saving, and aesthetic results. In this stage, novices spend much time particularly and feel hesitant during practice. Therefore, this study utilized paper prototyping to conduct operational pre-testing for the augmented reality (AR) woodworking cutting and arranging tool, allowing novice woodworkers to simulate AR-assisted tool operations intuitively and gather firsthand feedback to assist novices in arranging components. Experimental records indicate that researchers could quickly observe defects in AR system design during the experiment and make rapid adjustments. After model updates, participants could focus on task operations. Through participant interviews, it was evident that users provided positive feedback on the AR teaching tool's willingness to increase practice frequency, reduce task completion time, improve satisfaction with wood grain arrangement, and enhance operational confidence. These results align with AR tools' real-time and non-destructive nature, enabling students to try operations without worries, eliminating spatial cognition uncertainty, and increasing practice frequency to reinforce component arrangement assumptions. This study confirms that early implementation of paper prototyping in AR tool design facilitates rapid operational simulation verification and process optimization, enhancing novice woodworkers' willingness to learn and motivation to operate in material cutting and arranging. This lays the foundation for the subsequent development of AR woodworking cutting and arranging teaching tools. The study also proposes some improvements for using paper prototyping in AR simulations to make simulated operations smoother and more immersive.

Keywords: Augmented reality, Paper prototyping, Vocational education and training, Cutting diagram

INTRODUCTION

In vocational education, students spend considerable time engaging in practical exercises to convert acquired knowledge into procedural memory (Lai & Lin, 2017). Although Taiwan has gradually emphasized the importance of vocational education in recent years, societal norms still prioritize traditional academic pathways, with general high schools and colleges remaining the preferred choices for many individuals (Lee & Huang, 2023). Within the curriculum of university industrial design departments, students often need to validate and produce their designs, frequently requiring hands-on fabrication. However, despite a keen interest in hands-on activities, most college students from general high school backgrounds lack practical experience. While courses may offer practical instruction in model-making techniques, these typically span only one semester, making it challenging for students to become proficient in using of common tools and fabrication techniques. This study focuses on a woodworking product and design practice course offered by the Department of Industrial Design at National Cheng Kung University, where most students are woodworking novices with little to no understanding of woodworking processes, design, fabrication knowledge, or tool operation. The course is designed to complement students' lack of practical experience in factory equipment operation. For 18 weeks, totaling 54 hours, the objective is to guide over 20 woodworking novices from zero experience to independently completing finished products. However, the course presents significant challenges in terms of curriculum design, scheduling, and safety maintenance. During instructional demonstrations, students may face barriers such as limited auditory or visual access to the teacher's on-site demonstrations; practical exercises may be restricted by limited access to equipment, preventing students from gaining proficiency through repeated practice. Additionally, teachers may struggle to provide individualized demonstrations while monitoring all students' progress. To address these challenges, this study aims to develop an AR-assisted interactive system to provide instructional support. AR technology enables users to interact with their environment in novel ways, creating new visual experiences (Freitas, Pinho, Silveria & Maurer, 2020). AR technology transcends spatial and temporal constraints with its ability to seamlessly blend virtual objects with the real world and conduct multiple simulated operations without physically altering objects (Billinghurst, 2002). This study focuses on the component arrangement stage before material cutting, a critical step bridging design drawings and fabrication operations. In this stage, students must plan and arrange all design components within the material to be cut, ensuring efficient and complete fabrication. By incorporating AR technology, this study anticipates students can avoid irreversible errors discovered after cutting and practice various arrangement possibilities before sawing. However, comprehensive AR software like Unity requires significant expertise and investment of time and resources, making subsequent modifications challenging (Freitas et al., 2020). Therefore, this study adopts paper prototyping, which is extensively used in UI design, leveraging its low cost and rapid iteration advantages to conduct operational design validation of AR teaching tools and obtain feedback promptly.

AUGMENTED REALITY TO NOVICE WOODWORKER EDUCATION

In recent years, the application of AR technology has become increasingly prevalent and diversified, with many educational applications emerging, providing students with unique learning experiences (Gün & Atasoy, 2017; Yip et al., 2019). Augmented reality refers to the technology that overlays digital content onto physical objects in the real world, making it suitable as an auxiliary tool for technical education courses, with related technologies being applied in classroom teaching (Cuendet et al., 2013). Since skill acquisition requires hands-on practice for students to transform absorbed knowledge into technical proficiency, such courses necessitate more time for observation and practice, consuming more course time and physical space than general academic subjects.

In the woodworking course of this experiment, due to space constraints and students' unfamiliarity and lack of proficiency with the subject, it is challenging for students to fully observe course demonstrations and engage in maximum practical exercises within the limited course time. For students who are all woodworking novices, the woodworking process involves transforming design concepts from 2D drawings to three-dimensional products through hands-on manipulation of tools, making it difficult to imagine the outcome of material manipulation at each step without experiencing the entire process (O'Malley & Fraser, 2004). O'Malley and Stanton Fraser (2004) mention another important aspect of learning: the coupling between cognition and bodily experience. Students in vocational education can train their spatial concepts and abilities to convert 2D to 3D through continuous practice. However, students in this course lack these abilities. Using AR instructional systems provides a balance of immersion and real interaction, allowing for the experiential and situational learning described by Mantovani and Castelnuovo (2003) as the "sense of presence," which can enhance users' spatial abilities. Therefore, AR is highly suitable as a tool medium for woodworking instruction and practice for novice woodworkers.

AUGMENTED REALITY AND WOODWORKING COMPONENT ARRANGEMENT

Component arrangement for cutting is common in industries involving material cutting, such as steel, fabric, paper, and plastic sheets. Typically, cutting materials only requires consideration of maximizing the number of components within a limited area for optimal cutting. However, woodworking presents a unique challenge due to the directional nature of the wood grain, which affects the structural strength. Therefore, in addition to considering the most economical arrangement, the orientation of the wood grain needs to be prioritized (Carnieri, Mendoza & Gavinho, 1994).

AR features the integration of virtual objects with the real environment, allowing users to interact with virtual objects in the real context and observe the relationship between the operation and the real environment. In the woodworking component arrangement phase, the wood to be cut can be considered part of the real environment, where each piece of lumber material is unique, and the patterns and defects on the material display the complexity of the real world. On the other hand, the components of the workpiece are relatively regular artificial objects that can be simulated with virtual objects. Through the ability of AR to interact between the virtual and real, learners can observe the relationship between the components arranged on the lumber, clarifying the effect of different arrangements on the appearance of the spare parts after cutting.

NOVICE WOODWORKES' CHALLENGES IN WOODWORKING COMPONENT ARRANGEMENT

Novices encounter numerous difficulties, particularly in making cutting diagrams before cutting, due to the comprehensive considerations required in woodworking, which is an integrative task. Firstly, consideration must be given to the available tools, as the type of tools influences the cutting method, and the thickness of the saw blade affects the extent of material consumption. Next, the arrangement sequence needs to be considered to ensure smooth cutting. Finally, it is essential to consider whether defects in the lumber will affect the appearance of the cut components and to avoid them during the arrangement. Experienced woodworkers typically calculate and confirm the dimensions directly on the saw table based on the lumber's actual condition and the components' size. Novice woodworkers often need to draw the components on the lumber surface to determine if all components can be cut from the lumber. This process takes time and is difficult to adjust, which makes it challenging to consider the reserved tool thickness. Moreover, encountering defects such as knots or cracks makes quick adjustments difficult. Therefore, this study utilizes the interactive nature of AR to develop AR woodworking component arrangement tools, aiming to improve student learning outcomes through practice and interactive teaching.

PAPER PROTOTYPING AND AUGMENTED REALITY

Existing AR development tools such as Unity require a considerable level of expertise and extensive time investment to complete system development, and a small bug can cripple the entire system (Retting, 1994). For those without professional development skills, using high-fidelity models at the early stages of development is impractical, necessitating a low-cost and rapid method to verify the system's conceptual feasibility (Freitas et al., 2020). According to Freitas et al. (2020), paper prototyping is the preferred method for rapid and low-cost simulation. Paper prototyping was proposed by IBM in the 1980s (Retting, 1994), using readily available office materials such as paper, markers, and scissors to roughly create the operational interface of the system for human-computer interface testing. Despite its rough appearance, due to its low production cost and rapid operation, research shows that it is almost as effective as feedback from sophisticated computer-based prototypes (Lim, Pangam, Periyasami & Aneja, 2006; Alkhaldi & Al-Sa'di, 2018; Sefelin, Tscheligi, and Giller, 2003) and is widely used in the early stage of interface design. Today, products for human-computer interaction have evolved from fixed devices such as computers to mobile devices such as phones, with wearable devices also beginning to emerge. As wearable devices do not have a fixed interaction range like traditional screen-based devices, interface development and design are much more challenging compared to traditional screen-based devices.

This study uses paper prototyping to quickly assess the operational feasibility of the design process, prioritizing smoothness and operability while excluding the influence of factors such as appearance design and aesthetics. Additionally, consideration must be given to how to simulate the interface display of HUD devices and interact with the real environment.

INTERFACE DESIGN AND TESTING

In previous research, the researchers decomposed the AR teaching system into five major blocks: sawing parameters input, design work input, material parameters input, manual layout operation, and sawing processing suggestions. To conduct simulation testing using paper prototyping, this study organized and summarized the layout tasks and drew a functional flow chart, as shown in Figure 1.

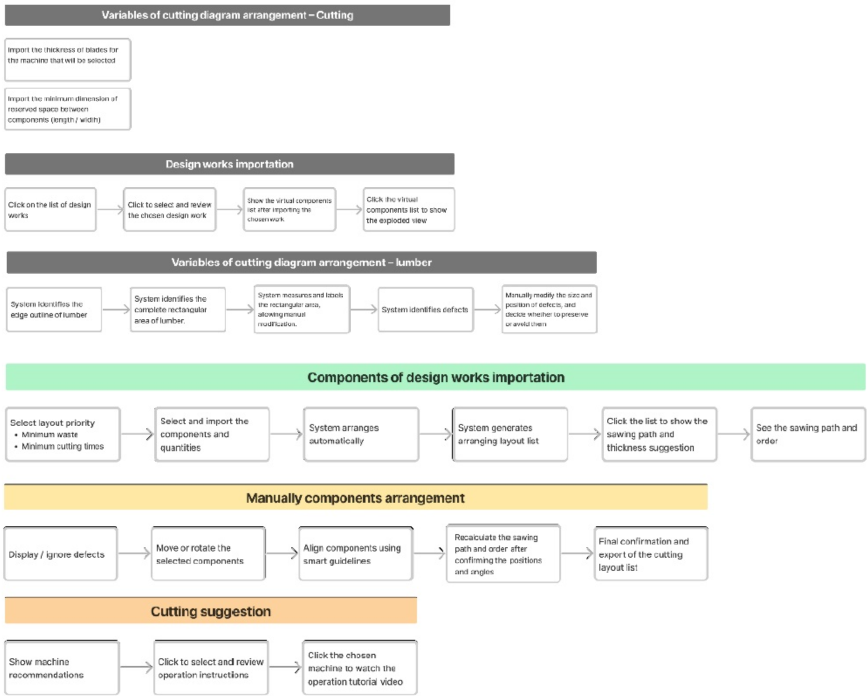

Figure 1: Functional flow chart.

Based on the functional flow chart, the simulation operation process was pre-planned, and a preliminary UI design was conducted to create a preliminary UI operation process, as shown in Figure 2.

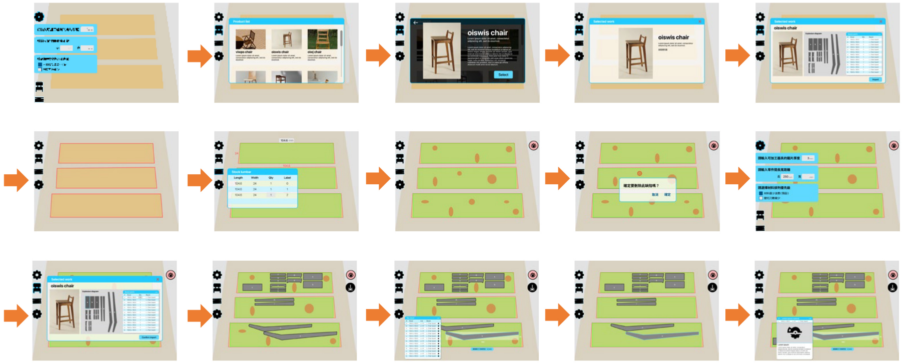

Figure 2: Interface design.

To avoid interference from interface appearance design on operational feedback, the operational components of paper prototyping were presented most simply, eliminating interference from component shapes and colors. To simulate the display effect of head-mounted devices, transparent acrylic was used for the simulated screen of the interactive interface, allowing components to paste on the acrylic to simulate the situation of seeing virtual components floating in space. Additionally, this study focuses on exploring participants' operations in arranging design work components; therefore, acrylic was also used to simulate virtual design work components, allowing participants to manipulate the components directly. Preparation of the experimental environment included: 1. Placing real wood lumber on the desktop to represent the actual material to be sawn; 2. Pre-arranging simulated components made of acrylic on a large acrylic sheet to simulate the situation where the system automatically arranges components; 3. Marking the position of wood defects with a red marker on another acrylic sheet covered with Scotch tape; 4. Attaching interface components to another acrylic sheet for participants to operate in a suspended manner. 5. Setting up cameras and recording audio to document the operation process. The setup of the experimental environment is illustrated in Figure 3.

Figure 3: Test environment setting.

DISCUSSION

In this study, students without any woodworking experience from the Department of Industrial Design at Cheng Kung University were recruited as participants to simulate students with similar backgrounds enrolled in the course. The researcher first simulated course instruction, explaining the purpose and operation methods of layout planning, and then asked the students to simulate using the AR system with paper prototyping for components arrangement practice. During the operation process, participants were required to verbally describe their actions, such as clicking, dragging, rotating, etc. The experimenters recorded the operation process and any issues encountered, conducted a review after the operation, updated the process or components, and then repeated the simulation. Due to the characteristics of paper prototyping, the operational inefficiencies and missing icons were quickly identified during the experiment. Experimenters provided real-time explanations and added components to correct the process, allowing participants to conduct another simulation round within five minutes.

However, in addition to the positive feedback on the AR woodworking cutting diagram layout system observed during the experiment and obtained from participant interviews, several issues were identified: (1) Due to the "what you see is what you get" nature, when all parts can be arranged within the material area, participants may overlook the actual size of the material. (2) Since paper prototyping applies real-world objects to simulate AR, participants initially cannot distinguish which components represent reality or virtuality. (3) There is still a gap between using paper prototyping and actual operating environments, requiring clear definitions of the meanings of each action during simulated operations, such as using a marker to write representing typing input or voice input. (4) Participants must be encouraged to bravely try clicking on interface components to trigger all software functions. (5) Using acrylic to simulate AR's floating display prevents participants from releasing their hands during operation. (6) Participants may be distracted while operating the floating panel due to concerns about accidentally dislodging floating components. (7) Since the simulated part templates use transparent acrylic, participants can see through the material and clearly observe defects on the material, leading to the neglect of the function to display material defects. (8) There is a time delay between participants' actions and the simulated system feedback, requiring waiting time. (9) Some simulated components are more labor-intensive and cannot be modified promptly during testing.

The issues above do not significantly impede the use of paper prototyping to improve system processes, but they may affect the experience of simulating AR operations. Future improvements can focus on addressing these issues to enhance the smoothness of simulated operations.

CONCLUSION

The experiment conducted three rounds of simulated operations. Despite the time required for modifying the fabricated components, through timely adjustments, the overall operational process became significantly refined by the end of the third round. Participants were able to simulate system operations smoothly, demonstrating that the application of paper prototyping in preliminary testing of AR systems can effectively optimize the system.

Since AR combines virtual and real-world environments while paper prototyping presents in physical form, it's essential to consider whether the materials used can simulate the AR operating environment. It may be advisable to familiarize participants with the operation of paper prototyping before conducting actual tests. It is recommended to utilize modular production way to create components of the AR display interface, reducing the complexity of components and their influence on the user experience. Although using acrylic to simulate the visual effects of the AR display interface is visually appealing, it affects operability. Therefore, it is suggested that in the future, a suspension method be used to fix and free the user's hands for a better experience.

Through the paper prototyping simulated operations in this study, it was also observed that when woodworking novices become familiar with the AR system operation process, they are more willing to try various cutting diagram layout possibilities. Subsequently, based on these findings, the process will be optimized in collaboration with professional software designers to develop a practical woodworking AR cutting diagram layout teaching aid.

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