Prototype Hardware for Personal 5DOF Laser Cutting Enabled by Compact Diode Lasers

Antonius Naumann
Human Computer Interaction Lab
Hasso Plattner Institute
Potsdam, Germany
antonius.naumann@hpi.de

Abstract*— *There has been a recent advent of diode-based laser cutters and a significant uptake among makers. In this paper, we argue 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—previously available only to industrial users—to makers. We anticipate this evolution and present a prototype of a diode-based 5DOF laser cutter built on technology available to makers today. We finally ask: Which hardware designs might be enabled if the trend of shrinking diode lasers continues?

I. Introduction

Laser cutting is faster than 3D printing [2], can cut natural materials, and is easier to handle than CNC milling, as it does not require fixtures [24]. 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* [40]), many load-bearing joints (such as *dovetails* [15]), and many types of mechanisms [20].

Many such designs could be enabled if laser cutters with tilting heads were widely available. Such 5-degree-of-freedom laser cutters do exist in industry [39], but unfortunately, are unfit for makers: (1) The wavelengths used by fiber lasers [25] are unfit for the materials used by makers (such as MDF or wood [8]). (2) CO_2 lasers with 5 degrees of freedom use optical paths across at least five mirrors, which requires an undue amount of maintenance [32].

However, the recent advent of *diode lasers* [23], which are small enough to be mounted directly on the gantry, might change this in the not-so-distant future. While today's diode laser modules are still relatively heavy (>1kg for a 70W module [16]), mainly due to their low efficiency and the resulting large heat sinks, this avenue is worth pursuing, as diode laser heads are shrinking: Due to growing efficiency (Fig. 1), *heat loss* is currently halving every 9 years [19][31] allowing heat sinks to shrink and ideally disappear. At this point, adding five degrees of freedom (5DOF) could become a commodity.

Encouraged by this outlook, we created a hardware prototype (Fig. 2) of a desktop 5DOF laser cutter from maker-available components. We then discuss the implications for future hardware designs, provided this trend continues.

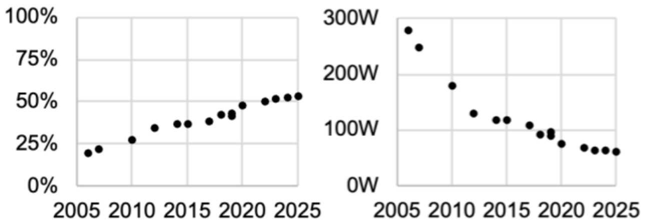

Fig. 1. (a) Laser diode efficiency is continuing to grow, causing (b) waste heat and thus heatsinks to shrink exponentially (data aggregated from [19] and [31]).

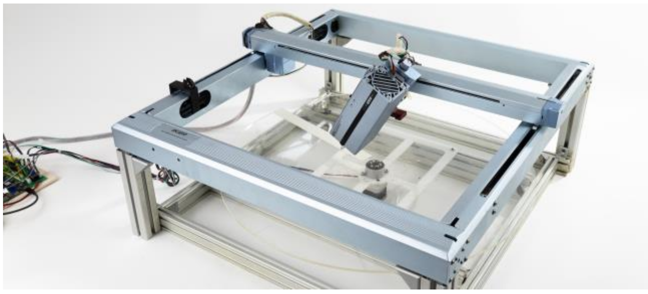

Fig. 2. Our hardware prototype of a 5DOF desktop laser cutter

II. Related Work

A. Fabrication Machines w/ Additional Degrees of Freedom

Researchers have started exploring additional degrees of freedom to enable additional use cases. *On-The-Fly Print* [27] explores a 6DOF 3D printer that allows printing low-fi features onto existing models during 3D modeling. *RoMa* [26] shows a 3D printhead mounted on a 6DOF robot arm with a rotating build plate, printing the model *in situ*. *RevoMaker* [9] uses a 2DOF revolving platform to enable printing around a prefabricated cuboid. *Patching Physical Objects* [37] adds a mill and two additional degrees of freedom to modify existing prints. *Isa et al.* add a rotational axis to enable freeform surfaces without the staircase effect [17]. Similarly, *Dai et al.* add a rotational axis to print overhangs without supports [4].

In 3D printing, the S3-Slicer [42] generalizes slicing for multi-axis printing, while Open5X [13] presents a slicer for five-axis 3D printing targeted at desktop users.

We present a prototype of a desktop-sized 5DOF laser cutter and use it to explore the different applications it enables, in particular models without visible joints, load-bearing joints and *cut-in-place* mechanisms.

B. 5DOF Laser Cutting

Laser cutting beyond three degrees of freedom today is largely limited to industrial use [39]. In industry, however, 5DOF laser cutting has a decades-long history. In the 1980s, *Prima Industrie* [12] 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 [39]), but remain complex to maintain [32]: As CO2 laser sources are large, the laser is routed through a mirror system on the gantry and through a hollow 2DOF robot arm [25] containing rotating mirrors that are hard to align [5].

While more recent fiber lasers simplify the optical path down the robot arm [21], reducing maintenance to a fifth [32], they are limited to cutting metal [34], and are unsuitable for cutting materials used by non-experts, such as wood [8]. Thus, five-axis machines have been limited 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* [10] achieves this by putting the CO2 laser tube on the gantry [11]. Apart from specialized use cases, such as rotational add-ons [38] for engraving round objects, 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* [22] achieves up to 10W optical output with a single emitter, others, such as *XTool* [41], combine multiple smaller diodes (6W), resulting in up to 70W output power with 25% efficiency [16]. This low efficiency requires heavy heat sinks for cooling. To reduce weight, *Atomstack* [1] uses water cooling for its 120W optical output module. Even higher output power has been achieved by *TeraDiode* [14], which invented a method for combining multiple diodes to achieve a beam quality suitable for cutting in the kilowatt range.

III. Personal 5DOF Laser Cutting Machines

A. Existing Machine Prototype

Our prototype device is based on an off-the-shelf 70W diode laser cutter (*iKier Pro 70W* [16]). We added motorized *tilt* and *yaw*, the latter via a rotating cutting table. Fig. 3 shows how we inserted the tilt mechanism.

As illustrated by Fig. 3c, the tilt mechanism's main mechanical component is the stepper motor (Nema 14, 5Ncm torque, 0.9° step angle [36]). 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. To prevent imprecision from slack, we use a non-slack gearbox (*PGFUN Harmonic Gear Drive* [28]). We hold parts together using a custom CNC-milled aluminum mount. Fig. 4 shows a more recent iteration that integrates the end stop.

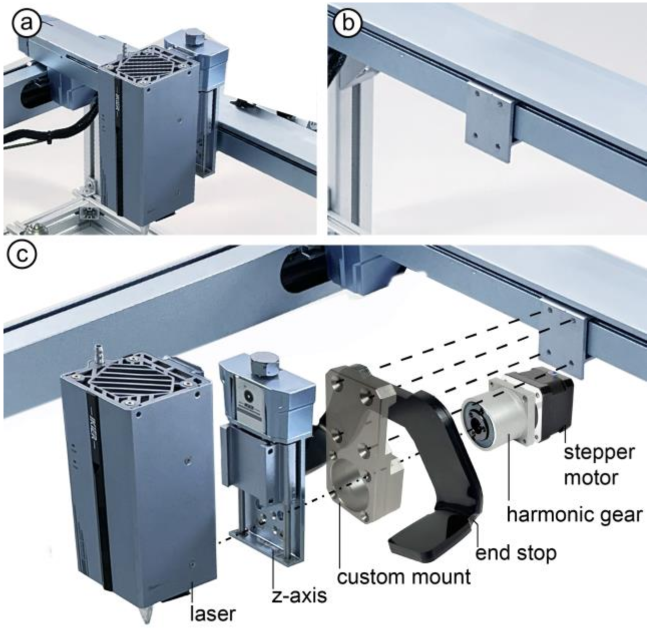

Fig. 3. We added head tilt to an off-the-shelf laser cutter by (a) removing the laser head and z-axis from the gantry, then (b) using the exposed mount (c) to insert a stepper motor and a gearbox, held together by a custom mount.

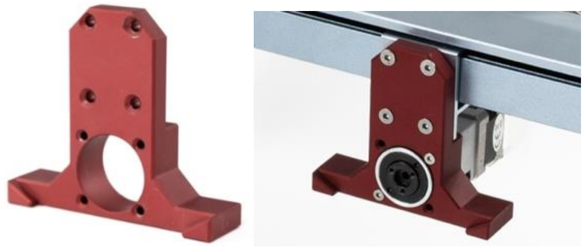

Fig. 4. More recent iteration of the custom aluminium mount that integrates the end stop for cutting at up to a ±60° cutting angle

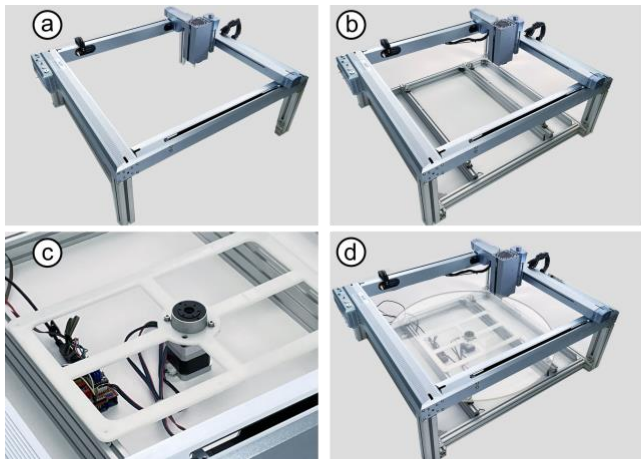

Fig. 5. (a) Starting with an off-the-shelf laser cutter [16], we add yaw by (b) extending the frame with a mount, (c) adding a stepper motor and non-slack gearbox, and (d) adding the round table

As shown in Fig. 5, we add a second degree of freedom by rotating the table. The benefit is that it reduces imprecision and increases stability [3] compared to a double-tilt design. We extend the bottom of the casing with a mount and four bearings to support the rotating table, into which we mount a second stepper motor (Nema 17, 26Ncm torque, 0.9°

stepping angle [35]), again geared down 50:1 using a non-slack gearbox (*PGFUN Harmonic Gear Drive* [28]), giving us a 90µm resolution along the perimeter when rotating the workpiece. On top, we mount the round cutting table.

B. Controller

Our hardware prototype described in the previous section uses five stepper motors to actuate the device in x, y, z, b (tilt), and c (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.

We picked a CNC controller board capable of controlling five machine axes (*FluidNC Corgi* based on an *ESP32* [6]) and the matching control software (*FluidNC* [7]).

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 plan to open-source along with the CAD files for the hardware prototype.

C. Future Miniature Designs

We imagine a future in which consumers have access to 5DOF laser cutters. What remains is to assess the expected cost of the hardware: what will a 5DOF machine cost compared to an otherwise comparable 3DOF machine?

If the current trend of more shrinking diode laser sources continues, one would re-evaluate the form factor (Fig. 6). All these designs have their own strengths and weaknesses. However, the double tilt-mechanism shown in Fig. 6e 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 no-slack gearboxes), and an (injection-molded) mount, making 5DOF a low-cost feature.

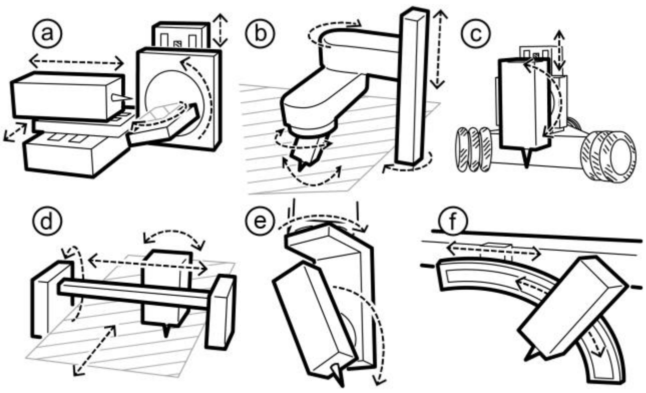

Fig. 6. What might be the form factor of future 5DOF laser cutters? Drawing inspiration from milling machines may include (a) *PocketNC* [29], (b) *SCARA* [18] and Dobot [30], (c) *Goliath* [33], (d) Glowforge [10], and (e) [39]. (f) Or an entirely new design?

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.

IV. Responsible innovation

With the increasing adoption of fabrication devices, mainly 3D printing, exploring ideas through rapid (physical) prototyping. While laser cutting is fast and can process natural materials such as wood without fixtures, 3D printing is often preferred for its geometric expressiveness. We demonstrate how 5DOF laser cutting enables new applications for laser cutting in personal fabrication (Fig. 7).

Fig. 7. Our hardware prototype enables new applications for laser cutting, such as objects without visible joints or edges, load-bearing joints such as dovetail joints and *cut-in-place* mechanisms

We plan to open-source our hardware modifications along with our software toolchain to increase access to 5DOF laser cutting. Future hardware iterations would focus on achieving smaller form factors relevant for non-expert users.

V. Author bio(s) / experiences

My name is Antonius Naumann, and I am currently in my second year as a PhD student at Hasso Plattner Institute, advised by Patrick Baudisch. I am curious about how personal fabrication will evolve with more compact fabrication devices, particularly shrinking laser cutters. For my first project, which is partially presented in this submission, I am looking into how the trend of shrinking diode laser cutters enables personal 5DOF laser cutting, from building a desktop-sized prototype device to integrating existing file formats and toolchains used by makers with 5DOF laser cutting.

In future projects, I plan to explore miniature fabrication devices such as laser cutters through hardware prototypes.

VI. Acknowledgements

Thanks to the Research School on System Design at Hasso Plattner Institute for supporting this work, and my advisor, Professor Patrick Baudisch, for his supervision.

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