Engaging Young People in the Expressive Opportunities of Digital Fabrication Through Craft-Oriented CAM-Based Design

Ashley Del Valle
University of California
Santa Barbara, CA, USA
adelvalle@ucsb.edu

Mert Toka
University of California
Santa Barbara, CA, USA
merttoka@ucsb.edu

Jennifer Jacobs
University of California
Santa Barbara, CA, USA
jmjacobs@ucsb.edu

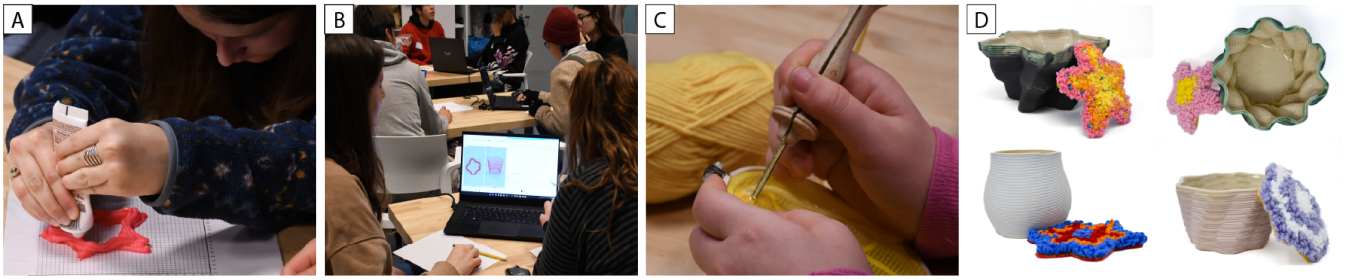


Figure 1: We present a craft and project-based curriculum to engage young people with Computer-Aided Manufacturing (CAM)-based design for additive fabrication. We evaluated this curriculum through a three-day workshop with high school students involving (A) interactive activities, (B) computational design and 3D printing, (C) punch needle embroidery, and (D) the creation of 3D printed clay and textile artifacts as final projects.

ABSTRACT

Digital fabrication can be a rich creative domain for young people. Most youth-oriented digital fabrication activities focus on CAD, where practitioners design solid geometry. Professional designers frequently bypass CAD and instead design at the level of the machine toolpath. This CAM-based design process allows for material exploration, unique textures, and complex shapes. We recognize young people's role as designers and seek to adapt professional digital fabrication techniques to meaningful youth design activities. We present a youth-oriented CAM-based design curriculum consisting of 1) hands-on activities that introduce machine toolpath concepts, 2) a learner-oriented CAM software interface that scaffolds digital toolpath creation, and 3) project-oriented design activities that integrate CAM-based design and manual craft for ceramics and textile production. We evaluated our approach through a workshop with twelve high school students. Our research shows that young people can skillfully apply CAM-based design and manual craft to create functional and personally meaningful artifacts.

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1 INTRODUCTION

Digital fabrication and computational design present significant opportunities for introducing powerful concepts, skills, and creative tools to youth [6]. Affordable digital fabrication machines are increasingly accessible in various learning environments, including schools, makerspaces, and homes. HCI researchers have explored strategies to engage youth in digital fabrication through a series of activities like games [4, 61], workshops [3, 5, 15, 27], and digital tools [34, 69]. These studies highlight how, with effective scaffolding, digital fabrication can enable young people to create artifacts, foster personally meaningful creative experiences, and promote a sense of ownership over digital tools and outcomes. We recognize young people's potential as designers and seek to expand their opportunities to use digital fabrication for design applications.

Most digital fabrication activities for youth utilize Computer-Aided Design (CAD) software, such as Tinkercad [59], LeoCAD [44], and BlocksCAD [7], to create 2D and 3D digital representations of objects. One area of digital fabrication that has been unexplored as a design method for youth is Computer-Aided Manufacturing (CAM). CAM software assists designers in generating low-level machine instructions, known as G-Code, to command computer numeric control (CNC) machines [2]. Conventional additive digital fabrication workflows begin with CAD, where a designer creates solid geometry with machine-agnostic modeling software. The designer then converts the geometry into machine toolpaths using CAM slicing software. This software breaks down the geometry into layers and generates the corresponding toolpaths for the fabrication process [63]. Alternatively, designers may bypass CAD design entirely and instead design directly at the level of the toolpath, a process known as CAM-based design [2]. Researchers, professional designers, craftspeople, and small entrepreneurial businesses

often employ CAM-based design methods rather than CAD because it supports the creation of innovative and novel artifacts and functionality [31]. Working at the level of CAM requires a deep understanding of low-level parameters, such as machine kinematics, tool geometry, feed rates, and material properties. Researchers have increasingly adopted CAM-based design to achieve intricate textures, forms, and geometries [41, 50, 57]. They have harnessed CAM's precision control to explore the fusion of craftsmanship and digital fabrication, resulting in robust textile structures [19, 24, 58], unique ceramics forms [8], and detailed wood carvings [60]. Craftspeople have also extended their traditional manual techniques by integrating CAM-based design approaches [31].

We argue that youth can similarly benefit from the diverse forms of expression inherent in CAM-based design and the distinctive artifacts that can be digitally fabricated using this method. Because toolpaths are described numerically, often with symbolic tools, CAM-based design provides a practical application of mathematical and programming principles (e.g., coordinate systems, geometry, transformations, measurements, and units). Moreover, the fundamental principles of CAM-based design extend across various fabrication domains, encompassing plastics [50, 57], biomaterials [66, 70], and food [46]. Some forms of CAM-based design share a stronger connection with manual craft techniques than CAD-based design [31], allowing the integration of craftsmanship and digital fabrication in textiles [19, 24, 41], ceramics [8, 43, 47] and wood carving [60]. This connection can be appealing to young people interested in craft. Working with CAM-based design provides a valuable opportunity to blend material-driven craft skills and techniques with digital tools, enabling the creation of individualized designs. Most existing CAM-based design workflows require specialized industrial software or low-level symbolic programming languages [31]. Current instructional methods for CAM-based design target expert adult designers [17]. We see an opportunity to support youth in digital-physical creation through youth-specific CAM-based design practices and technologies. In this work, we investigate the following research questions: (1) How can we support young people using CAM-based methods to design and fabricate physical artifacts? and (2) How does CAM-based design shape young people's understanding of digital fabrication technologies? To address these questions, we designed a curriculum that integrates CAM-based design with manual craft concepts, specifically focusing on clay 3D printing and punch needle embroidery. We define a curriculum as a structured framework that outlines the educational goals, project objectives, and activity structures for a particular course of study. Collectively, these elements encompass a cohesive series of projects and techniques to guide learners toward acquiring specific skills and achieving desired learning outcomes within a specific subject area or field of study.

Our project-based curriculum engages youth in CAM-based design through hands-on interactive activities. The curriculum encompasses introductory lessons on CAM-based design and additive fabrication, as well as hands-on experiences with computational design, 3D printing, and manual crafting techniques. To investigate the efficacy of our approach, we deployed our curriculum with 12 high school students in a comprehensive three-day workshop. By the end of the workshop, all students designed and fabricated personal 3D-printed ceramic and textile artifacts using CAM-based design methods.

We make the following contributions:

- A project-based curriculum for CAM-based design for young people. The curriculum includes activities introducing CAM concepts without computers and craft-compatible projects for clay and thermoplastic 3D printing.
- The adaptation of two expert-oriented CAM-based design systems into a constrained, slider-based design software for young people.
- An evaluation of the curriculum through a workshop with high school students. The workshop demonstrates how young people can skillfully use CAM-based design to produce diverse and beautiful ceramic and textile artifacts.

2 RELATED WORK

We draw from three areas of research: project-based learning, computational design, and digital fabrication aimed at youth, as well as current CAM-based design tools.

2.1 Engaging students in project-based learning

Our curriculum is centered around project-based learning (PBL) because it offers a hands-on approach that encourages exploration, problem-solving, and creativity. This approach enables students to engage with the material actively, fostering a deeper understanding, essential skills development, and a sense of ownership in their learning. Over the years, researchers have implemented different PBL methods to design workshops and curricula, introducing youth to key ideas in computer science, engineering, and technology. For example, numerous initiatives have employed game development activities [18, 35, 55, 67], construction kits [23, 36, 39, 68], storytelling [12, 13, 26] and physical activities[65]. Further initiatives have combined hands-on craft activities with emerging technologies, like e-textiles [10, 37, 49, 53] and paper electronics [29, 51, 52]. From specialized materials like conductive components to paper printables, these initiatives share a common goal of broadening participation and engaging young learners.

In our curriculum design, we considered insights from Chan and Blikstein regarding the merits and challenges of project-based learning. They recognize that while PBL enhances student engagement and learning outcomes, it may necessitate significant teacher training and support [14]. Moreover, our curriculum is shaped by the understanding that crafting activities are among the most creative, unique, and patient endeavors for young individuals as they mold their identities and transition into adulthood, as noted by Eisenberg [22]. By integrating these insights, we aim to provide youth with a platform to explore their interests in design and digital fabrication while fostering the creation of intricate, personalized, and beautiful craft artifacts. Resnick and Rosenbaum's tinkering approach, characterized by a playful, experimental, and iterative style of engagement [54], significantly influences our curriculum design. We emphasize hands-on exploration, experimentation, and iteration, mirroring the tinkering philosophy. Overall, we strive to integrate Papert's constructionist learning theory, which emphasizes active, hands-on learning through making artifacts where

learners explore, create, and collaborate to construct their knowledge [48]. This learning theory also underscores the importance of personal meaning, collaboration, and embracing mistakes as opportunities for learning. Our work resonates with Papert and Turkle's call for inclusive education, emphasizing diverse perspectives [62]. By integrating their ideas, our curriculum encourages learners to explore and construct knowledge from various viewpoints.

2.2 Engaging young people with computational design and digital fabrication

Engaging youth in computational design and digital fabrication serves multiple purposes, each contributing to their holistic development and preparation for the future. This work aims to support youth as designers, empowering them to explore, create, and innovate in an increasingly technology-driven world. The rise of spaces such as Clubhouses, Fab Labs, and Makerspaces underscores a common objective: encouraging amateur engineering, DIY projects, and technological creativity. These initiatives are renowned for their active commitment to engaging and empowering youth. Dougherty underscores the maker movement's importance and potential to empower individuals as creators and innovators, democratizing access to tools and knowledge typically reserved for experts [21]. Dougherty's insights influenced our curriculum by emphasizing the importance of hands-on, project-based learning to cultivate creativity, problem-solving skills, and a maker mindset among students. Blikstein highlights the potential of Fab Labs, workshops equipped with digital fabrication tools like 3D printers and laser cutters, to foster creativity, innovation, and hands-on learning experiences in educational settings [6]. Gershenfeld discusses how these labs enable individuals to design and produce a wide range of customized objects [25]. Both authors recognize Fab Labs as environments that empower individuals to explore their creativity, experiment with new ideas, and turn imagination into reality through digital fabrication technologies.

On the other hand, Morgan also examines the drawbacks present in maker cultures, including disparities in resource access, inclusivity issues, and the co-optation of maker movements by commercial entities [1]. Despite these challenges, HCI researchers strive to strengthen and improve the benefits of youth engagement in Making. Past works used digital fabrication to incentivize students to explore programming [38, 56] and engineering [27, 28]. Jacobs' work emphasizes hands-on project-based learning to empower students to craft tangible artifacts [33, 34]. Chytas's research aims to cultivate the intrinsic motivation of youth in crafting physical objects using computational design and 3D printing tools, echoing the hands-on, project-based learning approach emphasized in related studies [15]. These studies highlight the need to tackle learning challenges and support structures when integrating computational design and digital fabrication into education. Hudson suggests addressing these challenges through the lens of casual makers—users with no prior fabrication experience, predominantly utilizing walk-up-and-use 3D printing services at public centers like libraries, universities, and schools [32].

2.3 Expanding creative expression through CAM-based design

CAM-based design enables the creation of custom machine behavior that expands the creative possibilities of digitally fabricated artifacts. For example, the artist LIA creates a series of 3D-printed thermoplastic sculptures by generating G-Code to explore the medium's behavior [45]. Stefan Hermann, a 3D printing hobbyist, shared his experience in creating custom G-codes to facilitate the production of non-planar pieces. This CAM-based design allows for swift design iterations, enabling bends at various angles with increased printing success rates [40]. HCI researchers use CAM-based design to study the blend of crafts and digital fabrication. This includes mimicking textile structures for creative clothing and wearables [19, 24, 58] and designing surface textures in ceramics [8, 43]. Pezutti-Dyer and Buechley developed an open-source Turtle Geometry library for 3D printing, which generates G-Code based on the path traveled by a LOGO-inspired Turtle [50]. During a computational fabrication course with college students, Buechley studied new avenues for research in computational fabrication, learning, and HCI [9]. This work highlights how engaging college students in advanced computational topics can provide unique opportunities for philosophical reflection, personal expression, real-world use, and social connection. Subbaraman presents p5.fab [57], a system for makers and programmers that generates toolpaths from the creative coding environment p5.js. Subbaraman demonstrated that toolpath control helped participants negotiate common 3D printing problems with creative goals. While prior research emphasizes the creation of intricate artifacts through CAM-based design, they usually cater to expert crafters or people with a programming background. We aim to involve youth in digital fabrication through a CAM-based design approach, allowing them to explore and achieve visually appealing results like those showcased in prior research.

3 RESEARCH TEAM

This paper reflects the research team's interest in expanding the youth's expressive and creative opportunities with CAM-based design. The work is primarily motivated by the background and objectives of Ashley– a Ph.D. student studying the pedagogical opportunities of integrating manual craft and digital fabrication. Ashley's interest in this domain stems from her experience running a manual textile craft business in Puerto Rico and her desire to broaden emerging technologies' economic and creative opportunities for underrepresented groups within HCI and engineering. Mert is a Ph.D. student who develops computational fabrication systems and material techniques for manual-computational craft workflows. Jennifer is an Assistant Professor who directs a digital fabrication research lab. We informed the curriculum, in part, by drawing upon the collective personal experiences of the authors and their fellow lab-mates, who have engaged in learning, utilizing, and advancing CAM tools.

4 PRELIMINARY STUDY

This section outlines a formative study conducted before developing and evaluating our curriculum. This preliminary study aimed to assess the guidance needed for newcomers in digital design and

fabrication practically, utilizing a CAM-based tool to produce physical artifacts. During this study, we gathered feedback, insights, and data to inform the development of feasible software interactions, identify learning challenges, and evaluate the time and effort required by the facilitation team.

4.1 Preliminary study – Methodology

This study involved a group of seven adults, comprising one participant aged 55-64, another aged 25-34, and the remaining individuals aged 18-24. Participants engaged in a six-hour workshop spread over two weekends. All participants had prior interest or experience in textile crafts and their integration with 3D printing.

We conducted our formative study with adults rather than children for several reasons. First, adults can provide informed consent, whereas children typically provide assent according to Institutional Review Board (IRB) guidelines. Second, adults are generally considered less vulnerable in research settings, making them suitable candidates for initial testing of our workflow. Third, adults are more accessible than children, who are often reached through outreach partners. We collected participant data through group discussions and utilized pre- and post-surveys comprising a mix of multiple-choice, Likert scale, and open-ended questions. In the pre-survey, all participants indicated little to no experience with 3D printers and parametric design, while 57% reported prior experience with textile crafts.

Participants engaged with PunchPrint [19], a workflow comprising a parametric CAM-based design tool, 3D printing, and punch needle embroidery. We chose PunchPrint for its straightforward workflow and support for punch needle embroidery, which has a relatively low learning curve. The workshop began with a brief lesson on FDM 3D printers and their connections with textiles. Participants then learned and practiced punch needle embroidery before being introduced to PunchPrint's design component in Rhino and Grasshopper. In Rhino, participants selected the outline and inner designs of their fabric from predefined curves, while in Grasshopper, they had granular control over their fabric's size, thickness, and attachment points. Subsequently, we exported the G-code from Grasshopper and 3D-printed the designs over the following week. Participants spent the majority of the second workshop session punch-needling their designs.

4.2 Preliminary study - Results

All of the participants were able to use PunchPrint's software to design 3D-printed fabric artifacts (Figure 2A), and although the manual punch needle process required additional time for some participants, they showcased specific design intent (Figure 2B). During a post-survey, most participants reported that they would like to continue learning ways to integrate crafts with new technologies. Participants also indicated that doing punch needle on the 3D-printed fabric was easy and enjoyable. During the group discussions, participants identified various challenges while embroidering on the 3D-printed fabric. Specifically, they noted the difficulty of punch needling around the edges of the fabric due to the obstructed spaces that made it challenging for the needle to pass through. Additionally, participants expressed difficulties in learning and using the design tool, such as navigating the distinct interfaces of Rhino and Grasshopper and understanding essential software terms such as curves and bake.

4.3 Preliminary study – Takeaways

Through this workshop, we confirmed the feasibility, from a logistical standpoint, of newcomers utilizing a CAM-based design approach to create digitally fabricatable artifacts. Predictably, participants faced challenges in navigating the Rhino and Grasshopper software. This suggests that further support and guidance may be necessary to help users overcome the learning curve associated with these complex design tools. Furthermore, we observed that providing a series of designs for participants to select from constrained participants' ability to embrace their role as designers fully. This suggests that while simplifying the design process can improve efficiency, it may limit participants' creative freedom and sense of ownership over their designs. Finally, we observed that most of the design activity occurred during the manual craft stage, where participants showed the highest levels of confidence and enjoyment. This suggests that we can shift the focus of engaging with key design concepts away from software and towards hands-on activities. This formative study served as a valuable foundation for refining our curriculum, allowing for iterative improvements in engaging newcomers with CAM-based design and digital fabrication. The insights gained from this study informed the design and development of the curriculum presented in the following section.

5 CURRICULUM DESIGN GOALS

In this section, we explain the concepts in design and manufacturing for additive fabrication covered in our curriculum. Following this, we describe our curriculum design process, including goals and development. We also share the motivations and perspectives of our research team in undertaking this work.

5.1 Key concepts of additive digital fabrication using various materials

CAM-based design techniques require a fundamental understanding of CNC machining concepts and the capabilities of additive fabrication technologies. These concepts form the foundation of our curriculum. They include concepts related to *additive layer structure* (e.g., adhesion, layer count, layer-to-layer transformations), *material extrusion* (e.g., nozzle size, nozzle material compatibility, flow rate), and *toolpath specification* (e.g., Cartesian coordinates, G-Code syntax). We also included geometric representations of concepts such as radius, scale, rotation, square wave, sinusoidal wave, amplitude, and period. We interactively introduced and reinforced these concepts with short lessons, hands-on activities, and CAM software developed in response to the formative study. We argue that teaching additive fabrication with multiple materials enhances the understanding of these key concepts. Our activities and software support CAM-based design using clay and thermoplastic materials, helping students comprehend the distinct properties of each material, which is crucial for aligning toolpaths with material characteristics. For example, clay permits overhangs and manual adjustments but needs moisture control [11]. In contrast, thermoplastic demands precision and disallows manual changes during

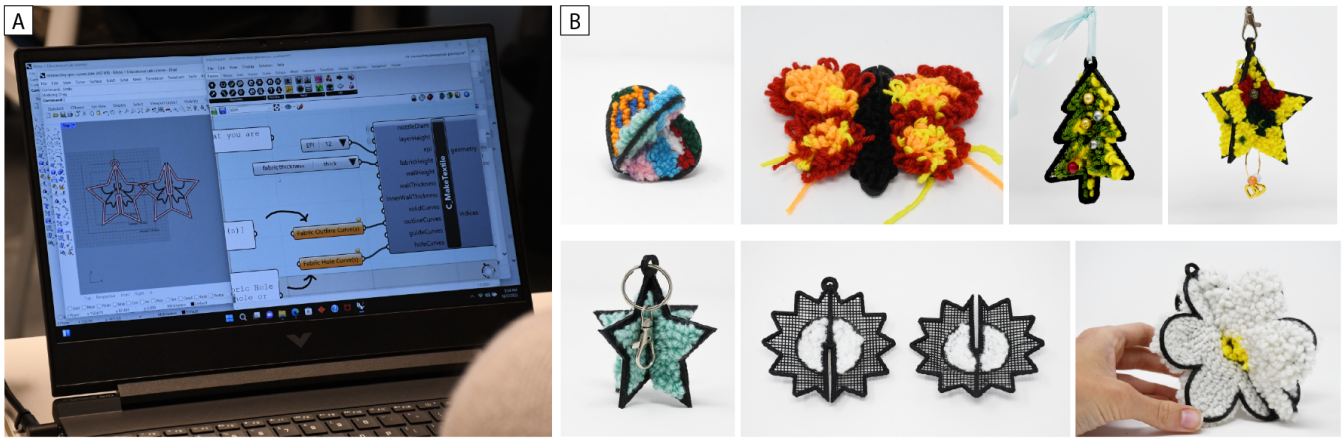


Figure 2: We conducted a preliminary study with seven adults. (A) Participants used the PunchPrint CAM-based tool to design a textile compatible with punch needle embroidery. (B) Participants created three-dimensional punch needle projects made of two intersection geometries.

printing, yet precise control yields flexible and detailed textile-like materials [24, 50, 58].

5.2 Curriculum design methodology

We guided our curriculum development with the following design goals (DG):

(1) Scaffold student engagement with key concepts and constraints of additive fabrication through hands-on activities with physical materials.
(2) Establish meaningful intersections between CAM-based design and arts and crafts activities for youth.
(3) Contextualize CAM-based design by creating functional applications with connections to professional fabrication methods.
(4) Support students in producing unique and beautiful artifacts through CAM-based design.
(5) Reduce the need to rely on general-purpose CAM-based design technologies (e.g., symbolic programming) while still providing young students with a design agency.

To meet our design goals, our curriculum combines initial hands-on activities with physical materials (no screens) to explore CAM principles, followed by guided activities using CAM software. We used an iterative approach to create our curriculum. All authors collaborated to identify concepts from prior digital fabrication research/practice that could apply to youth engagement in CAM-based design. Ashley selected a subset of these activities and worked to refine them into an initial curriculum, with regular feedback from Jennifer. Ashley and Mert then collaborated to develop the documentation and instruction materials necessary for deploying the curriculum in a workshop with young people and subsequently facilitated the workshop.

To investigate how we can support young people using CAM-based methods to design and fabricate physical artifacts, we conducted a three-day workshop based on our curriculum. The workshop served to evaluate the curriculum and approach to engaging young people in CAM-based design. During this workshop, we evaluated the artifacts created by the participants and gathered insights into their experiences with CAM-based design.

We partnered with the School of Scientific Thought (SST) Program [64], a Saturday initiative tailored for high school students, aimed at expanding their understanding of scientific concepts beyond traditional classroom settings. The workshop involved 12 high school students, primarily in the 10th and 11th grades. Among the participants, 58% identified as girls, 33% as boys, and 8% as non-binary. In the pre-survey, it was revealed that 91% of the students had minimal to no prior experience with 3D printing, 75% had limited or no experience in programming, and 83% had little to no experience with 3D modeling. However, a majority (84%) reported having crafting and making experience.

We organized all lesson materials on a website, allowing students to access and review written and visual content conveniently. For interactive activities, participants were paired and encouraged to share tasks evenly. Each workshop session began with an icebreaker, fostering a collaborative and creative atmosphere. We evaluated the workshop using surveys, daily feedback, and group discussions. The initial survey gauged participants' prior experience in digital fabrication, crafting, making, and 3D design. To investigate how CAM-based design shapes young people's understanding of digital fabrication technologies, we conducted daily surveys with a combination of multiple-choice, Likert scale, and open-ended questions from which we gathered our insights and feedback. The final survey centered on post-workshop experiences. We also conducted two group discussions during the last sessions, lasting 15-33 minutes each, which we recorded and transcribed. These discussions allowed participants to share their highlights, challenges, and learning experiences during the workshop. Following the completion of the workshop, Ashley reviewed all transcripts, survey data, and visual documentation to identify preliminary themes and key data fragments in the form of quotes and observations. Ashley and Jennifer then met regularly to discuss this preliminary analysis over a period of three weeks to finalize the organization of our primary results and takeaways.

6 WORKSHOP

This section describes our daily workshop activities to illustrate our curriculum and evaluation in detail.

6.1 Day 1 – Cardboard activity to introduce layer-based additive fabrication

We began our activity intending to introduce students to additive fabrication and its relationship with layer-based design. We aimed to allow students to explore the design process of layer-based additive fabrication and layer manipulation in a tangible context without the added difficulties of software. To achieve this, we adapted an established activity of stacking 2D laser-cut cardboard shapes to create 3D forms [42]. Before the workshop, the research team designed three unique 3D models in Grasshopper and laser-cut the models using cardboard. We provided the students with the pieces and glue and guided them to explore different forms and structures by stacking and adhering (Figure 3). We specifically encouraged them to consider rotation and offset as they created forms, but we refrained from providing specific instructions regarding the pieces' order, position, or orientation. This activity lasted for 30 minutes. We asked students to reflect on and discuss their design strategies, challenges, and the specifics of the layer manipulations they used.



Figure 3: Through the cardboard activity, we aimed to introduce students to additive fabrication and its relationship with layer-based design. (A) Students were given 2D laser-cut cardboard shapes and (B) instructed to assemble them to create 3D forms.

6.2 Day 1 – Acting as the machine activity to introduce machine kinematics and material behavior

For the remainder of the first day, we engaged students with the concepts of toolpath, G-Code, nozzle size, and material behavior. Our goal was to introduce the concept of toolpaths and present the mathematical information they convey. Furthermore, we aim to briefly summarize how this mathematical data is encoded into G-code. We aimed to allow students to experience and reflect on material properties in conjunction with the machine behavior. The design of this activity draws from hands-on activities aimed to foment explorations with materials and forms of making [20]. We designed two activity sheets: one with an X-Y coordinate system and one with a simplified linear movement section of a G-Code with blank spaces for students to fill in coordinate values. Participants were asked to draw a closed shape on the X-Y coordinate

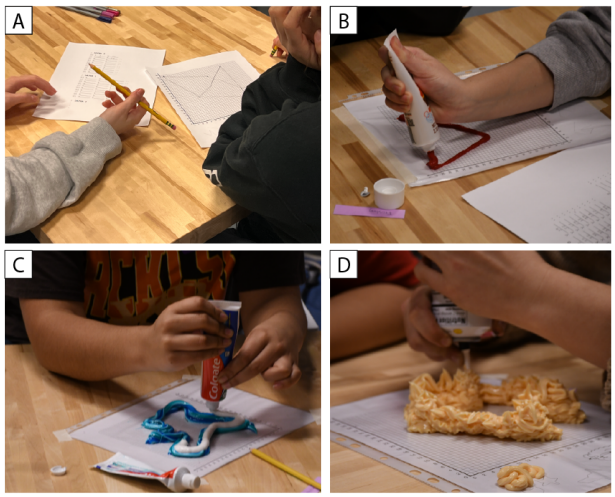


Figure 4: Through the acting as the machine activity, we aimed to familiarize students with toolpath, nozzle, and material behavior concepts. (A) Participants completed two worksheets where they drew a closed shape, extracted its coordinates, and used them to create a simplified version of a linear movement section of G-Code. Students then traced their shapes using (B) cake frosting, (C) toothpaste, and (D) spray cheese. They followed their toolpath to construct a 3D shape with the maximum number of layers.

activity sheet with no more than ten segments. They extracted the coordinates of each point and used them to fill in the missing coordinates of the G-Code (in the second activity sheet). Then, we provided students with frosting tubes, toothpaste, and spray cheese. These materials presented ideal properties for quick iterations and low-risk explorations (Figure 4). Participants were instructed to extrude along the segments of their shape to stack as many layers as possible along the Z-axis. This activity lasted 40 minutes. During the last minutes of this activity, we encouraged students to think about the differences between the materials used. We also asked students to reflect on the size of the nozzle of each material extruder and what behaviors we should expect if the nozzle size increases or decreases.

6.3 Day 2 – Slider-based learner-oriented CAM-based design software & clay 3D printing

We initiated our activity with the intention of introducing students to the CAM-based design workflow. We aimed to introduce the CAM-based design tool they would use and explain the concepts they needed to create their intended designs successfully. We used two expert-oriented CAM-based design tools as the foundation of our tool: PunchPrint[19], a parametric design tool to design 3D-printed textiles compatible with punch needle embroidery, and CoilCAM [8], a system that enables the design of 3D-printed clay artifacts through mathematical toolpath operations. These CAM-based design tools offer close connections to established manual craft practices. PunchPrint and CoilCAM were developed with the

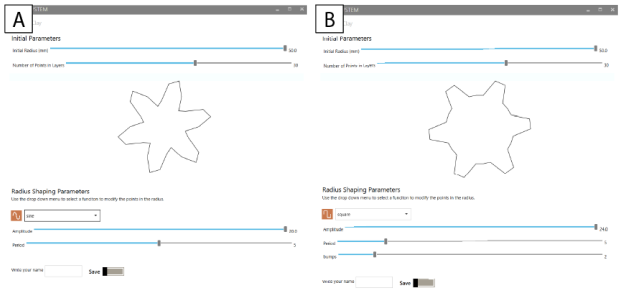


Figure 5: The interface for designing the textile offers the opportunity to engage with four radius shaping parameters that greatly impact the form of the textile: waveform type, amplitude, period, and bumps. Participants start their textile design with a circle. (A) Opting for a sine wave pattern creates smooth curves, whereas (B) employing the square wave with the same amplitude values produces sharper curves.

Rhino CAD software and Grasshopper programming language; as a result, they require numerical text entry and proficiency in the Grasshopper visual programming interface.[1] We created a slider-based interface (Figure 5) with the HumanUI plugin [30] within Grasshopper to address challenges identified in navigating Rhino and Grasshopper software during our preliminary study (4.3). The purpose of this interface was to mitigate the learning curve for students new to CAD and visual programming. This modification allowed students to dedicate more time and attention to designing artifacts, minimizing the complexities associated with software navigation. The interface has two tabs for controlling the parameters of textile and clay designs. Both designs are done following the mathematically defined operations of CoilCAM. We generated one layer of toolpath in CoilCAM to be used as the PunchPrint fabric's 2D outline. [2] Our objective was to allow students to design a variety of textile and clay artifacts using the concepts of layer manipulation that we covered on Day 1. We aimed to support participants' explorations and creativity while ensuring all outcomes could be successfully printed. Students began by designing the textile. They controlled six parameters to edit the fabric's size and overall shape (Figure 5A). Students could design geometrical shapes, from triangles to circles, and edit them using the radius shaping parameters of CoilCAM to create irregular shapes (Figure 5B-C).

Next, students proceeded to design the clay artifact. While the textile design was visualized within the interface, the visual feedback for the clay vessel was provided in the Rhino viewport. The general workflow for crafting the clay artifact involved four steps, with no specific order. Firstly, participants adjusted the three initial parameters: size, the number of layers, and the number of points per layer (Figure 6A). They then modified the radius shaping parameters, similar to their approach with the textile (Figure 6B-C). Viewing the artifact from a top perspective could be helpful. Subsequently, students adjusted the scale and rotation of each layer. We told students to explore all the parameters until they reached a

[1]We are currently developing a JavaScript web-based version of CoilCAM to enhance the accessibility and usability of the software's core functionalities for future users.
[2]For more information about CoilCAM JavaScript Library, visit www.coilcam.com.

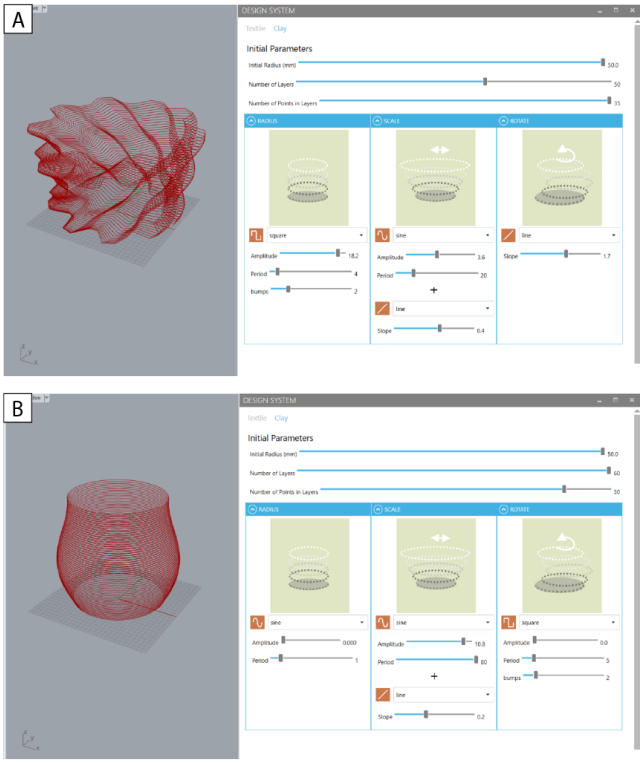


Figure 6: The interface for designing the clay artifact was divided into four main sections: initial parameters, radius, scale, and rotation. All participants started with a predefined cylindrical shape. The range of available parameters allowed students to create various shapes. For instance, (A) one student opted for a textured and intricate design, while (B) another student expanded the initial parameters to create a smoother, more traditional-looking artifact.

design they enjoyed, which prompted them to consider the artifacts' function and design characteristics. Participants spent 50 minutes designing both artifacts.

Following the design session, we demonstrated clay 3D printing to the group by printing one student's design on a Potterbot Super 10. During the allocated 75 minutes, we printed a series of designs. Throughout this session, every student was engaged in some clay-related activity: watching the printer, making small figures with extra clay, trimming around the bases of printed pieces, and discussing clay printing technology.

6.4 Day 3 – Creating a continuous path activity to introduce toolpath design

We began our activity intending to reinforce the concept of toolpath. We also aimed to showcase the diverse opportunities of CAM-based design and introduce ways it enabled new forms of textile production and interactions. Our objective was to enable students to explore path planning from a tangible craft perspective instead of an algorithmic approach. We provided students with an activity sheet and highlighter pens. We instructed them to explore possible

paths of filling the inside of a cloud and a star, raising the pen as little as possible. They started at the center of both shapes and then decided the most optimal direction to progress (Figure 7A). This activity has a duration of 15 minutes. At the end of the activity, students were asked to reflect on the advantages and disadvantages of their paths, particularly focusing on how their paths could affect their design decisions.

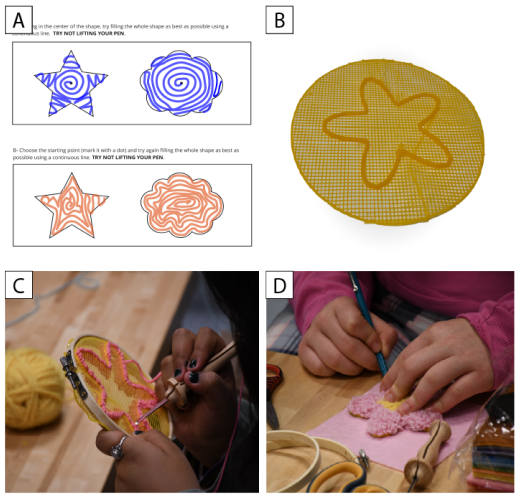


Figure 7: Through the continuous path activity, we aimed to reinforce the concept of toolpath design and establish its connection with the manual craft workflow of punch needle embroidery. (A) Initially, students worked on a worksheet, exploring various paths to fill a closed shape without lifting the marker. (B) Following that, students interacted with the 3D-printed fabric they had designed, and (C) received instruction on punch needle techniques. (D) Students employed diverse strategies in designing and completing their punch needle pieces.

6.5 Day 3 – Learning punch needle embroidery

We introduced students to punch needle embroidery, which parallels toolpath programming. Like CAM designers who plan and optimize machine toolpaths, punch needle practitioners plan the trajectory of yarn for specific designs and textures. This activity aimed to give students the knowledge and capability to use punch needle embroidery to create a finished embroidery design. We provided students with the 3D-printed fabric they had previously designed (Figure 7B). Offering a variety of colors, students were told to punch needle their fabrics while thinking about how this item would interact with their clay 3D-printed vessel. Students dedicated 90 minutes to learning punch needle embroidery techniques and completing their final textile pieces.

7 LIMITATIONS

While our curriculum and workshop showcase the potential for involving young people in CAM-based design through a project-based craft approach, a more longitudinal study is essential to thoroughly explore our curriculum's impact. Our evaluation primarily focuses on assessing the participants' ability to apply CAM-based design concepts to create and fabricate artifacts. Moreover, comprehensive strategies and methods to evaluate actual learning depth and knowledge retention are lacking. Furthermore, our curriculum simplifies CAM-based design through a slider-based interface, limiting engagement in symbolic programming and thus reducing exposure to crucial programming and computational skills associated with CAM-based design. While our study did not experience this issue, it is important to emphasize that 3D printing with TPU and clay carries an inherent risk of print failures, which could potentially disrupt planned timelines. Additionally, while the hands-on activities do not depend on specialized technology and are easily reproducible, we recognize that access to both our CAM-based software and clay 3D printers may be limited in certain educational settings.

8 FINDINGS

This section highlights key findings from hands-on activities, final projects, and participant attitudes. Preliminary activities showcased diverse layer-based design explorations with positive feedback. Final projects demonstrated the successful use of the slider-based interface for creating varied clay and textile artifacts.

8.1 Preliminary activities outcomes

During the cardboard activity (Section 6.1), participants reflected on the different approaches for building a 3D object layer by layer. Participants' outcomes show their explorations of concepts like overhangs (Figure 8A) and rotation (Figure 8B). Students shared on a post-survey that the activity was enjoyable. One participant shared during a group discussion:

> *I enjoyed being able to experience everything hands-on and using my own ideas in our builds. The most challenging thing was designing something stable.* (Participant 6)

During the following activity (Section 6.2), participants created 3D shapes from frosting, toothpaste, and spray cheese. The outcomes of this activity were meant to be temporary due to the non-structural nature of the used material. Therefore, the shapes were thrown out after the activity and reflection session since most of them melted over time.

Participants indicated during a group discussion the *acting as the machine* activity aided in their understanding of how 3D printers worked and the relationship between the nozzle, the material, and the toolpath (Figure 4). One participant shared:

> *Although it was cheese, I think it helped us understand what different pressure and [nozzle] size could do.* (Participant 6)

In addition, this activity supported the punch needle embroidery design process. A participant shared during a group discussion:

> *I found the last [activity] really effective for when we actually started to punch needle. We could use what we learned when we drew on the paper to make the path of where we were going with the yarn.* (Participant 5)

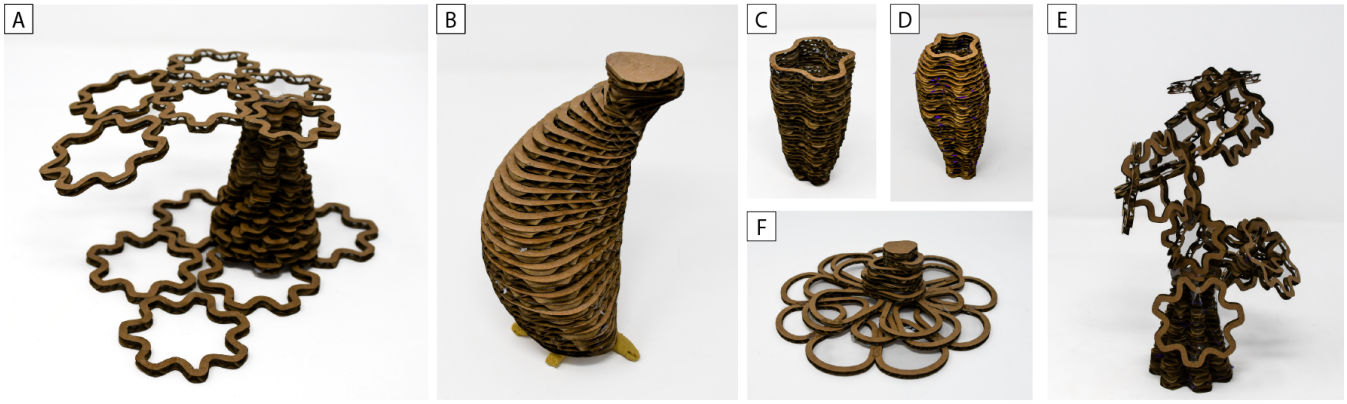


Figure 8: Without any specific design instructions, students explored crucial concepts in layer-based design and additive fabrication, like overhang and layer transformations. All participants created different artifacts regardless of having repeated forms, demonstrating the capacity for diversity and the potential to include additional key concepts to this activity.

8.2 Final project outcomes

During the discussion, students expressed how the 'Creating a continuous path' activity influenced their punch needle final designs. They emphasize how the activity supported a quick assessment of optimal paths they could create to give their designs the desired look and reduce time and effort during the punching process.

Furthermore, participants used the slider-based interface (CoilCAM and PunchPrint) to design and produce diverse and robust clay and textile artifacts (Figure 9). The ceramic pieces have unique textures, sizes, and shapes. Some students coordinated design choices between their textile and ceramic pieces, aiming to use the punch needle pieces as coasters. The clay pieces were fired and glazed based on the colors that participants selected. During a group discussion, all participants indicated an intent to use their artifacts as decorative or functional pieces.

8.3 Participant experience

We report on survey responses and discussion topics to describe participants' experience on workshop subject matter, software use, and project outcomes.

8.3.1 Attitudes towards the workshop. In the post-survey, which received 11 responses, participants overwhelmingly expressed their positive sentiments about the workshop. All participants indicated that they liked (or even loved) various aspects of the program. These included lecture sessions, interactive activities, using the design interface, and the opportunity to learn about clay 3D printing and punch needle techniques. Overall, participants found the activities easy to follow, except for one individual who found learning punch needling somewhat challenging. In terms of the duration of each activity, responses varied. Most participants felt that the length of most activities was "just right." However, four participants found the lecture sessions too lengthy, and an equal number believed the clay 3D printing demonstration was too short.

8.3.2 Participants' reactions to the slider-based design software. In a post-survey, all the participants agreed that the design tool was easy to use and helped them iterate through design alternatives easily. Except for two participants, the rest of the students reported understanding how the sine and square mathematical functions affected their design. Furthermore, one participant also expressed frustration about the constraints of some sliders and the lack of aid for visualizing the object's dimensions.

8.3.3 Participants' reactions to their textile and clay outcomes. In the final survey, all participants indicated they were happy with their clay and textile artifacts. One participant shared in the post-survey:

> *I liked being able to make tangible objects that will last for a long time and be useful.* (Participant 8)

All participants learned to punch needle using the 3D-printed fabrics. Many participants indicated during a group discussion that they enjoyed learning the technique and felt they could be creative with it:

> *I thought it was fun. It was easy, and when you messed up you could just fix it. It wasn't that hard. I would do it again. It was easy for beginners, and I feel once you get really good at it, you can do as many things as you'd like.* (Participant 3)

Students could transfer the skills learned in this activity to doing punch needle embroidery. A student with previous experience doing punch needle embroidery mentioned:

> *I found it much easier than using actual fabric, because you could still put it on the embroidery loop, and it was tight enough so you could do it like that, but you can also do it without that. And with fabric, you have to have it on something to make it tight and then sometimes it'll get too loose. And I also thought the grid pattern on it was easy to see.* (Participant 5)

During our curriculum, we also embraced the sense of community that crafts create. We paired students in every activity and observed how they actively collaborated and discussed their design decisions.

> *When we were doing the punch needle, I think I kind of felt peace of mind because I was just focusing on doing*



Figure 9: All participants successfully created unique ceramic vessels and punch needle artifacts. These outcomes demonstrate the capability of our curriculum and software to support creative expression.

> *that. So, I feel like I would apply some of that craft to my life. I think doing it with other people, like your friends, can be fine because if someone's struggling you could laugh it off and then just help each other. So I think as a group, it'd be great and fun.* (Participant 3)

9 DISCUSSION

In this section, we delve into the impact of our hands-on activities on young learners' understanding of CAM-based design and digital fabrication. We highlight the effectiveness of analog design exercises, the meaningful integration of crafts, and the potential for reduced dependence on general-purpose CAM software.

9.1 Introductory hands-on activities for conceptual learning

This subsection shows how our hands-on activities supported approachable and ease of use. Additionally, we will discuss two key activities: the 'Cardboard activity' and the 'Acting as the machine' activity, demonstrating their benefits, opportunities for expansion, and associated challenges.

In our curriculum design, we sought to scaffold student engagement with key concepts and constraints of additive fabrication through hands-on activities with physical materials (DG1). Our findings suggest that it is feasible to introduce design and fabrication concepts without computers, utilizing hands-on activities that depend on accessible and relatable materials. This suggests that hands-on learning about digital fabrication is possible without investing in digital fabrication technologies or software licenses. Instead, only minimal financial investment may be required, making it more feasible for educational institutions with limited resources. Our findings share similar characteristics with CS unplugged activities[16, 65], reducing the dependency on technology for learning and engaging with technological skills Moreover, using materials and techniques that are familiar and relatable to young learners can make digital fabrication more approachable and inclusive. This approach reduces the requirement for domain-specific knowledge and experience from the instructor and the participant. During the workshop, we noticed how using familiar materials boosted students' engagement, confidence, and creativity, enabling them to explore design and digital fabrication concepts more effectively. The hands-on activities featured in our curriculum share similarities with Devendorf's work [20], which explores the intersection of craft and digital fabrication, emphasizing embodied experiences in the making. While Devendorf's work centers on discerning the roles of the machine and how different materials affect these roles, our approach aims to enhance our understanding of 3D printing functionality through hands-on explorations. Moreover, as noted by Chan and Blikstein [14], project-based learning can

Table 1: Our curriculum encompasses three days of active student engagement, featuring hands-on activities in basic additive fabrication, toolpath design, and CAM-based design. Additionally, students interact with slider-based learner-oriented software to design a 3D-printed textile and clay vessel.

Activities	Duration	Goals	Materials
Day 1 – Cardboard activity	30 mins	• Introduce students to additive fabrication and its relationship with layer-based design. • Allow students to explore the design process of layer-based additive fabrication and layer manipulation.	• 2D laser-cut cardboard • glue sticks
Day 1 – Acting as the machine activity	40 mins	• Introduce the concept of toolpaths. • Provide a brief overview of how toolpath's mathematical data is encoded into G-code. • Allow students to experience and reflect on material properties in conjunction with the machine behavior.	• frosting tubes • toothpaste • spray cheese • X-Y coordinate activity sheet • G-Code linear movement activity sheet
Day 2 – Slider-based learner-oriented CAM-based design software	50 mins	• Introduce the CAM-based design tool and connect layer transformation concepts previously explored.	• CAM-based design tool
Day 2– Clay 3D printing	75 mins	• 3D print student's designs. • Allow students to observe and participate in 3D printing their design.	• clay • clay 3D printer • design files
Day 3 – Creating a continuous path activity	15 mins	• Reinforcing the concept of toolpath. • Showcase the diverse opportunities of CAM-based design in textile design and production.	• activity sheet • markers with a chisel tip
Day 3 – Learning punch needle embroidery	90 mins	• Introduce students to punch needle embroidery techniques and best practices. • Allow students to design and craft punch needle textile artifacts.	• punch needle • yarn • scissors • embroidery hoop • fabric (3D printed fabric)

enhance student engagement and learning outcomes, but it may also require extensive teacher training and support. This led us to develop thorough documentation that is accessible to anyone, regardless of prior experience, to facilitate the workshop effectively.

Our research indicates that the hands-on activity, the 'Cardboard activity' (section 6.1), offers a modular and versatile quality that makes it an effective tool for fostering creativity and exploration for youth. Each cardboard piece could be easily stacked in various configurations, allowing for endless possibilities in creation. Hence, students could readily engage in iterative design processes without facing permanent consequences, allowing for exploration in many positions and order. The modular nature of the activity provided a supportive environment for students to unleash their creative skills as designers. Students demonstrated their understanding of the intended concepts, such as layer-by-layer construction, rotational transformations, overhangs, and support structures in their designs, as illustrated in Figure 8. By grasping these concepts, students can design and fabricate more effectively, ensuring their creations' stability, functionality, and integrity. A deeper understanding of these concepts also empowers students to explore more complex design challenges and expand their creative horizons.

Furthermore, our findings indicate that the 'Acting as the Machine' activity (section 6.2) effectively enabled participants to explore essential concepts of digital fabrication and CAM-based design. By manually controlling various everyday materials with "nozzles", participants engaged in hands-on experimentation with concepts such as extrusion, extrusion rate, extrusion velocity, and materiality. We suggest expanding the range of materials used in this activity to simulate the experience of 3D printing with clay, where adjusting the clay's consistency by adding water is a common practice. One option could be pancake mix, which allows participants to finely adjust the liquid-to-powder ratio and explore how it impacts their designs through iterative experimentation. Furthermore, we propose incorporating a brief discussion session after completing the activity sheets (Figure 4A) to enhance participant engagement. We observed lower levels of engagement during this phase, likely due to its limited hands-on exploration and interaction opportunities. This observation prompts us to reassess both our

teaching methodology and the design of the activity sheets. We emphasize the importance of student engagement with these sheets as they serve as a gateway to introducing the mathematical aspect of toolpaths and how such information is conveyed in the G-code. In summary, we carefully designed hands-on activities that allowed students to interact directly with physical materials, guiding them through experiences that gradually introduced and reinforced key concepts and constraints of additive fabrication. We provided hands-on experiences aligned with the principles and processes of additive fabrication while ensuring the learning progression is scaffolded to support student's understanding and skill development.

9.2 Craft's role in empowering and accomplishing CAM-based design

In this subsection, we emphasize the meaningful intersections we identified between CAM-based design and arts and crafts activities for youth. We discuss how toolpath design can be taught through punch needle embroidery, identifying similarities between punch needle design processes and toolpath design in CAM. Additionally, we highlight the implications of this exploration, such as the manual exploration of toolpath design strategies without the need for software. We also examine how expanding students' understanding of the craft can create more complex and beautiful artifacts.

In our curriculum design, we aimed to establish meaningful intersections between CAM-based design and arts and crafts activities for youth. Our research indicates that students can be effectively introduced to the toolpath design concept through punch needle embroidery's needlecraft technique. We've identified significant parallels between the design processes involved in punch needle embroidery and CAM toolpath design. In the 'Creating a Continuous Path' activity (section 6.4), students utilized an activity sheet, shown in Figure 7A, to actively explore design strategies that would generate the most continuous and efficient path. In clay 3D printing, toolpath planning is vital as it directly influences not only the visual outcome of the printed object but also its structural integrity and overall quality. In punch needle embroidery, the path chosen can determine the unique aesthetics of the design. Understanding toolpath design empowers designers to optimize clay deposition, minimizing waste and ensuring structural integrity. For youth new to digital fabrication, mastering this skill provides essential foundations, boosting confidence in crafting intricate designs.

During this curriculum, we also sought to contextualize CAM-based design by creating functional applications connected to professional fabrication. Both clay 3D printing and punch needle embroidery offer rich opportunities for crafting, presenting numerous project possibilities. Our findings indicate that beginners can successfully undertake projects such as creating vessels and coasters in both mediums. This insight suggests that young learners can effectively engage in practical projects in clay 3D printing and punch needle embroidery while developing fundamental skills. Although our design approach did not rely on symbolic programming, these findings resonate with research on CAD-based computational fabrication methods for middle school students [34] and computer science undergraduates [9]. Jacob's work demonstrates that young individuals can craft sophisticated computer-generated items such as garments, accessories, and other personalized creations, showcasing their unique style preferences. Our curriculum provides a different approach to supporting similar benefits.

Our curriculum design also strives to support students in producing unique and beautiful artifacts through CAM-based design (DG4). While designing and fabricating punch needle textiles and ceramic 3D-printed pieces is intricate, the results from our workshop showcase that young individuals can produce distinctive forms, textures, and functionalities (Figure 9). This suggests a correlation between their impressive final outcomes and the effectiveness of our curriculum in equipping students with the foundational knowledge, skills, and tools needed to proficiently engage in digital fabrication and CAM-based design. Upon examining the participants' final ceramic and punch needle pieces (Figure 9), a rich array of design choices and personal touches emerges, evident in the variation of shape, color, motifs, and texture. For the punch needle artifacts, most design decisions occurred independently of the design software. Students freely explored options for yarn colors, patterns, and stitch styles. For example, one student spontaneously crafted a butterfly from shapes resembling a butterfly despite not intending to do so initially. Similarly, a different student utilized the flat side of the punch needle textiles to craft a logo inspired by a favorite show, leveraging the surface to achieve a higher definition for linear designs. On the other hand, students had less manual control over their ceramic designs. However, our design tool allowed for quick iterations within a constrained parametric space, so they crafted unique ceramic artifacts without fully mastering Grasshopper and our system. To expand the range of design choices beyond software constraints, we suggest enhancing physical interactions with their 3D-printed clay artifacts. This might include adding handles or carving textures, promoting deeper creative engagement. Such manual crafting opportunities can shift design agency away from software reliance. The outcomes of this integration suggest that craft practices can play a larger role in youth engagement with digital fabrication technologies and CAM-based design. For instance, aside from including craft as a way to motivate craft-oriented youth or as personalizing projects, craft techniques can effectively immerse youth in comprehending CNC machine behavior by exploring the craft's inherent design methods. In summary, we purposefully chose punch needle embroidery due to its similarities with toolpath design. Engaging in this craft design practice, students gained a deeper appreciation for the significance of effective toolpath design. Supported by our curriculum, all participants successfully crafted ceramic vessels and punch needle coasters, showcasing a range of shapes, colors, and textures.

9.3 Engagement with CAM-based design without general-purpose CAM-based design software

In this subsection, we explore the implications of simplifying complex CAM-based design tools and offering restricted parameters that significantly impact participants' design capabilities. While our primary focus wasn't on creating new software tools for young designers, insights from our preliminary study and CAM-based design tool shed light on considerations for developing youth-oriented CAM-based design systems.

Our tool design aimed to reduce the need to rely on general-purpose CAM-based design technologies (e.g., symbolic programming) while still providing young students with a design agency (DG5). Our findings demonstrate the feasibility of engaging young students with CAM-based design tools for textile and clay design through a slider-based interface scaffold. This approach facilitated positive and efficient interactions with the design tool, contrasting notably with the preliminary study outcomes described in section 4, where adult participants expressed frustration and lacked enthusiasm for exploring the tool. While slider-based interactions are renowned for their benefits, our findings present exciting opportunities for involving youth with additional innovative and expressive CAM-based design tools like those presented in section 2.3. This would broaden opportunities for youth engagement in CAM-based design and contribute to ongoing efforts to make CAM software more accessible to design and fabrication novices.

Moreover, our curriculum showcased similar design qualities to those observed in the preliminary study. For punch needle artifacts, most design decisions were made independently of the software, with students freely exploring options for yarn colors and stitch styles. For instance, one student spontaneously crafted a butterfly from shapes resembling one. At the same time, another created a logo inspired by a favorite show, leveraging the surface for higher definition in linear designs. Furthermore, our design tool allowed for quick iterations within a constrained parametric space, supporting participants in crafting unique ceramic artifacts without needing full mastery of Grasshopper and our system (see Figure 9). To expand design choices beyond software limitations, we suggest enhancing physical interactions with their 3D-printed clay artifacts or after the piece is printed. This could involve adding handles or carving textures, encouraging deeper creative engagement, and shifting design autonomy away from software reliance.

While our study highlights the benefits of simplified digital fabrication design tools for young learners, it underscores the importance of preserving transparency in the fabrication process. Our systems engaged students with concepts like layers, layer transformations (e.g., scale and rotation), and the number of points in a layer, which they found valuable for achieving desired outcomes. We advocate for CAM-based software that, while less feature-rich than professional tools, maintains transparency rather than fully automating and obscuring the fabrication process.

10 CONCLUSION AND FUTURE WORK

Digital fabrication offers numerous opportunities for youth to express their creativity. While many youth-centered activities and software focus on CAD-based design, we believe there are advantages to engaging youth with CAM-based design instead. However, introducing youth to CAM can be challenging due to its abstract and technical nature. In response, we have developed a craft-oriented curriculum designed to introduce key CAM-based design concepts through a series of interactive hands-on and craft activities. These activities are aimed at fostering inquiry, creativity, and expressiveness. Using a slider-based interface, students successfully designed and fabricated 3D-printed ceramic pieces and textiles adorned with punch needle embroidery. Our preliminary findings demonstrate the feasibility of engaging high-school students with CAM-based design concepts and digital fabrication through screen-free activities. This paves the way for the creation of intricate design tools. Looking ahead, we envision expanding our methodology to incorporate other craft-originating domains in digital fabrication, such as weaving and knitting, to further enrich young people's manual and digital learning experiences. Furthermore, we advocate for the development of CAM-based software tailored for young users. Such software should strike a balance by providing a simplified set of features compared to tools for professionals while maintaining transparency in the fabrication process. By providing young learners with this type of software, we aim to empower them with design agency and facilitate a smoother transition into the world of digital fabrication. Future iterations should consider integrating programming and the creation of youth-centric CAM software, bridging the gap between professional techniques and meaningful youth design activities.

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