The Future of 5DOF Laser Cutting Is Personal

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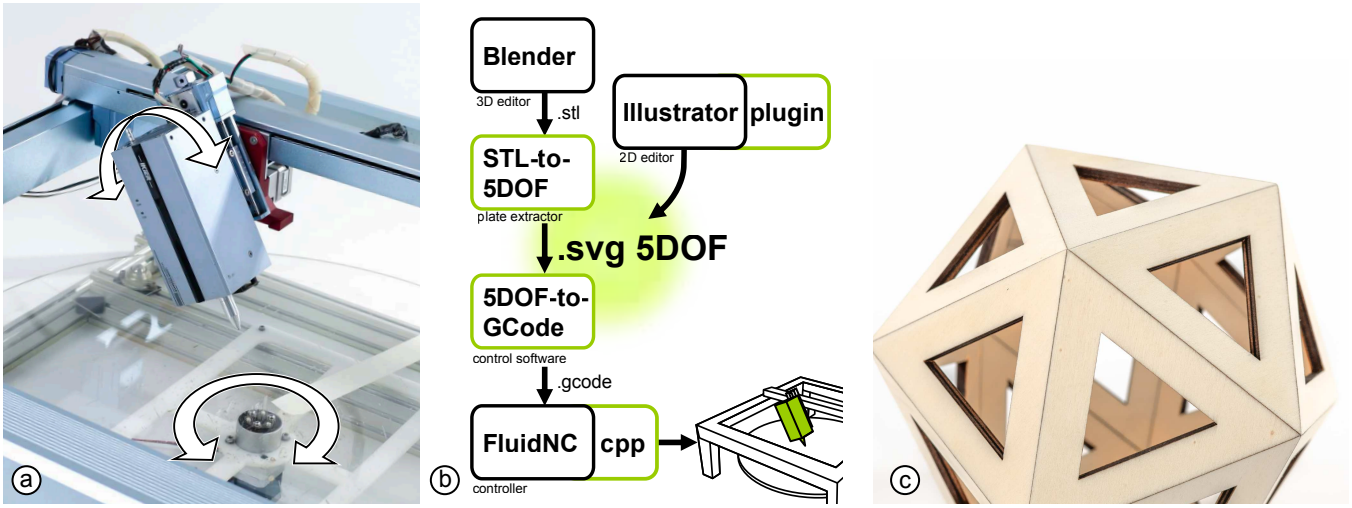


Figure 1: Can diode-based laser sources bring laser cutters capable of tilting their heads to makers, and if so, how to enable this? (a) To explore this question, we created a hardware prototype of a desktop 5DOF laser cutter from maker-available components. (b) We then created a toolchain for controlling the device exclusively by extending programs and file formats used by makers today. We extended the SVG file format to 5DOF and created four extensions and converters around it, here highlighted in green. (c) We then applied the prototype and the toolchain to maker-friendly materials, suggesting that future makers might use 5DOF machines to fabricate hidden joints (as well as load-bearing joints and cut-in-place mechanisms).

Abstract

There has been a recent advent of diode-based laser cutters and a significant uptake among makers. In this paper, we reason that this new technology will also lower the bar for making laser cutters capable of tilting their heads, creating the opportunity to bring 5DOF laser cutting to makers. We anticipate this evolution and present a prototype of a diode-based 5DOF laser cutter built on technology available to makers today. Using this prototype, we explore how to embed 5DOF cutting into makers' existing software ecosystem to ease adoption. We tackle this by starting from a popular toolchain and then, step-by-step, extending every program, file format, and workflow to 5DOF: We present a 5DOF variant of SVG, we extend Adobe Illustrator with a plugin, and we present a converter for 3D models. We then use our prototype and toolchain to explore what future makers might fabricate using such machines, including hidden joints that provide models with a clean look, load-bearing joints that take 5.8x times higher loads, and cut-in-place mechanisms.

CCS Concepts

• **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → *Computer-aided manufacturing*; *Computer-aided design.*

Keywords

personal fabrication, hardware, laser cutting, five-axis, maker

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1 Introduction

Laser cutting is a maker favorite: it is faster than 3D printing [10], allows cutting natural materials, yet it is easier to handle than CNC milling, as it does not require fixtures [53]. However, laser cutting tends to be less "expressive", i.e., there are shapes that typical laser cutters cannot produce, such as most types of hidden joints (such as *miter joints* [74]), many load-bearing joints (such as *dovetails* [32]), and many types of mechanisms [42] (such as nuts & bolts).

Many such designs could be enabled if laser cutters could not just move in X and Y, but also *tilt* their heads. Such 5-degree-of-freedom laser cutters do exist in industry [71], but unfortunately are unfit for makers: (1) The wavelengths used by fiber lasers [54] allow cutting steel, but are unfit for the materials used by makers (such as particle board, acrylic, or wood [24]). (2) CO_2 lasers with 5 degrees of freedom use optical paths across at least five mirrors, which requires an undue amount of maintenance [62].

However, the recent advent of *diode lasers* might change this in the not-so-distant future. Diode lasers are entirely solid-state [52], and because of this, diode lasers have the potential to resolve both issues listed above: (1) they produce suitable wavelengths and (2) they conceptually can be mounted directly to the head of a gantry, thereby eliminating all mirrors.

With today's technology, mounting a diode laser to the head of a gantry is still inherently large, heavy, and slow: since current diode lasers produce relatively little power output (such as 5W) and are of low efficiency, creating a useful (e.g., 70W) diode laser requires combining multiple laser diodes (e.g., 14 x 5W) using knife-edge mirrors and a polarizing beam splitter [61]. A maker-available laser head [34] weighs over 1kg, caused mainly by the heatsinks. Such a large and heavy head is not only hard to accelerate, making cutting slow, but would also require a correspondingly large tilt mechanism, making it even larger and slower.

However, this avenue is worth pursuing, as diode laser heads are shrinking: with laser diode efficiency growing continuously (Figure 2), *heat loss* is currently halving every 9 years [41, 50]. With heatsink size generally proportional to power, this allows heatsinks to shrink. With heatsinks shrinking and ideally disappearing, laser heads will ultimately become small and light. At this point, adding 5DOF could become a commodity (see also Section "Conclusion and Outlook").

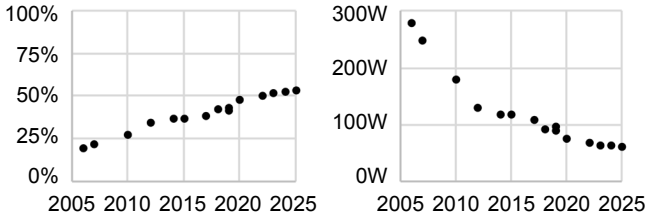


Figure 2: (a) Laser diode efficiency is continuing to grow, causing (b) waste heat (here for 70W output) and thus heatsinks to shrink exponentially (data aggregated from [41] and [50]).

In this paper, we explore this perspective. Will laser cutters with additional degrees of freedom become relevant to the maker movement, and what would it take to enable this? As illustrated by Figure 1a, we created a hardware prototype of a desktop 5DOF laser cutter from maker-available components. (b) Using this prototype, we explore how to embed 5DOF cutting into makers' existing software ecosystem to ease adoption. We present a 5DOF variant of SVG, we extend Adobe Illustrator with an exporter plugin, and we present a converter for 3D models. (c) We then applied the prototype and the toolchain to maker-friendly materials, giving us a glimpse of what future makers might fabricate using such machines. We find that 5DOF laser cutting may indeed be the future of laser cutting for makers.

2 Contribution, Benefits, and Limitations

Our main contribution is an exploration of the mid-term future of laser cutting, i.e., whether it will be desirable to bring 5DOF to makers and, if so, what it would take to enable it.

Along this journey, we make three technical contributions: (1) a proof-of-concept implementation of a *desktop* five-axis laser cutter, (2) extensions and converter tools that extend three tools and formats popular with makers today to 5DOF (Blender, Illustrator, and SVG), and (3) an exploration of what classes of new functionality results makers might derive from such a device, i.e., load-bearing joints, hidden joints, and cut-in-place mechanisms.

Limitations: (1) Being built on the inefficient diode lasers available today, our prototype device cuts slowly. For example, a thread on 8mm birch (see Figure 26) takes 5min cutting time. (2) Current diode lasers cannot cut translucent materials, such as clear acrylic. (3) Our prototype is limited to cuts up to ±52° cutting angle compared to vertical; after that, we could not focus the laser anymore for cutting through plywood.

To help readers build on our findings, we open-source our code.

3 Related Work

Our work builds on the following research areas.

3.1 Fabrication Machines with Additional DOF

Typical personal fabrication machines have three degrees of freedom. While these 3DOF platforms already enable users to create complex objects, researchers have started exploring additional degrees of freedom to enable additional use cases. *On-The-Fly Print* [56] explores a 6DOF 3D printer that allows printing features onto existing models, enabling the fabrication of low-fidelity models during 3D modeling. *RoMa* [55] shows a 3D printhead mounted on a 6DOF robot arm with a rotating build plate, printing the model *in situ* during modeling. *RevoMaker* [25] uses a 2DOF revolving platform to enable printing around a prefabricated cuboid. *Patching Physical Objects* [69] adds a mill and two additional degrees of freedom to remove and reprint features on existing prints. *Isa et. al.* add a rotational axis to enable freeform surfaces without the staircase effect [36]. Similarly, Dai et al. add a rotational axis to print overhangs without supports [15].

Researchers have also explored adding different toolheads to fabrication machines to enable new functionality. *Katakura et al.* [39] add a hook to 3D printers that can pick up different 3D-printed end effectors to assemble objects automatically. *Rhapso* [6] extends a 3D printer with a string-laying mechanism to fabricate string-actuated structures. *LaserFactory* [51] augments laser cutters with a

pick-and-place mechanism and a solder dispenser to add electronic components during laser cutting.

Some of the use cases we hope to enable, such as miter joints and dovetail joints, are possible with CNC milling machines. However, while some attempts at making five-axis milling machines of desktop size exist (*PocketNC* [58]), the key challenge here is that milling machines need to withstand mechanical forces, thus requiring fixtures, and are slow. We thus focus on laser cutting, which is much faster and provides a viable path to shrink the machine.

3.2 5DOF Laser Cutting

Laser cutting beyond three degrees of freedom today is largely limited to industrial use [71]. In industry, however, 5DOF laser cutting has a decades-long history. In the 1980s, *Prima Industrie* [30] developed the first CO2-based 5DOF laser cutter. The resulting designs performed slanted cuts, enabling several novel industrial applications, such as the laser cutting of pre-formed parts (e.g., in the car industry [71]).

However, CO2-based 5DOF laser cutters were and continue to be complex to maintain [62]. As CO2 laser cutter sources are heavy, they are not mounted on the toolhead. Instead, the laser is routed through a mirror system on the gantry and through a hollow 2DOF robot arm [54]. Additionally, rotating mirrors, required for 5DOF, are harder to align [19].

More recently, the industry began using diode-pumped solid-state lasers, such as fiber lasers [64]. The use of optical fibers simplifies the optical path down the robot arm [47], requiring only a fifth of the maintenance [62]; unfortunately, the fibers are only suitable for transmitting wavelengths for cutting metal [64], and are unsuitable for cutting the materials non-expert users care about, such as wood [24]. Both aspects combined have limited five-axis machines to industrial use.

At the same time, consumer-targeted laser cutters have become widely available. This has been enabled by efforts to reduce maintenance and enable a compact footprint. *Glowforge* [26] achieves this by putting the CO2 laser tube on the gantry [27]. Apart from specialized use cases, such as engraving round objects for which manufacturers sell a rotational add-on (*Trotec* [70]), these machines are limited to 3DOF cutting.

The recent trend of diode-based laser cutters, with laser sources lightweight enough to be mounted to the head, changes this. While *Mr. Beam* [48] achieves up to 10W optical output with a single emitter, others, such as *XTool* [75], combine multiple smaller diodes (6W), resulting in up to 70W output power with 25% efficiency [34]. This low efficiency requires heavy heatsinks for cooling. To reduce weight, *Atomstack* [7] uses water cooling for its 120W optical output module. Even higher output power has been achieved by *TeraDiode* [33], which invented a method for combining multiple diodes with a beam quality suitable for cutting in the kilowatt range.

3.3 Hiding Fabrication Artifacts

A key challenge for personal fabrication is to enable non-experts to produce models with a high-quality, clean finish, as current fabrication technologies often leave visual traces.

In 3D printing, researchers proposed controlled acetone vapor smoothing [28] (e.g., for ABS) to deal with FDM artifacts and hiding gaps in models assembled from multiple parts in areas of low visual impact (*reducing visual artifacts* [22], *Chopper* [45]). Another approach is to mitigate the effects of fabrication artifacts by adding fine textures [72] and surface patterns [68]. Powder bed fusion and SLA resin printing provide a higher quality finish; however, users still tend to post-process, e.g., with media blasting.

Laser cutting is particularly challenging when it comes to hiding fabrication artifacts. While CNC milling remains the go-to technique in subtractive fabrication for creating hidden joints (e.g., *mitered edge joints* [74]), laser cutting is considerably faster (*Roadkill* [2], *HingeCore* [3], *Flaticulation* [21]). However, laser-cut joints form highly visible artifacts. Similarly, *Su et. al.* note that laser-cut box joints, for example, leave gaps and protrusions for odd angles [67]. *PopCore* [1] somewhat mitigates this effect by creating objects using a paper-foam-paper composite called foamcore. *PopCore* keeps the outer paper layer intact over the object and hides the joints under it.

We demonstrate hiding laser-cut joints and plywood edges by using miter joints fabricated with our prototype 5DOF laser cutter, thereby removing fabrication artifacts.

3.4 Joints Robust Against Tension Loads

Integrating box joints into laser-cut objects allows the production of load-bearing objects. While box joints are strong against compression [9], they tend to be weak against tension. Makers have addressed this by adding captive nuts to box joints to improve tensile strength [59]; however, this complicates assembly. Another solution is to add reinforcement plates (*FastForce* [4]) or enable the user to assemble laser-cut objects with mallets (*Mallet-based Assembly* [38]), resulting in tighter press-fits, increasing tensile strength (*Kerfmeter* [40]).

Dovetails, on the other hand, are strong against tension; however, 3DOF laser cutters are unable to produce the geometry and require manual work with a chisel [73].

By adding two additional degrees of freedom, we enable the fabrication of dovetails and other load-bearing joints on desktop laser cutters.

3.5 Laser Cutting Objects in a Single Integrated Process

Researchers have explored fabricating objects in a single integrated process. *LaserOrigami* [49] creates 3D models using a single piece of acrylic. The piece is heated, then, using an additional DOF on the workpiece, it is rotated, and gravity is used to bend it into the desired shape. *Fibercuit* [76] uses a similar approach to create artifacts that resemble origami. *Lamifold* [42] incorporates mechanisms into laser-cut objects by cutting and then gluing multiple layers of material.

Inspired by this work, we propose cut-in-place mechanisms, i.e., multipart objects that are cut at an angle from both sides, creating incisions that hold the parts in place, thereby creating a functional mechanism in a single integrated process.

3.6 Modeling for 5DOF Fabrication

Recent work has simplified access to digital fabrication machines that go beyond the typical 3DOF through fabrication-aware tools. In 3D printing, the S3-Slicer [77] generalizes slicing for multi-axis printing, while Open5X [31] presents a slicer for five-axis 3D printing targeted at desktop users.

In laser cutting, there is a host of tools for 3DOF laser cutters. *Joinery* [78] and *CutCAD* [29] aid users in editing joints in 2D by generating matching joints for connected edges. *Fresh Press Modeler* [13] converts 3D models into a set of plates connected by box joints, while *FlatFitFab* [46] and *Kyub* [9] offer specialized editors for authoring 3D laser-cutting models that export the model plates as SVG files. *Cuttle* [14] offers parametric editing features for 2D cutting plans.

In this paper, we propose extending the ecosystem of programs and file formats for 3DOF to 5DOF, including Adobe Illustrator and SVG.

4 Prototype Hardware

Figure 1a shows our prototype device. The device is based on an off-the-shelf 70W diode-based laser cutter (*iKier Pro 70W* [34]), to which we added motorized *tilt* and *yaw*, the latter via a rotating cutting table. Figure 3 shows how we inserted the tilt mechanism: (a) Building on the off-the-shelf laser cutter, (b) we temporarily removed the laser head and Z-actuator, mounted to our custom tilt mechanism. We then reattached the laser head together with its Z-axis *onto* our custom tilt mechanism.

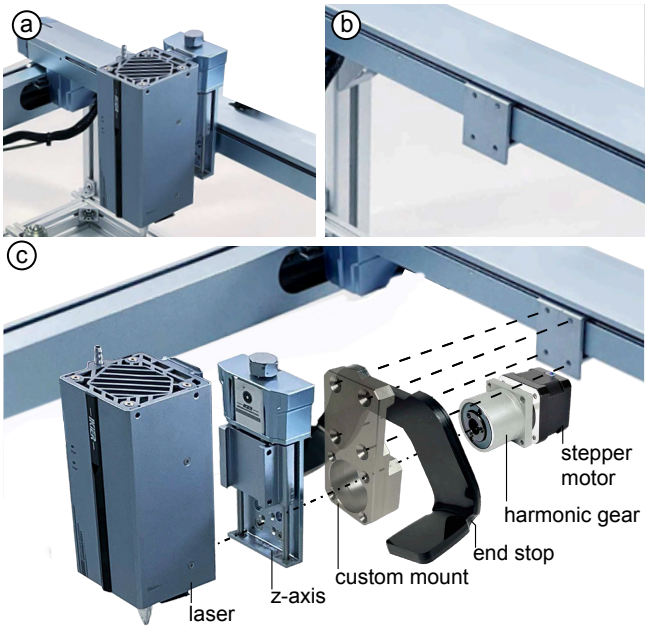


Figure 3: We added head tilt to an off-the-shelf laser cutter [34] by (a) removing the laser head and z-axis from the gantry, then (b) using the exposed mount (c) to insert a stepper motor and a gearbox, held together by a custom mount.

As illustrated by Figure 3c, the tilt mechanism's main mechanical component is the stepper motor (Nema 14, 5Ncm torque, 0.9° step angle [65]). To achieve an angular resolution of 0.9°/50 = 0.018°, we geared the stepper motor down 50:1. This reduces head tilt error on x/y to 50μm positional resolution on the material surface. To prevent imprecision from backlash, we use a zero-backlash gearbox (*PGFUN Harmonic Gear Drive* [57]). We hold parts together using a custom CNC-milled aluminum mount.

As illustrated in Figure 4, we add a second degree of freedom by rotating the table holding the workpiece. The benefit of this design is that it reduces imprecision and increases stability [12] compared to a double-tilt design (see Section "Conclusion and Outlook"). (a) Starting with the off-the-shelf casing, (b) we extend the bottom of the casing with a mount and four bearings to support the rotating table, (c) into which we mount a second stepper motor (Nema 17, 26Ncm torque, 0.9° stepping angle [66]), again geared down 50:1 using a zero-backlash gearbox (*PGFUN Harmonic Gear Drive* [57]), giving us a 90μm resolution along the perimeter when rotating the workpiece. (d) On top of this, we mount the round cutting table.

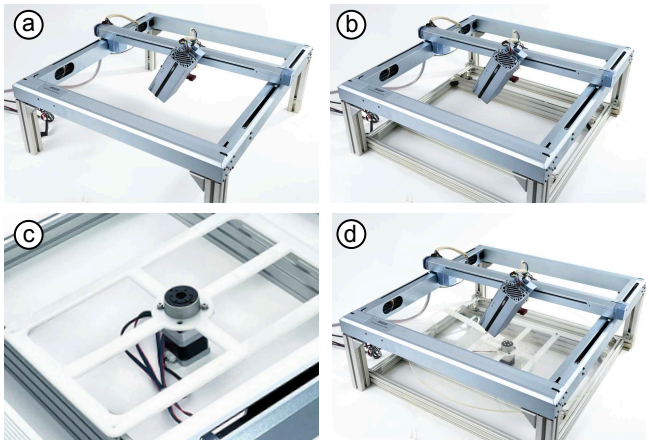


Figure 4: (a) We added yaw by (b) extending the casing with a mount, (c) mounting a stepper motor and zero-backlash gearbox, and (d) adding the round table.

The cost of our prototype amounts to $1900, dominated by the diode laser cutter ($1300) and the harmonic drives (2 x $150). Alternatives to harmonic drives include Archimedes drives, gearboxes with torsional preload, or, if the laser source becomes sufficiently lightweight in the future, direct-drive control with micro-stepping, combined with encoder feedback to ensure accuracy.

4.1 Safety

To ensure optical shielding and proper ventilation, a suitable enclosure, equipped with safety interlock switches and connected to an air filter, must be used when operating a laser cutter. Our prototype fits into a typical diode laser cutter enclosure (76 x 74 x 42cm) sold by the manufacturer. To physically limit head rotation to ±60°, we added end stops to our custom mount.

5 5DOF Toolchain Designed to Address Makers

Based on the prototype device, we explored how future makers may want to interact with such a device. The traditional "industry approach" to encoding 5DOF models is to use 3D CAM software that produces machine-specific G-code. However, this format, we argue, is not suitable for the user base that future low-cost diode-based 5DOF laser cutters will address: similar to 3D printing and 3DOF laser cutting today, these users expect the machine to produce the model automatically, rather than manually generating toolpaths.

We therefore explore what a future toolchain designed to address makers might look like if built on the tools makers use today. As illustrated by Figure 1b, our objective here is to help makers integrate 5DOF laser cutting into their existing workflows. We achieve this by extending existing tools and file formats, and providing converter tools (highlighted in green in Figure 1b).

We will now go through this toolchain bottom-up, i.e., starting from the device and G-code, working our way up to the higher levels of abstraction increasingly suitable to addressing today's makers.

5.1 Level 1: Adapting a Milling Controller

Our hardware prototype described in the previous section uses five stepper motors to actuate the device in x, y, z, tilt, and yaw. Each of them is controlled by a motor driver (*TMC2209*). This now requires a controller that receives G-code and executes it by translating it into motor movements.

Given that laser cutting is not too dissimilar from milling at this level, the obvious approach is to build the software stack for a 5DOF laser cutter on the technology developed for 5DOF milling machines. Following our agenda of picking software and hardware already in use by makers today, we picked a controller board popular with the maker community (*FluidNC Corgi* based on an *ESP32* microcontroller [18]) and the matching control software (*FluidNC* [17]).

We then adapted FluidNC to the mechanical design of our prototype. FluidNC allows this by accepting a motor configuration in the form of a C++ source file containing three methods: *transform_cartesian_to_motors()* translates model coordinates into motor positions (aka inverse kinematics), *cartesian_to_motors()* interpolates the laser movement between two coordinates, and *motors_to_cartesian()* provides feedback about the position of the laser head in terms of model coordinates (aka forward kinematics). Implementing all three in *rotated tool center point* (RTCP) control took 300 lines, which we open-source.

Similar to milling, we calibrate the rotation axes by performing test cuts (Figure 5a and b). 5DOF Calibration takes significantly longer than 3DOF calibration, not just because of the additional degrees of freedom, but also because some dimensions, such as head tilt, require more careful calibration, as small deviations can cause large position errors.

Unlike milling machines, which reach predefined depths through physical movement along the z-axis, laser cutters need to achieve predefined depths by modulating cutting power. We (c) calibrate cutting power for reaching predefined depth by intersecting angled cuts.

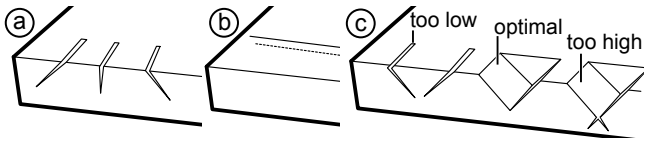


Figure 5: Calibration patterns for (a) tilt center, (b) table center, and (c) cutting depth

5.2 Level 2: Extending SVG to 5DOF

In the current industry ecosystem, the G-code received by the controller is either generated by users from industry-specific CAD/CAM tools or edited manually. Future makers, however, are not familiar with industrial CAD/CAM tools. Thus, to ease adoption, our goal was to instead create a toolchain based on tools users are familiar with.

This format that makers today are familiar with is the scalable vector graphics, or SVG, format, i.e., makers encode and visualize their (3DOF) models in this format [78]. For good reason: SVG is a two-dimensional format, meaning it displays on two-dimensional outputs, including screens and print. The two dimensions of SVG are sufficient because the Z-axis in laser cutting does not typically change during cutting, and thus it is sufficient to delay dealing with the Z-axis until G-Code generation. The same holds for the execution order of the line segments.

SVG furthermore comes with a wide range of visualization and editing tools [5, 14, 35] that makers may already be familiar with. Many of these tools stem from the use of SVG in 2D graphics, which is yet another opportunity for makers to become familiar with these tools, even prior to laser cutting.

When designing a toolchain for 5DOF laser cutting, it is therefore paramount to include, or better yet, build on SVG, we argue. The resulting design question thus was: "How to extend SVG so as to represent the additional two degrees of freedom?"

Figure 6a illustrates what we call *SVG5DOF* at the example of a simple ocarina. Most of the model is traditional 3DOF; only the mouth hole is slanted.

The SVG5DOF file (b) contains mostly regular (black) lines and a single gray line. Starting with the black lines, SVG5DOF encodes all 90° cuts in traditional 3DOF format, i.e., as simple lines (here shown in black, but can also be set to red to match maker standards). Taken directly from SVG, SVG5DOF thus encodes perpendicular cuts using <path/> elements, such as `<path d="M 5 2.5 L 5 22.5" />` to produce a line from (5, 5) to (5, 25).

This means that SVG5DOF is backward-compatible, i.e., any SVG file is also a valid SVG5DOF file. This also allows encoding 5DOF models that contain a large percentage of traditional perpendicular cuts as simple lines, which is *efficient* and keeps visual complexity manageable.

The gray line, in contrast, is part of the mouth hole, which contains a single slanted cut. SVG5DOF encodes slanted cuts as *pairs* of (poly)lines, here shown as a black line on top and a gray line (partially hidden) below. We call the black line on top the *entry line*; it defines the position where the laser *enters* the material from the top. The gray *exit line* defines the position where the laser *exits* the material at the bottom. SVG5DOF defines the correspondence between entry and exit lines by grouping them. Example: the shown

entry line from (5, 5) to (5, 25) and exit line from (11, 5) to (11, 25) are encoded as `<g><path d="M 5 5 L 5 25" class="entry"/><path d="M 11 5 L 11 25" class="exit" /></g>` with the "<g>" being SVGs group tag.

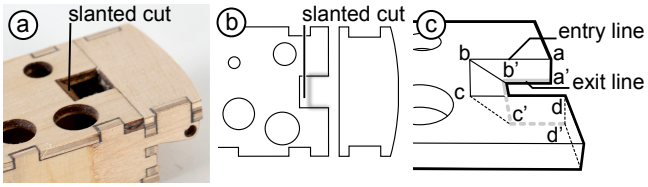


Figure 6: (a) When encoding this ocarina model for 5DOF laser cutting, (b) existing SVG-based designs (black) are combined with features (black/gray) that require slanted cuts. (c) Each segment in an SVG5DOF file defines a tool path as the linear interpolation between entry line and exit line.

Any piece of 5DOF geometry is composed of a sequence of slanted cuts (Figure 6c), each of which is defined as a sweep from a start (entry point, exit point) to a target (entry point, exit point), extracted from a group of entry and exit lines described above. The correspondence between individual points in the *entry line* and the *exit line* is defined implicitly by the order of control points in the two shapes, i.e., the first entry point is matched up with the first exit point, and so on. To make this matching unambiguous, SVG5DOF requires that the entry and exit lines contain the same number of control points.

By default, SVG5DOF maps entry lines to thin black lines and exit lines to broad gray lines. We found this to help visual interpretation, as the look appears as if observed through frosted glass, where lower layers are blurred.

SVG5DOF files specify the thickness of the material in the header, such as `<svg data-thickness="6">` to specify a material of 6mm thickness. Unlike 3DOF, 5DOF requires this, as the conversion to G-Code requires specifying angles (such as the tilt angle of the mouthpiece above), and that angle depends on the material thickness.

As illustrated by Figure 7a, SVG5DOF allows specifying cuts that penetrate the material only to a certain depth. *SVG5DOF* allows defining such partial cuts by replacing the keyword *exit* with the intended depth, such as `<path d="M 11 5 L 11 25" class="depth_3mm" />` for a cut to depth "3mm". Alternatively, users may specify percentages, such as "depth-50" (for "50%") to cut through half of the material.

SVG5DOF allows specifying (b) cuts consisting of *multiple* slants, required, for example, for *cut-in-place mechanisms* (see Figure 25). *SVG5DOF* allows defining these by packing additional lines into the group. By default, additional lines are equally spaced. Alternatively, users assign each contour a specific cutting depth, such as `class="depth_2mm"`.

SVG5DOF allows specifying (c) contours slanted in Z (required, for example, for threads, see Figure 26) by providing samples in paths with an additional Z component, such as `<path d="M 11 5 L 11 25" class="depth-ramp start_3mm end_5mm" />` for a cut from depth `3mm` to `5mm`.

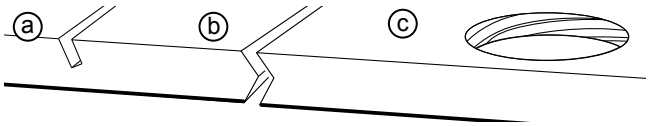


Figure 7: SVG5DOF allows specifying (a) partial cuts, (b) multiple slants, and (c) cuts slanted in Z.

In order to fabricate, makers today use control software, such as *Lightburn* [44]. Since these tools are, of course, unaware of *SVG5DOF* at this point, we create a simple tool, *SVG5DOFToGcode,* that converts *SVG5DOF* to G-code (Figure 8), written in TypeScript for the user interface and Python for converting SVG5DOF to G-code (using *svgelements* for parsing SVG) and sending the G-code to the laser cutter.

Combined, the features presented above allow us to encode the models shown throughout this paper, while remaining backward-compatible. This is essential, as it allows makers to (1) make use of past experience, (2) continue to use old tools, and (3) encode future 3DOF and 5DOF models in a single format.

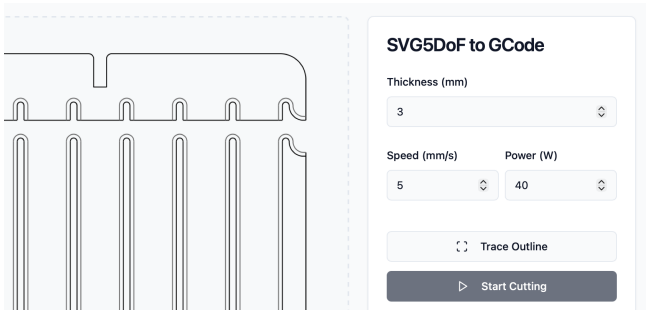


Figure 8: Our tool *SVG5DoFToGcode* allows users to send *SVG5DOF* files to the cutter (editing *connect four*, Figure 23).

5.3 Level 3: Extending Adobe Illustrator

Today's makers use a number of tools to edit their SVG files, such as *Inkscape* [35], *cuttle.xyz* [14], or *Adobe Illustrator* [5]. Our goal is to allow users to create and modify *5DOF* laser-cut models while continuing to use these tools.

SVG5DOF makes this possible: being not only backward- but also *forward*-compatible, any traditional SVG editor loads, displays, and allows editing SVG5DOF files.

Figure 9 shows how a user loads the ocarina from the previous figure into Adobe Illustrator. Here, the user has loaded the ocarina model into *Adobe Illustrator*, selected the mouthpiece, duplicated it, and made it 80% gray (SVG5DOF allows this as an alternative to adding the entry and exit labels), and grouped it with the entry line. The ocarina shows up in thin black lines with the single exit line as a thick gray line. Here, the user selects two points of the exit line using Illustrator's *Direct Selection tool* and adjusts the angle of the mouthpiece by moving the exit line. The user saves the result back into the same file. When editing in a traditional SVG editor, users can simply set the stroke color for entry (black) and exit (gray) lines directly.

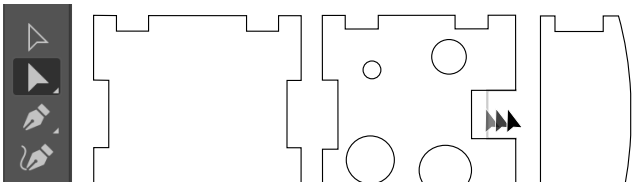


Figure 9: SVG5DOF is backward compatible, allowing users to modify SVG5DOF files in familiar SVG editors, here *Adobe Illustrator*. Here, the user has selected the gray exit line segment using the "direct selection" tool, adjusting it by dragging it to the right.

At the same time, editing an SVG5DOF in a traditional tool is somewhat inefficient and runs the risk of corrupting the file, e.g., by adding a control point to *only* an entry or *only* an exit line. In order to allow users to edit SVG5DOF files more efficiently and without risk of corrupting the file, we created the *5DOF plugin* for *Adobe Illustrator*, shown in Figure 10. As shown, the plugin offers shortcuts that allow providing 3DOF models with commonly used edge profiles.

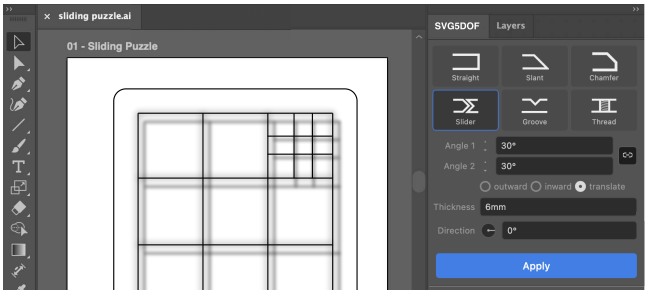


Figure 10: Our 5DOF plugin for *Illustrator* allows users to design a sliding puzzle (Figure 25a) by first drawing the model as a 3DOF model, i.e., just the entry line, select the 5DOF contour they want to create and apply it to the entry line.

Figure 11 shows a simple session, in which the user creates a bevel gear by (a, b) drawing a basic gear using standard Illustrator functionality, and then (c) provides it with a slanted edge. See Section "Mechanisms" for additional examples.

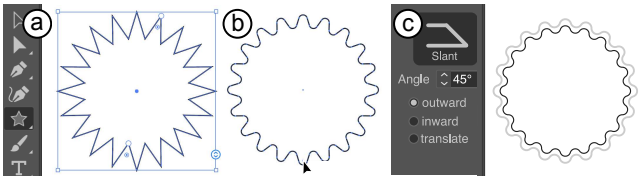


Figure 11: Users create a bevel gear using the (a) "star tool", then (b) round the corners via the corner radius handle, and finally (c) introduce a slant using our "slant outwards" tool.

5.4 Level 4: Converting from 3D Models

One of the application areas enabled by 5DOF is closed box structures that can now benefit from hidden joints (see Section "Hidden Joints"). Makers today create such models efficiently by not modeling individual parts, but by modeling the entire 3D structure in a 3D editing program, such as *Fusion 360* [8], *Rhino* [60], or *Blender* [11], and then extract 3DOF laser cut parts using an appropriate tool, such as using the "Unroll Surfaces" tool in Rhino or a joint generator [78].

To again leverage the software ecosystem 3DOF users are familiar with, we allow users to continue to do so by providing a matching converter tool, which we call *stlTo5DOF* (*TypeScript* frontend connected to *Python* backend via HTTP).

Figure 12a shows the user designing a 3D model in *Blender* and saving the model as an .stl (or .obj) file. As shown, users upload their 3D model, hit "start cutting", and *stlTo5DOF* converts the 3D model to a set of plates with bevel cuts.

StlTo5DOF responds by converting the individual surfaces of the model into solid 2D plates arranged in 3D space, so as to overlap along edges, then using the mesh segmentation algorithm (*Platener* [10]) to identify which parts of the model are represented as a single plate and which as a closed volume. It then creates miter joints by slanting each overlapping edge by half the dihedral angle, i.e., the angle between the adjacent faces, and finally removes overlapping corners by placing an *undercut*, i.e., a cut that reaches below the part. Figure 19 shows the resulting bust.

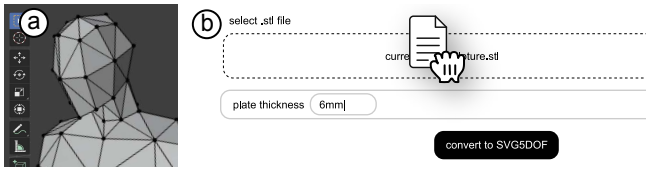


Figure 12: (a) Users start by designing their models in their preferred 3D editor, here Blender [11] and save it as a 3D model (here as .stl). (b) They upload their model to our custom converter tool, stlTo5DOF, (c) specify the material thickness they want to use, and (d) hit [convert] to obtain an SVG5DOF file.

This completes our toolchain. As discussed earlier, it lowers the entry barrier to 5DOF laser cutting for makers by mimicking the traditional 3DOF toolchain used by makers today, and by staying backward- and in many aspects even forward-compatible with existing formats and thus tools.

6 Maker-Oriented Projects Enabled by 5DOF

We used our prototype and software toolchain to explore what opportunities result when 5DOF transitions from industry to today's tech enthusiasts and makers. This means we focused on the materials used by this user group (especially plywood and MDF), the type of structures employed by this user base (cross joints [46], box joints, and T-joints [9]), and the types of models explored by these users.

We focused our exploration on three qualities enabled by 5DOF: (a) *hidden joints* give decorative objects a cleaner look, (a) *interlocking joints* allow taking load-bearing objects, and (c) *cut-in-place mechanisms* allow integrating mechanisms into laser-cut objects without assembly.

6.1 Load-Bearing Models

Traditional laser-cut 3D models held together by box joints and T-joints [9], making the resulting 3D structures robust against compression and shearing, but weak against tension [38]. As illustrated by Figure 13, 5DOF laser cutting can address this by extending the repertoire of available joints with dovetail joints.

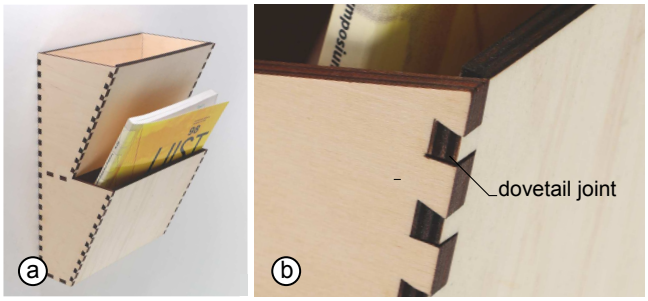


Figure 13: (a) Magazine rack created using our 5DOF prototype. (b) Dovetail joints prevent the front plate from falling out.

Figure 14a shows a laptop case we created using our prototype. (b) The dovetail joints close the chain that connects the bottom of the bag to the handles, allowing the bags to carry heavy loads.



Figure 14: (a) A laptop case based on dovetail joints. (b) Dovetail joints close the chain that connects the bottom to the handle.

Figure 15 shows how we implemented the handle using a dovetail variant of the T-joint.

Finally, as shown in Figure 16a, at times, just the fact that 5DOF allows cutting angled joints delivers a structural benefit, i.e., allowing angled T-Joints to be self-supporting.

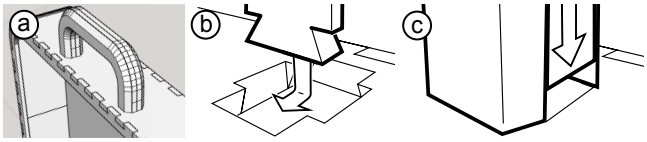


Figure 15: (a) This handle uses dovetail T-joints to withstand tension, which are inserted by (b) pushing the plate through a slot, then (c) sliding the plate into place to lock the joint.

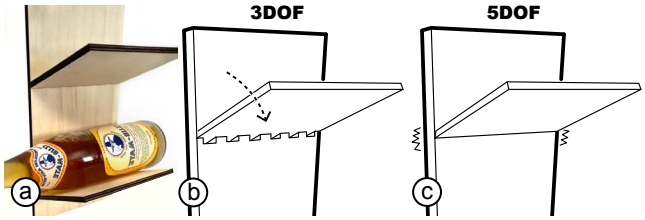


Figure 16: The fact that 5DOF allows cutting these T-joints at the correct angle allows them to take a load.

Technical evaluation: dovetails vs. box joints: To get a more tangible sense of the benefits 5DOF-cut dovetails can deliver, we conducted a brief technical evaluation. As shown in Figure 17, we applied a tensile load perpendicular to one of the joint plate surfaces while fixating the other plate. We repeated this for three test pieces of box joints and three test pieces of dovetail joints, both made from 6mm birch plywood, using our hardware prototype. For both conditions, we choose an interference fit so that the joints are "hand-tight", i.e., require ~100N assembly force [41]. The dovetails used an angle of 7°, matching the 1:8 ratio commonly used for hardwood dovetails [20].

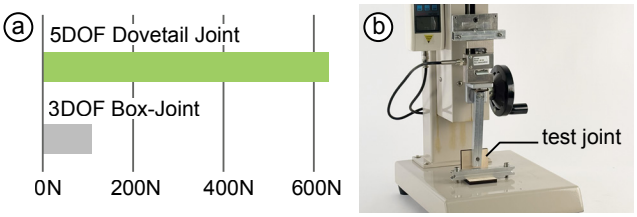


Figure 17: (a) Test setup. (b) Dovetail joints withstood 5.8x higher loads than "hand-tight" box joints.

As shown in Figure 17b, dovetails withstood a 5.8x higher tensile force before breaking than box joints, measured using a force sensor (*HF-5K*), with the dovetails failing because of the plywood itself delaminating.

6.2 Hidden Joints

Laser-cut 3D models traditionally explored by makers tend to be held together by box joints and T-joints. This produces a certain aesthetic dominated by visible plywood edges, visible joints, the latter by default with visible burn marks, and for certain angles also unintentional gaps (Figure 18a and b).

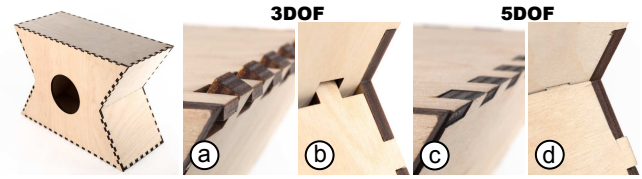


Figure 18: Angled box joints cut with 3DOF have gaps in (a) acute and (b) concave edges. 5DOF laser cutting (c, d) creates flush, angled box joints by cutting at the same angle the joint will meet, here shown on a slap-top cajon.

While some appreciate the distinct look, others prefer to soften the look by sanding down the joints. However, the look never fully goes away, making it difficult to integrate laser-cut objects with objects fabricated using traditional processes, such as objects made from solid wood or mass-produced goods covered with veneer.

Figure 18c and d illustrate an immediate benefit of 5DOF laser cutting, which is that it allows avoiding the gaps caused by slanted cuts. Extending the repertoire of available joints, by hidden joints, allows future 5DOF laser cutter users to integrate their designs with objects without visible fabrication artifacts. As illustrated in Figure 19, 5DOF miter joints achieve a solid wood or veneer aesthetic.



Figure 19: 5DOF enables models without visible joints.

As illustrated by Figure 20, users of traditional 3DOF laser cutters sometimes employ additional connector pieces [23] to connect plates at odd angles without box joints. As a result, the straight-cut edges are separated by gaps. (b) The 5DOF version based on miter joints bypasses these issues.

As illustrated by Figure 21, objects constructed entirely from hidden joints also allow for full-bleed engravings.

The models shown above all enclosed a volume, which allows employing miter joints to their fullest extent. As illustrated by Figure 22a, 5DOF also offers benefits for models made from individual plates: 5DOF allows eliminating the gaps caused by the slanted internal plates and hiding visible joints along the perimeter. However, front and back continue to show the plywood's end grain. (b) 5DOF allows covering these up using a wedge-shaped "veneer".

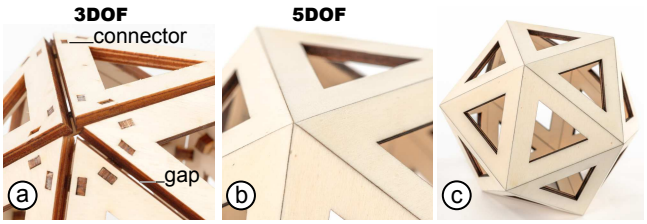


Figure 20: (a) This 3DOF model of an icosahedron desk lamp is held together by an internal support structure. (b) The 5DOF version based on miter joints requires no internal structure.

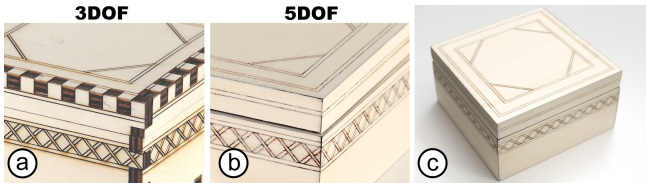


Figure 21: (a) On this traditional 3DOF box, the box joints interfere with the engravings. (b) The same box, made on 5DOF using miter joints, allows for full-bleed engraving.

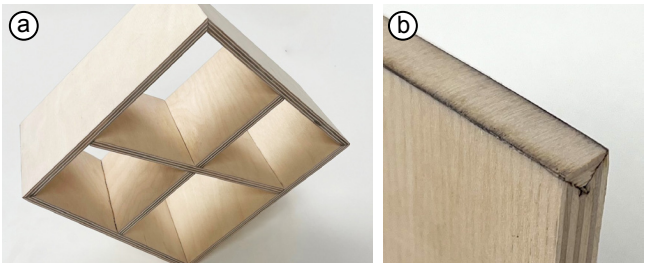


Figure 22: (a) Front and back of plate-based models continue to show the plywood's end grain. (b) 5DOF allows covering these up using a wedge-shaped "veneer".

6.3 Mechanisms

The maker community has produced a wide repertoire of laser-cut mechanisms, including rotating gears, sliders, and hinges. Since they often require stacks of plates [42], they do not offer an assembly-free experience, known from "*print-in-place*" mechanisms in 3D printing [43]. These achieve the same designs from a single part or even fabricate moving parts already in place.

With the transition to 5DOF laser cutting, some of the benefits currently reserved for 3D printing become available to laser cutting, including what we call *cut-in-place* mechanisms.

As illustrated in Figure 23, *cut-in-place* mechanisms trap a piece of material inside the sheet. The trapped piece can move freely in-plane but does not fall out. Figure 24 shows how *cut-in-place* mechanisms are created by cutting from both sides at the example of a simple slider. To cut from the backside, users flip the workpiece and then reinsert it into the remaining material to ensure alignment.

Figure 25 shows variations of *cut-in-place* sliding mechanisms that could not otherwise be assembled, combining (a) multiple

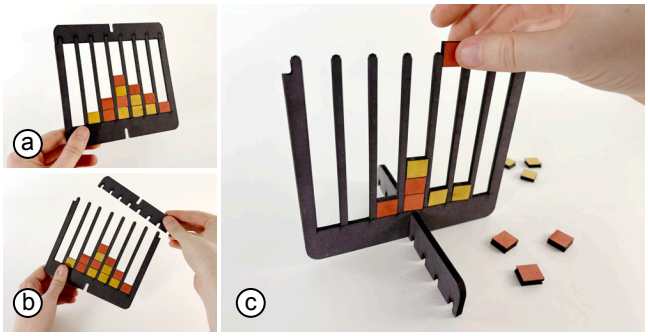


Figure 23: (a) Cut-in-place "Connect Four". (b) The profile of the column prevents the game pieces from falling out (c) but allows them to slide down.

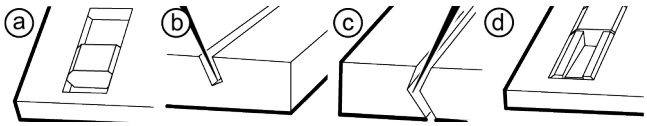


Figure 24: Figure 24: (a) This cut-in-place slider is cut by (b) cutting at an angle to half depth, (c) flipping the part to cut from the backside, and (d) removing excess material to allow the knob to slide.

sliders in a grid or (b) applying a polar transform to the slider mechanism to create a rotary sliding mechanism.

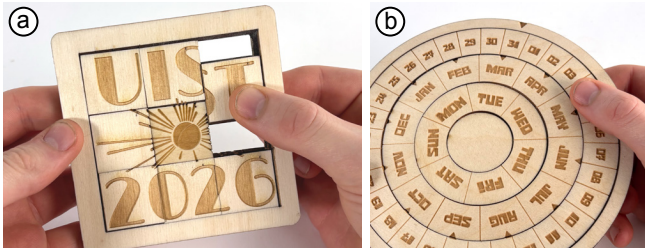


Figure 25: Cut-in-place sliding mechanisms allow creating parts with (a) multiple moving pieces (here, a sliding puzzle) and (b) rotary sliding mechanisms (here, a circular calendar).

In the example above, all relevant contours are horizontal. By making contours drop along the perimeter, 5DOF machines allow creating cut-in-place threads (Figure 26).

Technical evaluation: cutting depth control: To test the reliability of making cuts with a controlled depth, here for creating *cut-in-place* mechanisms, we performed a simple technical evaluation. We performed a series of cuts on 6mm plywood at an angle of 30 degrees from the vertical, with power set to 25%, 50%, and 75%, 10 trials each. Cutting speed was set so that 100% power cuts through. We then assessed the outcomes by cutting the material in half so as to reveal the cuts; this allowed us to measure the cutting depth using a flatbed scanner.

The resulting cutting depths were 20.1% (SD = 1.3), 50.4% (SD = 2.9), 75.9% (SD = 1.8). This suggests that partial cuts up to 75% depth can be calibrated reliably without accidentally cutting through the material.



Figure 26: Piano stool based on a stack of threaded plates.

7 Conclusion and Outlook

In this paper, we reasoned that diode-laser technology will lower the bar for making laser cutters capable of tilting their heads, creating the opportunity to bring 5DOF laser cutters to makers. We anticipated this evolution and presented a prototype of a diode-based 5DOF laser cutter built on technology available to makers today. Using this prototype, we showed how to embed 5DOF cutting into makers' existing software ecosystem to ease adoption: We implemented a 5DOF variant of SVG, an Adobe Illustrator plugin, and two converters. We then used our prototype and toolchain to show what future makers might fabricate using such machines. We found hidden joints, load-bearing joints, and cut-in-place mechanisms.

Which leaves us with the question: will it happen? Whether a technological transition actually takes place depends on the ratio of cost to benefit. In this paper, we have identified potential benefits and demonstrated how to minimize adoption costs by proposing a backward-compatible software toolchain. What remains is to assess

the expected cost of the hardware: what will a 5DOF machine cost compared to an otherwise comparable 3DOF machine?

As shown in Figure 2, the efficiency of laser diodes continues to increase without an obvious limit. Therefore, we anticipate that this evolution will continue to the point of a laser source delivering the required power without heatsinks and from a single laser diode.

At this moment, one would re-evaluate the form factor (Figure 27), e.g., using the form factors of 5DOF milling machines as a basis. All these designs have their own strengths and weaknesses. However, the double tilt-mechanism shown in Figure 27e will probably come out on top: for a tiny and light laser head, this mechanical design comes down to two small stepper motors (with appropriate resolution to eliminate the zero-backlash gearboxes), and an (injection-molded) mount, making 5DOF a low-cost feature.

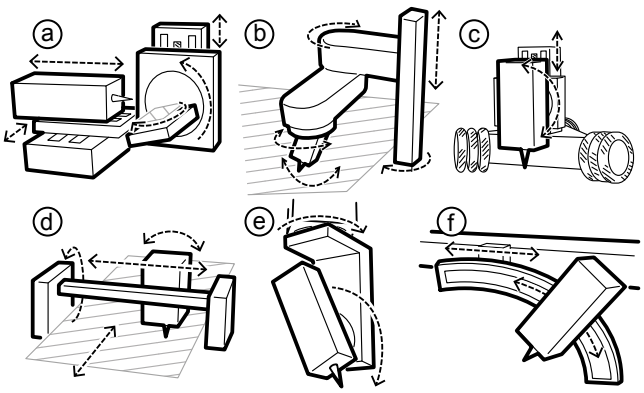


Figure 27: What might be the form factor of future 5DOF laser cutters? Drawing inspiration from milling machines may include (a) *PocketNC* [58], (b) *SCARA* [37] and *Dobot* [16], (c) *Goliath* [63], (d) *Glowforge* [26], and (e) *Trumpf* [71]. (f) Or an entirely new design?

Given the low cost and the easy-to-adopt toolchain, the added value we found in our exploration makes it quite conceivable that, in the future, essentially *every* laser cutter sold to makers might offer 5DOF capabilities.

As future work, we plan to continue our exploration by prototyping such a future miniaturized 5DOF device.

Acknowledgments

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