PROJECTABLES

Augmented CNC Tools for Sustainable Creative Practices

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Abstract. CNC cutting machines have become essential tools for designers and architects enabling rapid prototyping, model-building and production of high quality components. Designers often cut from new materials, discarding the irregularly shaped remains. We introduce ProjecTables, a visual augmented reality system for interactive packing of model parts onto sheet materials. ProjecTables enables designers to (re)use scrap materials for CNC cutting that would have been previously thrown away, at the same time supporting aesthetic choices related to wood grain, avoiding surface blemishes, and other relevant material properties. We conducted evaluations of ProjecTables with design students from Aarhus School of Architecture, demonstrating that participants could quickly and easily place and orient model parts reducing material waste. Contextual interviews and ideation sessions led to a deeper understanding of current work practices and sustainability issues with CNC cutting-machines, and identified useful features for interactive packing to reduce waste while supporting aesthetic concerns for exhibition quality design projects.

Keywords. CNC cutting; sustainability; digital fabrication; visual augmentation.

1. Introduction

In recent years, digital tools have revolutionized the field of architecture from parametric modeling in CAD, form acquisition using spatial scanning, and construction of functional components in 1:1 scale using CNC fabrication machines

(Picon 2010). Large format cutting using laser, knife, and waterjet have become basic tools for model building, exploration of form, and construction of formworks. Architects are expected to demonstrate a fluency in customizing and even creating digitally enhanced tools and processes whether to develop new visual expressions or new construction methods that support goals of sustainability in the workshop (Fleischmann et al. 2016; Kolarevic 2001). Design schools and architecture studios represent a unique user group of digital fabrication tools - the individual jobs vary tremendously, the level of finish is often very high, and work practices such as rushing to meet deadlines for public exhibitions result in huge amounts of waste. The 'whatever it takes' attitude frees the designer in some ways, however, in most craft professions such as woodworking, weaving, metalworking, the conservation of expensive material is ingrained into the learning process. There is an increasing demand in the design fields to support sustainable practices (Beorkrem 2012) through the development and customization of digital fabrication tools. Including designers and architects in the design process of digital fabrication tools offers the benefit of developing sustainable solutions that fit appropriately into the existing practices and potentially reveal unmet needs (Sanders and Stappers 2008). A typical approach in architecture and design schools for learning and disseminating skills with new digital fabrication tools involves holding workshops to guide students through a project (Merritt & De Azambuja Varela 2014) with a constrained design case that incorporates learning by doing. Often the learning outcomes involve reflection on the frustrations, constraints, and idiosyncrasies of the software and hardware (Seely 2004; Varela & Merritt 2016).

We introduce ProjecTables, a visual augmented reality system for sustainable reuse of sheet materials on CNC cutting machines. The design of ProjecTables has been informed by an investigation into the current practices of design students at Aarhus School of Architecture when using CNC cutting machines. Concretely, users can interactively pack a 2D CAD model on one or more sheet materials on the work surface of the CNC machine or on a separate table away from the CNC machine. The system uses an overhead projector, which superimposes the 2D CAD model on the sheet materials, and a traditional mouse for manipulating the model. The system allows for reuse of irregularly shaped sheet materials that would previously have been thrown in the trash, reduces the idle preparation time at the CNC cutting machines by using a separate table for packing the CAD model on the materials, and supports designers in making aesthetic choices related to wood grain, avoiding surface blemishes, and other relevant material properties. Figure 1 and this short video demonstrate the system in use (Rasmussen et al. 2016). We conducted evaluations of ProjecTables with design students from Aarhus School of Architecture, demonstrating that participants were able to quickly and easily place and orient model parts on scrap materials thereby enabling reuse and reduction of material waste. Furthermore, contextual interviews and ideation sessions with these design students revealed issues with current work practices and unsustainable use of the CNC cutting-machines at the school, and identified new useful features for interactive packing to reduce waste while supporting aesthetic concerns for exhibition quality design projects.

Figure 1. *ProjectTables process flow: a) scrap material is found, b) designer places the scrap material on the ProjectTables preparation table to scan the contour or c) directly on the CNC cutting surface d) CAD model parts are projected on the material for position adjustment, d) model parts are cut by the CNC cutting machine, e) resulting model is built.*

2. Related Work

Subtractive techniques in fabrication usually result in material waste, driving architects to explore strategies of waste reduction while maintaining high aesthetic value. In the Umwelt Arena, architects designed the interior and exterior balustrades to be produced from a single sheet material such that all parts become elements in the construction with no material waste (René Schmid 2012). While zero waste may be a design ideal, it is important that the tools remain flexible to support the variety of challenges and ways of working in design studios. The work presented in this paper builds upon recent research on digital fabrication tools, interactive fabrication that brings the designer closer to the act of fabrication, and interactive packing using visual augmentations to assist in positioning CAD model parts on fabrication materials.

There has been some exploration into closing the physical gap between the digital fabrication tools and the crafted object, bringing the designer's hand closer to the moment of fabrication. Sharing some of the aims with the framework of Direct Manipulation (Schneiderman 1983), prototypes presented as explorations in Interactive Fabrication (Willis et al. 2011) investigate opportunities for real-time input to digital fabrication tools in the creation of physical form. These prototypes place the designer in more direct interaction with shaping the material and building upon the emerging form. In order to deal with the unpredictable results of free-hand, interactive digital fabrication, Interactive Construction (Mueller et al. 2012) maintains the step-by-step design process of interactive fabrication, but introduces geometric constraints to the drawing tools enabling users to take advantage of the precision of CNC machines to construct functional mechanical devices. Olwal et al. augment a CNC machine with real-time data on occluded tools and processes using a transparent holographic optical element, overlaid onto the safety glass (Olwal et al. 2008). Saakes et al. introduce the concept of interactive 2D packing of CAD models for effective material reuse on CNC cutting machines (Saakes et al. 2013). Sakes et al. evaluate a set of interaction techniques for interactive 2D packing using a prototype, PacCAM, which consists of an overlooking camera, which captures the sheet materials on the CNC cutting bench, and a nearby screen-based interface, wherein the CAD model is visualized and manipulated on top of the sheet materials. Visually augmenting the physical surface of a sheet material with a CAD model by use of a projector has been explored in low fidelity prototypes by (Winge et al. 2014). In that research focused on designers as users,

and feedback from the users suggest that such visual augmentations can be helpful for positioning model parts for cutting and that the familiarity of the standard mouse provides a simple input modality for moving and placing model parts. The present paper extends the work on interactive 2D packing and visual augmentations of CNC machines, by exploring visual augmentations of 2D CAD models directly on sheet materials to be cut. Our aim is to support practices that are more sustainable through a reduction in material use while enabling aesthetic practices and techniques within the creative context of a school of architecture.

3. Current practices

We conducted an initial inquiry involving observations and contextual interviews at Aarhus School of Architecture, which identified three main issues that design students encounter using the CNC cutting machines at the school: 1) Reuse of scrap materials is difficult, 2) students need to make design choices based on the properties of the materials, 3) waiting to use the CNC cutting machines can involve long delays during busy periods. We address these issues in the design of ProjectTables.

3.1. MATERIAL REUSE

Observations in and around the workshop at the architecture school revealed that students usually nest their CAD model parts into a tight rectangular shape in the CAD software, and they try to place this rectangular shape of model parts as close to the edge of the sheet material as possible to optimize material use. Some students use tape to align the CNC workbench and material to ensure alignment of the rectangular shape to the material. However, when nesting on a scrap material they rarely take into account its shape and cutouts, which results in a nested rectangular shape of model parts that are placed sub-optimally, making the scrap material even more difficult to reuse after the cutting job.

Likewise, observations revealed various material scraps were thrown out including pieces with large uncut regions as shown in figure 2. Students rarely make attempts to reuse scrap material if the remaining piece is small or irregularly shaped for a variety of reasons.

Figure 2. Scrap materials found in the workshop dumpster and waste bins at the school of architecture: a-e) large areas of uncut material with a notable tendency for cutting to take place around the edges and corners, f) & g) scrap material with difficult to use uncut regions.

Industry-standard CAM software has no knowledge of the size, shape, or appearance of the scrap material on the cutting bench, and thus the CAM software cannot provide direct visual information to the student on where to place her CAD

model within the material bounds, making reuse a difficult and time-consuming task. Also, students often make one-off models. This means that a student will buy a new piece of sheet material such as medium density fiberboard (MDF), use a portion of it for a project, and then store the rest for later in her workspace or office. However future projects may require different thicknesses and types of materials. Therefore, over the course of a school year a student will accumulate a lot of different scrap materials from different projects, until a decision is made to throw them out because they either take up too much space or are too damaged from being moved around. When students occasionally do attempt to reuse a scrap material, it is typically during project deadlines, when no new materials are available, or when the material is very expensive.

3.2. USING MATERIAL PROPERTIES AS DESIGN CONSTRAINTS

Our contextual interviews showed that the students' attention to material properties - such as smudges, holes and burned edges - is almost instinctive and that the importance of the appearance of a model depends on its design purpose. The appearance of a model used internally in the design process is not as important as the appearance of exhibition models. For instance, for a model that is going to be exhibited it matters that interlocking parts with a texture, such as wood grain, are oriented in the same direction or following a consistent strategy. Similarly, waste cardboard has been elevated to a precious material for designer lamps (Graypants 2016), which utilize alternating orientation of cardboard layers to provide an attractive play of light. For a quick and dirty model, scrap materials can be used because any small holes or burned edges in the material do not necessarily matter. Additionally, when using a wooden material, the direction of the grain on some model parts matters for a functional reason, as the strength of the parts may depend on it. For instance, a long rectangular part of veneer with the grain going in the opposite direction of its length may easily break when handled.

3.3. WAITING TO USE THE CUTTING MACHINES

During the contextual interviews, the students told us stories of how the line of users waiting to use the CNC cutting machines would sometimes close to project deadlines be so long that they would have to wait for days to get access to the machines. Students spend a large portion of the total time of a cutting job on preparing the job - placing the CAD model correctly on the material and assigning tools to the paths of the model - at the CNC cutting machine (Winge et al. 2014). During this time the machine is idle. However, if the machine could be cutting during the preparation of cutting jobs, this would reduce the line to the CNC cutting machine.

4. Design of Projectables

It is evident from the accounts of current practices that the way students currently manage scrap materials involves haphazard and ad hoc strategies, thus in the design of Projectables we address the identified issues with the mission of supporting designers toward more sustainable digital fabrication tools and practices.

The ProjecTables system consists of two main parts: the preparation table and the cutting bench of the CNC cutting machine. Each provides a planar surface where the user, the designer or design student, places sheets of materials they want to prepare for cutting.

Initially, the user prepares a CAD model for fabrication on one or more materials at the preparation table, a normally sized table dislocated physically from the CNC cutting machine. The user does so by placing materials arbitrarily on the preparation table and telling ProjecTables to capture the material contours with the overlooking camera. ProjecTables provide feedback on the capturing process by superimposing the material contours on top of the physical materials using the projector. The user then opens up a CAD model and ProjecTables superimposes the model on the materials in 1:1 scale using the projector. The user may select, translate and rotate parts of the model to manually pack the parts within the materials, using a mouse as input device. When the user is satisfied with the placement of the model parts, she tells ProjecTables to save the material/model configuration. Thereby ProjecTables saves the position and rotation of the model parts on the materials in the cloud. The user picks up the materials from the preparation table, transitions to the CNC cutting machine and throws the materials arbitrarily on the cutting bench. She tells ProjecTables to capture the material contours using the overlooking camera. Then, ProjecTables looks for a match between the current materials on the cutting bench and previously saved materials from the preparation table. If a match is found, the position and rotation of the model parts are restored from the cloud and superimposed on the materials. The matching takes approximately 5 seconds. If the user is still satisfied with the placement of the model parts, she can confidently start the cutting process. However, if the user would like to alter the placement of one or more model parts, this is possible before cutting, again using a mouse as input to manipulate the model parts. Finally, the user starts the cutting process, and the model parts are cut out directly where they are superimposed on the materials.

The hardware of ProjecTables currently consists of one preparation table and one CNC cutting machine. The preparation table consists of a table, an overlooking projector, an overlooking camera, a computer, and a mouse for manipulating model parts. The table is coated with a dark gray matte paint suitable for projection. The CNC cutting machine is likewise rigged with an overlooking projector, an overlooking camera, a computer, and a mouse. See figure 3 (left) for a technical overview of the ProjecTables system. The software of the ProjecTables system is written in Java using the Processing framework and OpenCV. Machine code conversion of CAD model files to HP-GL commands for moving the CNC cutting head is handled by proprietary software.

5. Evaluation

In order to understand the benefits and drawbacks of the ProjecTables system and to gain input on how to design useful features for the system, we invited architecture and design students, who are frequent users of CNC cutting machines, to take part in evaluations using the prototype. This involved a mix of quantitative and qualitative measures. Ten participants took part in a quantitative evaluation test-

ing their performance in packing shapes on to scrap materials using existing CNC cutting software to gain an overall sense for completion time and cutting errors. We then conducted the same packing task and contextual interviews with four additional participants using the ProjecTables prototype to explore possible features in future iterations of the system.

Figure 3. (left) *ProjecTables* system overview: CNC cutting machine with overhead projector and camera connected through the internet to the preparation table, also with camera and projector for capturing material contours and displaying model parts. (right) *Packing task*: Participants were tasked to fit the model parts in the available pockets of space on the scrap material. Model parts are white with a red outline, holes in the material are solid black.

The 10 Participants, 1 female and 9 males with average age of 25.6 years, were asked to pack model parts onto a piece of scrap material, taking care to ensure that the parts would be cut and not overlapping with the holes or edge of the material. The challenge of the task was to find the small pockets of space in the material, where specific parts of the model would fit as shown in figure 3 (right). This is a typical task faced by designers and it typically requires careful measuring and verification of the bounds of the part fitting properly. The participants performed this task using standard CNC cutting software, which they were familiar with and had used at their institution. Completion time and number of errors were measured. The results of the packing task confirm the observations at the architecture school that the placement and cutting of individually placed model parts takes a considerable amount of time and often results in miscut parts. Individual parts took between 2 and 4 minutes to place and this time varied widely between participants ($M=168.7$ seconds $SD=33.8$). Furthermore, 20% of the attempted cuts resulted in errors - placing pieces of model parts in cutout regions of the material. Performing this task using ProjecTables is up to 30x faster and is categorically different from using standard CNC cutting software, because the standard software requires the user to measure the material and jog the origin laser indicator to set the origin and then explore the bounds of the parts.

We selected 4 additional participants, who use the CNC cutting machines regularly (5-30 times per month), to go through a packing task using ProjecTables and to take part in a contextual interview. All participants spent between 1 - 3 minutes completing the packing task (8 - 26 seconds per individual model part) and made no cutting errors. During the interview we had them reflect on their current practices and problems with the CNC cutting machines at their institution and conducted ideation sessions with them to generate and discuss possible features for ProjecTables, which would be useful to them in their everyday design practice. We asked them to reflect on their interactions with ProjecTables and invited them to share feature ideas pertaining to improved packing and support of sustainable

practices. Four main ideas emerged: 1) snap-to angles for improved efficiency of packing, 2) providing a visual margin between parts to account for the sacrificial material that is cut/burned away by the tool - for instance when laser cutting thick plywood, larger burn marks appear on both sides of the cut line compared to thin plywood, 3) sharing of paths between parts to optimize material use, and 4) automatic visualizations to identify possible packing locations of model parts, thus reducing the time for manual exploration of where to fit the parts.

Additionally, we asked participants to describe how ProjecTables could support them in using material properties and visual augmentations hereof to inform and constrain their designs aesthetically and functionally, which resulted in two main ideas including 1) the selective automatic alignment of model parts according to the material grain or texture, and 2) allowing the user to choose the level of material fidelity. The latter idea would involve visually marking up areas on the material as “no-go” zones where model parts may not be placed. Through deeper discussions, it was clear that the directionality of texture and quality of model parts is only important for the visible parts of exhibition-grade models and for models where the structural strength is crucial.

When participants were asked to compare the use of ProjecTables with current practices, 3 participants described how they believed the system to better support reuse of scrap materials than current systems at the architecture school, because they found the system to be easier and faster to use. 1 participant described that he would prefer to use the CAD program, Rhino 3D, when packing a model consisting of many small parts, as he would want to be in precise control of defining the distance between parts to save space. Participants agreed with the overall reasoning for the preparation table - they had all experienced long wait times of hours, some even days, to get access to the CNC cutting machines at the school. Moving the activity of preparing models and materials away from the CNC cutting machines to reduce the idle time of the machines thus made good sense to them. Interestingly one participant also noted how preparing a model on the preparation table, rather than on the bench of a CNC cutting machine, was more ergonomically pleasant as he could walk around the table, while preparing his material, and he could lean in over the table without worrying about security sensors going off. Thus the participant claimed to have more freedom in his actions at the preparation table than on the CNC cutting machine.

6. Discussion

Participants of the contextual interview expressed concerns that automatic tools, such as automatic nesting of CAD models on materials, impose constraints and limit control causing them to change the design in ways they do not appreciate or which does not make optimal use of the material. Thus, they wanted future automatic and intelligent tools of ProjecTables to be optional and easy to override for support creative freedom. This is reasonable considering that architectural designers working with digital tools of fabrication ‘struggle for clearer control over the parametric relationships’ that make up the design process (Beorkrem 2012).

ProjecTables augments the CAD model directly on the sheet materials by use of

a projector, which differs from using a screen-based visualization. The disadvantage of a screen-based interface is that certain tactile qualities of a material, such as surface irregularities, cannot always be captured and represented on a screen, whereas using ProjecTables the material can be manipulated - moved around and felt - directly on the preparation table/cutting bench with the hands. Yet, as became clear in our evaluation, some participants expressed a preference for using a screen-based interface and mouse for interactive packing. This may be due to the participants familiarity of the screen-based interface (Winge et al. 2014). It may also be due to the input from the mouse being experienced as detached from the output and the otherwise direct manipulation of the material on ProjecTables. Substituting the mouse input with touch input for manipulating the model parts, however, could complement the direct interactions with the material and make for a more coherent tangible experience where input and output is tightly coupled (Fishkin 2004). Still, we assume there are benefits and drawbacks of both approaches to visualization and thus an interesting future study would be to compare the two.

7. Conclusion and Future work

We presented ProjecTables, a visual augmented reality system for sustainable reuse of scrap sheet materials on CNC cutting machines that supports important aesthetic concerns and practices of architectural designers. In future longitudinal evaluations of the system at the architecture school we will examine how it supports the sustainable use of scrap materials in terms of quantitative reduction of material waste, reduction of idle time of the CNC cutting machine, and how the designers appropriate the system features into their work practices. We plan to develop a digital, web-based material library system to be used in combination with ProjecTables to experiment with different social models for sharing (scrap) materials between design students at the architecture school. To further drive a reduction in material waste, we are developing a smartphone version of the preparation table. This enables designers to quickly measure and determine if scrap materials, found away from the studio, are useful for their design projects. We hope that our work inspires the research community to focus on sustainability issues when developing interactive systems for fabrication, not only for the DIY and maker communities, but also engaging with the unique and important challenges encountered in architectural studios and design practice.

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References

- Beorkrem, C.: 2012, *Material Strategies in Digital Fabrication*, Routledge.
- Fishkin, K.P.: 2004, A Taxonomy for and Analysis of Tangible Interfaces, *Personal Ubiquitous Comput.*, **8**(5), 347-358.
- Fite-Georgel, P.: 2011, Is there a reality in Industrial Augmented Reality?, *Proc. of ISMAR'11*, 201-210.

- Fleischmann, K., Hielscher, S. and Merritt, T.: 2016, Making things in Fab Labs: a case study on sustainability and co-creation, *Digital Creativity*, **2**, 1-19.
- Graypants, G.P.: 2016, "Scraplights" . Available from <<http://graypants.bigcartel.com/>> (accessed 20 December 2016).
- Kolarevic, B.: 2001, Digital Fabrication: Manufacturing Architecture in the Information Age, *Proc. of ACADIA'01*, 268-277.
- Merritt, T.R. and De Azambuja Varela, P.: 2014, Designing and Building the Cork Vault: Reflections on a Two-week Digital Fabrication Workshop, *Proc. of DesignEd Asia*, 261-271.
- Mueller, S., Lopes, P. and Baudisch, P.: 2012, Interactive Construction: Interactive Fabrication of Functional Mechanical Devices, *Proc. of UIST'12*, New York, NY, USA, 599-606.
- Olwal, A., Gustafsson, J. and Lindfors, C.: 2008, Spatial augmented reality on industrial CNC-machines, *Proceedings of SPIE 2008 Electronic Imaging*.
- Picon, A.: 2010, *Digital Culture in Architecture*, Birkhauser Architecture.
- Rasmussen, T. and Merritt, T.R.: 2017, "ProjecTables System Overview Video" . Available from <https://youtu.be/0_7-j9UQVwk> (accessed 18 February 2017).
- Saakes, D., Cambazard, T., Mitani, J. and Igarashi, T.: 2013, PacCAM: Material Capture and Interactive 2D Packing for Efficient Material Usage on CNC Cutting Machines, *Proc. of UIST*, New York, NY, USA, 441-446.
- Sanders, E.B.N. and Stappers, P.J.: 2008, Co-creation and the new landscapes of design, *CoDesign*, **4**(1), 5-18.
- René Schmid, R.S.: 2012, "Umwelt Arena" . Available from <<http://reneschmid.ch/projekte/weitere-projekte/detail/kompetenzzentrum-fuer-nachhaltigkeit-umweltarena>> (accessed 20 December 2016).
- Seely, J.C.: 2004, *Digital fabrication in the architectural design process*, Ph.D. Thesis, MIT.
- Shneiderman, B.S.: 1983, Direct manipulation: a step beyond programming languages, *Computer*, **1**, 57-69.
- Varela, P.D. and Merritt, T.: 2016, CorkVault Aarhus: Exploring stereotomic design space of cork and 5-axis CNC waterjet cutting, *Proc. of CAADRIA'16*, 767-776.
- Willis, K.D.D., Xu, C., Wu, K.J., Levin, G. and Gross, M.D.: 2011, Interactive Fabrication: New Interfaces for Digital Fabrication, *Proc. of TEI'11*, New York, NY, USA, 69-72.
- Winge, K., Haugaard, R. and Merritt, T.: 2014, VAL: Visually Augmented Laser cutting to enhance and support creativity, *Proc. of ISMAR'14*, 31-34.