CutCAD - An Open-Source Tool to Design 3D Objects in 2D

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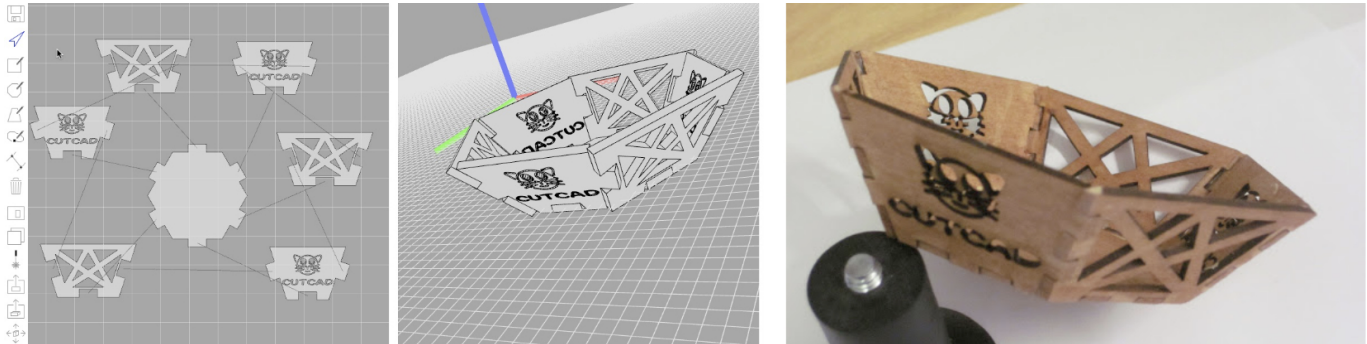
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Figure 1. The design process in CutCAD and its result. Left: The user specifies connections between the edges of 2D shapes. CutCAD automatically inserts the necessary finger joints and renders a 3D preview. Right: The resulting assembled object made from laser-cut elements.

ABSTRACT

Laser cutters are 2D tools, but their speed and compatibility with a variety of affordable materials also makes them a frequent choice to create 3D objects. We propose CutCAD, a tool to easily construct simple 3D objects from 2D faces, inspired by the process of paper modeling and magnetic construction kits. The user creates her 3D model by drawing or loading existing 2D shapes, and connecting their edges in the software. CutCAD then automatically resolves the resulting constraints, and folds the faces up into a 3D model that is previewed live. CutCAD also automatically creates the required finger joints based on thickness of the material and dihedral angles, for smooth assembly. Cutouts are easy to add by importing their outlines as vector drawings, and placing them onto faces. After the faces have been cut, CutCAD provides assembly instructions. Observations and feedback from using CutCAD show the resulting process to be easier to understand than traditional 3D modelling. CutCAD is open-source, and has been downloaded over 2,000 times.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces; Prototyping

Author Keywords

3D; physical prototyping; rapid prototyping; laser cutting; education; maker; fablab.

INTRODUCTION

The success of Fab Labs is based on the fact that enthusiasts get access to machinery usually restricted to trained specialists due to their cost and required maintenance. This allows non-technical people to produce their self-designed objects with high fidelity. While using machines like CNC mills and 3D printers has become much easier in recent years, creating models for these machines to fabricate still requires knowledge in 3D modelling. Tools like Tinkercad[1] or SketchUp[2] greatly lowered the entry barrier to 3D design tools. Yet, personal experience from our Fab Lab shows that for many tasks, such as designing a case for a custom electronics board, working in 3D complicates the process significantly. This makes users frequently move to the laser cutter to create such objects, because the underlying 2D design principles are easier to understand, the machine is much faster than 3D printing, and users have a larger choice of affordable materials.

We present CutCAD[3], a software that supports the user in constructing 3D objects from 2D shapes, leveraging the advantages of laser cutting. Similar to magnetic construction kits for children (e.g., Magformers) or building paper models, the 3D shape is assembled from 2D elements. The user draws these 2D shapes and specifies the geometric constraints, i.e.,

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[1]www.tinkercad.com
[2]www.sketchup.com
[3]hci.rwth-aachen.de/cutcad

which edges of the shapes should be connected. CutCAD automatically creates the necessary finger joints, taking into consideration the specified material thickness and the relative angle between the faces, and previews the resulting 3D object. After laser cutting the elements, the 3D preview of CutCAD assists the user in assembling these to the final object either by comparing the physical faces with their counterparts in the 3D preview or by finding the corresponding face in the 2D preview and highlighting it in both previews when hovering over it.

Apart from being in daily use in our local and several other Fab Labs around the world and having been downloaded over 2,000 times, CutCAD was also used in a local workshop with Fab Lab novices, letting them explore geometric concepts through experimenting with the program. During public presentations at Maker Faires we received extensive positive feedback. To demonstrate its capabilities, we present a gallery of objects designed and assembled using our tool.

RELATED WORK
Leveraging the strengths of laser cutters to prototype and build 3D object has received great attention. The simplest approach is to slice a 3D model along a certain axis into parts that can be laser cut and stacked to create the 3D object. The transformation into planar sections as done by Hildebrand et al. [5] or the *Slicer* for Autodesk Fusion 360 reduce the number of slices and thus the amount of material necessary. The resulting structures remain stable enough to be used as real furniture [13]. The disassembly into stable planar sections, however, is challenging as the 3D model does not only need to be decomposed, but the algorithm also needs to take the assembly of the resulting elements into account [14]. Beyer et al. [1] propose a more generic approach by disassembling a 3D model into as many laser-cuttable parts as possible in order to reduce production time. Curved surfaces are created using a living hinge pattern, and only elements that cannot be manufactured on a laser cutter are sent to a 3D printer. However, all these tools require a 3D model to start with, and for many use cases, such as enclosures with solid surfaces, a slicing approach is not viable.

LaserOrigami [8] adds the possibility to heat up acrylic in a lasercutter by moving the laser out of focus, such that gravity deforms the acrylic along that edge. The benefit is that the product can be used immediately without requiring further assembly. The process, however, is limited to thermoplastics and the deformability of the material, meaning that the depth of a recess is limited by the material available to create its walls. *LaserStacker* [16] also repurposes the laser to solder different layers of acrylic, removing the need for further assembly. *Foldem* [2] is a multi-layer sheet that incorporates different material properties. Depending on how deep the laser cuts through these layers, the joint is either bendable or flexible, with the former meaning that the material retains its bent shape. This enables the construction of 3D objects much like paper folding, but creating objects that cannot be made using a single cutout is difficult.

FlatFitFab [7] is a tool that supports the creation, simulation, and fabrication of planar section assemblies. The process starts from 2D shapes, and provides support to add the slits correctly and to simulate the end result. For simple, rectangular cases, websites like Makercase.com provide a good starting point, providing the user with 2D drawings of the faces for a box of specified size. The edge joints can either be flat, finger joints for a press-fit connection, or T-slot joints for a bolted connection. Based on these drawings, the user can insert cutouts or decoration using her preferred vector drawing application without having to go through the tedious process of creating joints manually. Similarly, Mueller et al. [9] provide automatic joint generation of various types in their *Constructable* system, in which the user interacts with the object directly on the laser cutter using different laser pointers. However, the geometric deconstruction of the target object into its 2D constituents is left to the user.

Joinery [19] is a tool to add parametric joints to 2D shapes. The tool provides a selection of joint types that can be adapted to various materials and thicknesses. CutCAD builds on this simple interaction in 2D with its automated creation of adaptive finger joints, and adds the constructive aspect as support for the creation of more complex geometric shapes and their assembly.

DESIGN PROCESS
The popularity of 3D printing has made 3D modelling simpler as design tools improve. 3D designs to be manufactured with the laser cutter can either be created with such 3D drawing programs (e.g., Tinkercad, Slic3r), breaking them down into planar pieces in the process, or by using a 2D drawing program and adding connections like finger joints (e.g., MakerCase, Joinery). To leverage the advantages of the laser cutter, we apply a design process that starts from 2D elements to construct a 3D object. In contrast to origami-like unfolding, in which the faces all need to be part of a single coherent piece (e.g., with Javagami [3]), our approach relies on a multitude of pieces, similar to a 3D paper model such as, for example, the result of a disassembly in the Pepakura Designer [15]. The user works with 2D elements (cf. Fig. 1), which are actually three-dimensional because they have a certain thickness. The 3D preview takes this into account and shows an accurate representation.

This design approach has proven sufficient for many everyday use cases that employ the laser cutter to construct 3D objects. One limitation is that this process only applies to objects with planar faces. However, if curved surfaces are important, the user can revert to a slicing approach.

INTERACTION DESIGN
The user starts designing a 3D object similarly to how one would design a paper-cut model or build it with a magnetic construction kit (see Fig. 2). The basic 2D faces that form the object can either be drawn directly within CutCAD, or imported from any 2D vector drawing program. In a second step, she connects adjacent edges of the same length using the *connect* tool in CutCAD. Both the first edge and the edge the mouse is hovering over are highlighted in different colors, both in the 2D working area and the 3D preview. CutCAD automatically aligns the shapes in a 3D preview. Every connection
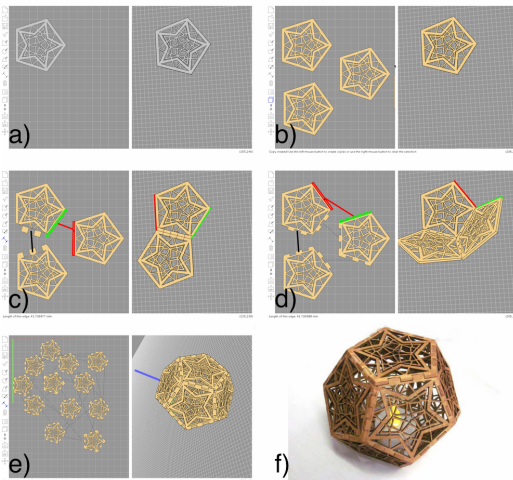
Figure 2. Designing a candle holder with CutCAD: *a)* Start with a basic shape or an imported SVG. *b)* Adjust material type and thickness, duplicate elements. *c)* Connect edges—CutCAD will automatically rearrange the shapes in the 3D view and generate finger joints. *d)* If edge-constraints cannot be resolved in the 2D plane, the faces will be aligned in 3D. Starting edge and cursor hovering over a second one are indicated in both views. *e)* Send the files to a laser cutter, and *f)* assemble them.

between two edges is a constraint on the position of the face in the resulting 3D object. CutCAD continuously tries to resolve all constraints in the 3D space, and presents the result in its 3D preview. Additionally, the program creates corresponding finger joints along the dihedral edges. The user can assign a material and thickness to each face, which CutCAD uses to generate the finger joints such that there are no gaps in the final object. CutCAD then generates one or several jobs to send to the laser cutter, depending on the number of materials and thicknesses used. After all faces are cut, the user can use the 3D preview as an assembly guide.

This basic workflow can be extended in two ways. If the user wants to add additional functional or decorative cutouts, she can export the faces she designed in CutCAD as an SVG file and edit them in a vector drawing application.This file can later be re-imported to CutCAD. Shapes within the faces are then recognized as cutouts, like the complex decorations on the pentagonal faces in our candle holder example (Fig. 2).

In the case of functional cutouts, such as in the common use case of creating a case for a DIY electronics project or other object [6], CutCAD can load a 3D model of an object into the preview, which allows the user to build the case to measure. Furthermore, cutouts can be placed at the right positions on the faces without further measurement. After adding the 3D object, the user can move and rotate it in 3D space, while she still works the same way as before in the 2D area to design a fitting housing, as shown in Figure 3.

Another interesting approach came up during everyday use. Instead of building a case around the 3D model of a PCB and positioning the cutouts graphically as intended initially, importing technical drawings of the PCB has shown to be an even faster alternative that results in more precise placement and dimensions.
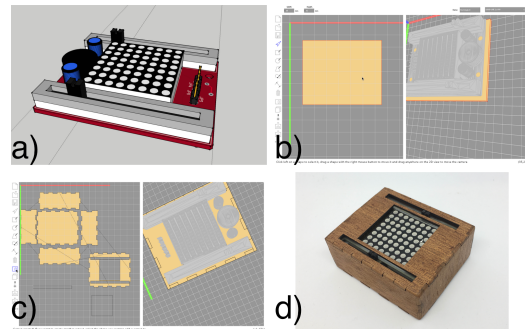

Figure 3. Designing a case around a 3D object: *a)* Import a 3D model in the 3D preview. *b)* Draw shapes and align them around the object. *c)* Insert cutouts and align them to the object. *d)* The resulting custom-fit case.

Limitations and Workarounds

A major current limitation is that each edge can only be connected to one other edge, and that edges can neither be placed in the middle of a face nor on cutouts. Therefore, we are currently limited to outer hulls, whereas inner separations or outer extensions on cutouts are not possible directly.

As every edge has to be connected manually, creating complex objects can become tedious. The most complex object we built was a truncated dodecahedron (soccer ball) with 90 edges to be connected (Fig. 4a). For such regular shapes, a set of templates or an automated assistant would be helpful. However, designing such shapes without templates is no easy task in a 3D design application either, and CutCAD only needs two regular shapes that can easily be copied and are aligned automatically. A calculation of angles is not directly necessary.

IMPLEMENTATION

The program is written in Processing/Java, which allowed us to use *liblasercut* [11] to integrate the laser cutter driver and the *VisiCut* [10, 12] material database to automatically adjust the laser cutter settings.

To resolve the constraints defined by the connected edges, the algorithm, first, tries to align the elements in 2D through translation and rotation. If this is not possible, the algorithm will try to find a position of both freshly connected faces in 3D by rotating them around their edges that are already connected, such that the edges to be connected overlap. For this purpose, the algorithm considers a planar projection of both rotation cycles of the non-common point of both edges on the common 2D plane of all three faces involved. If both lines in the planar projection intersect, a common point can be found in 3D with triangular calculation of the edge length and the intersection in the 2D plane.

The finger joints are created according to both the material thickness of the two adjacent faces and their relative angle, such that each finger joint fits together without gaps, resulting in a smooth structure after sanding.

EVALUATION

One problem of the laser cutter is that novices underestimate its usefulness for 3D construction. In contrast, 3D printers are immediately perceived as 3D tools whose fundamental
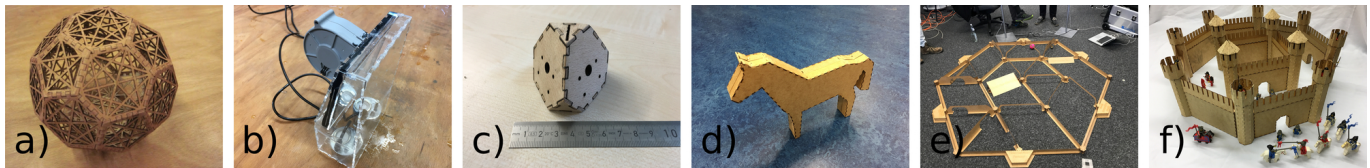
Figure 4. Sample objects created with CutCAD . a) Soccer ball: Using two regular pentagons and hexagons, we can construct a soccer ball by copying the faces and connecting their edges, without having to calculate any angles. b) Small Fog display: CutCAD allowed to easily add finger joints to a bevelled housing. c) Camera mount for four Raspberry Pi cameras. Design based on the technical drawing in CutCAD . Design and manufacturing combined were significantly faster than printing the corresponding 3D design alone. d) Horse: Starting from a simplified horse shape made of straight lines, we added rectangles adequate to the length of the lines and connected them in CutCAD. e) Labyrinth: CutCAD was used to build the small hexagonal connecting towers. f) Castle: CutCAD was used for towers and their ceilings as well as archways.

working principles are easy to grasp, and unlike laser cutters, they have become affordable enough to enter the private consumer market, making them more widespread and accessible. Nevertheless, an evaluation of the student pages [4] of the 2017 FabAcademy shows the laser cutter to be the favorite tool by far, being used in 80% of the final projects. The students had an introduction to all of the machines available in a Fab Lab, and thus could choose the most appropriate ones. This correlates with our experience in our Fab Lab: Visitors typically are attracted initially by the potential of 3D printing, but they often return because of the laser cutter, after discovering what it allows them to fabricate. CutCAD helps promote these advantages of the laser cutter for 3D construction.

The playful assembly of larger objects from basic components that CutCAD supports is also considered a key aspect of teaching the higher concepts of geometry [17]. Coincidentally, CutCAD's interface provides a structure similar to VRMath [18], a tool specifically designed to teach computational 3D geometry. Therefore, CutCAD can be considered a tool not just for design and fabrication, but also learning and education.

As a consequence of this insight, we used CutCAD in a one-day workshop with 8 NEETs (people not in education, employment, or training) of age 18–24. All participants received an introduction to drawing in the open-source vector drawing application Inkscape before our workshop. We introduced CutCAD , and then let participants experiment with 3D modeling in CutCAD. They were allowed to design freely, not constrained to the original idea of a case for electronics. Our goal was to let our participants explore the possibilities of the tool in more artistic ways. None stayed with the basic rectangular shape; instead, they experimented with the creation of various 3D shapes from 2D elements and how to include complex vectorized art for the cutouts. The effect as a learning tool became apparent when some participants wanted to build a spherical shape out of regular hexagons. Although some participants encountered limitations of the program in automatically aligning the shapes in 3D, all finished their design within the allotted time. Similar workshops are now run with CutCAD in other Fab Labs as well.

We presented CutCAD at various Maker Faires, where it sparked interest and where we received very encouraging feedback. Visitors liked the wider choice of materials that can be processed on the laser cutter, which allows the designer to opt for a material that gives the artifact a distinct appeal. They especially liked the wooden structures (in contrast to

3D printing), which convey a more valuable apparance than *"just plastic"*. The finger joints that CutCAD generated further support this aesthetic quality with their seamless fit. Similar to the comments at Maker Faires are the reactions to two objects designed with CutCAD we published on *Instructables: "This is beautiful! The pieces fit together so well too!"*[4]. An important aspect is the customization of basic shapes we provide as a template: *"How can we redesign a custom one like yours?"*[5]. For the reasons mentioned above, CutCAD has become a standard tool in our Fab Lab.

CONCLUSION & FUTURE WORK

In this paper we presented CutCAD, an open-source design tool to create 3D objects out of 2D faces. This allows the user to work in 2D only and still be able to design rather complex structures that can then be laser cut and assembled with a 3D preview as guide. Since this concept is similar to the one used to made simple 3D objects like lanterns out of paper, users are able to understand the concept quickly and also gain basic knowledge about geometry in a playful way. The import of 3D objects and technical drawings allows expert users to build custom project cases quickly. This software concept has proven its usefulness and interaction design both in everyday work and with a workshop with NEETs and real-world scenarios—for designing housings with well defined cut-outs beyond the basic rectangular box as well as for more complex, artistic objects.

Two features should be added in future versions: the possibility for advanced users to create edges with multiple connections, and support for inner struts that can improve robustness or support objects such as electronics boards inside the object. Future research should investigate the aspect of learning the geometric build-up in three dimensions and how to further improve assembly support. The different modelling approaches of CutCAD and traditional 3D CAD could be compared quantitatively regarding the time it takes to design and build a predefined model.

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[5]www.instructables.com/id/Woodball/

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