Design Different: Pen and Paper for Laser Cutting

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***Abstract*—Interdisciplinary teams and studies need new approaches to design prototypes using tools indistinguishable from the ones they are used to. We utilize a digital pen and physical paper, as the everyday life tools, to build a smart interface for laser-cutters, giving non-technical experienced people the possibility to rapidly, seamlessly, and collaboratively fabricate creative prototypes.**

One of the most potent tools humankind ever invented is the pen. People perceive it as a natural tool, an extension to their body to sketch ideas and be creative. In the digital age, its power is often underestimated due to its analog nature, simplicity, and intuitive handling. Utilizing purely digital computer-aided design tools for designing and sketching models, the natural haptic feeling and ease of use characteristic of a pen is lost. We investigate the use of pen and paper as an interface to rapidly prototype models for laser-cutting. Working with such a simplified pen-based design interface, the traditional, more complex process of designing a laser-cutting prototype can be abstracted. Users can focus on their design task and creativity rather than on the sophisticated toolchain behind laser-cutting and modeling.

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A laser-cutter is a precise instrument that allows cutting arbitrarily complex forms using a laser out of defined sheet material. Already heavily used in the industry for manufacturing, they entered the ecosystem of personal fabrication because of their rapidness, precision, and availability.[1] Using a laser-cutter to perform fast and precise operations dramatically reduces the time needed to produce the first prototype of an envisioned model. The creation of the laser-cutting model itself is usually based on sophisticated computer-aided design (CAD) or illustration software, which requires expert knowledge or trained personnel to get the desired results. These processes can be highly frustrating and annoying for people, especially for newcomers, as it can take quite a long time until they have their first prototype in their hands. Our work focuses on leveraging the benefits of physical pen and paper[2] to build a sketching interface for modeling objects for rapid prototyping with laser-cutters for novice users. The whole design to manufacture process is streamlined by hiding most of the complex laser-cutting processing steps from the user. Our proposed system provides an easy and intuitive to use tool with direct haptic and visual feedback.

Beside the pure digital laser-cutting process, there is evidence in psychology and education,[3] that pen and paper computing is highly beneficial in combining both worlds: first, the benefits of the digital technology (e.g., editing, sharing, and processing) and second, the benefits of pen and paper in having a haptic feedback, active motor function and cognitive stimulus while writing and sketching.[4]

RELATED WORK

Personal fabrication tools, such as laser-cutters[5] and printers revolutionize the design, production, and distribution of material goods. An essential requirement of rapid prototyping is speed,[6] as faster iterations allow for multiple improvement iterations, and thus, results in a better design within a mostly restricted time frame.[7] Rapid prototyping can be seen as a critical technique in the design process to get the right design and get the design right.[6] 3D printers are one of the most popular fabrication tools right now,[7] but printing more extensive, complex 3D models can easily take overnight. In contrast, laser-cutters are "lightning" fast, and users have the result in their hands within minutes and can iterate and improve their design. Fabrication speed is a crucial aspect that makes laser-cutters more appropriate for rapid prototyping.

Common to all personal fabrication tools (e.g., 3D printer, laser-cutter, CNC machine) is the need of a virtual representation, a schematic, a drawing, or a 3D model of the object to be produced. The well-established process of using specific CAD-based tools on desktop computers induces a steep learning curve for both beginners and experts. To overcome the limitation of the learning curve, more natural and creative ways of interaction were proposed. Mueller *et al.* presented a method,[8] where a laser pointer was used as an input device for directly drafting models onto the workpiece. Their system tracks the handheld pointer, beautifies the paths, and cuts the workpiece step by step. Song *et al.* proposed a system,[9] with which the physical paper prototype can be altered with different colored pens representing commands like annotations or shape edits. Other approaches use ordinary flatbed scanners, which are used to manually digitize physical object schematics into a machine-processable representation[5] or pen-based sketch manipulation on a desktop[10] or tablet-like computer.[11] Some proposed design solutions provide the ability to use tactile feedback[12] that would enrich the overall user experience. Using "classic" pens is not widely adopted in the existing personal fabrication tools. The outlined design methods represent a step backward in preserving the human hand manipulation of physical materials, which significantly contributes to the pleasure of craft and material experience while making the process more accessible.[13] We see these approaches as an excellent starting point for the generation and alteration of 3D and 2D objects by interweaving a physical and virtual representation of an object.

As paper does not yet incorporate the dynamics of a digital representation, the old and static pen and paper approach[14] provides users with direct feedback, is extremely flexible in augmenting, provides an easy to grasp creative interaction interface, allows fast annotation and is an inexpensive way to display and share information.[15] Considering these advantages in comparison to the currently published work, we see that most alternative rapid prototyping modeling interface approaches seem to neglect the easiness of the combination of pen and paper. The setups are first, stationary and with heavy hardware equipment (e.g., projectors or tracking systems), second, need great variety of tools (e.g., markers or laser pointers) to specify the laser-cutting behavior, thus, making the interaction overly complicated and attention consuming, third, require a long learning phase for a novice user, and fourth, do not provide a seamless automated process with excellent user experience.

We will utilize the beneficial usability characteristics of pen and paper-based design processes to be first, independent of working and fabrication environments to sketch the model and second, independent of specific mechanical and software tools. We do not intend to build the perfect and most accurate sketching solution, comparable in accuracy with expert CAD tools nor to build a software solution for tablets, as some of the specific pen and paper feeling would get lost. We intend to support rapid prototypers, who utilize personal fabrication processes for creating fast and adequate, accurate laser-cut research prototypes.

Figure 1. Overview of a tangram puzzle game for a user study, which was designed with SparkLaserCut and custom Bamboo Spark notebook with virtual paper buttons for the laser-cutter modes.

SYSTEM DESIGN

To achieve effortless handling, we opted for the Bamboo Spark digital notebook from Wacom, which is available for DIN A5 or DIN A4 paper sizes. Its primary use case is digital note-taking, but also sketching and illustration of graphics using pen and paper. The Bamboo Spark can utilize a wide variety of paper types and provides the characteristic pen and paper experience to the user. These features make it multifunctional, cost-effective, and adjustable to the application scenario (i.e., particular paper types and sizes: isometric or perspective paper, templates, mm- or inch-paper). Besides the excellent adaptability, Wacom's electromagnetic resonance (EMR) technology offers the highest pen-tracking accuracy while keeping the pen compact. The Bamboo Spark pen dimensions match closer to an ordinary pen compared to the other digital pen products that utilize the traditional infrared dot-positioning paper with cameras and buttons inside the pen.

Sketching a laser-cutter model on physical paper sets our approach apart from other pen-based interface combinations. The roughness and texture of the paper surface and the haptic sliding characteristics of the pen are entirely different compared to the "slippery" glass surface of tablets (e.g., Microsoft Surface or Apple iPad). Furthermore, most conventional digital pens for tablets have a large and bulky pen tip, which makes accurate sketching of fine details challenging.

Bamboo Spark—The Adapted Laser Cutter Interface

The Wacom Bamboo Spark does not need to be modified physically for the laser-cutter modeling use case. To provide access to the two major operating modes of a laser-cutter (e.g., cutting and engraving), a virtual paper button interface for selecting fabrication modes was implemented. We added four mode selection buttons (cutting, engraving, commenting, deleting) at the top of a custom-designed paper notebook for modeling laser-cut objects with our SparkLaserCut system (cf. Figure 1). In order to change the current mode, the user must make a stroke input with the pen in the desired mode selection box. A laser-cutter mode remains selected until the user makes another manual selection, or a new page is started. The comment state is set by default when on a new page. Additional guidance in the design process is provided through the millimeter paper layout of the notebook and optional sketching tools (e.g., rulers or set square) to the user.

Tablet Controller Application—The Middleware

A digitized sketch from the Bamboo Spark cannot be used directly for laser-cutting. Ideally, a vector graphics file with appropriate drawing path attributes for the different modes of the laser-cutter (e.g., cutting or engraving) is needed as input. Additionally, the previously described mode button inputs (cutting, engraving, commenting, deleting) need to be analyzed and applied to the paths of the document.

To identify the different modes (cut, engrave, comment, and delete) and encode them into the final data file for the laser-cutter, a stroke mode analysis algorithm has been developed. The algorithm analyzes the user input based on the 2D pen

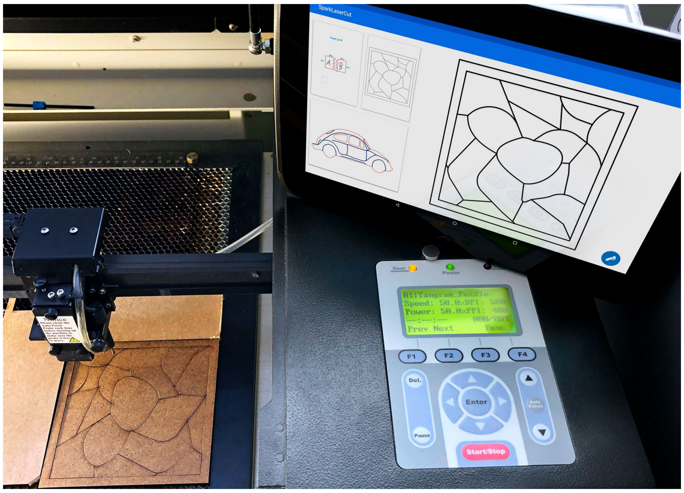

Figure 2. Overview of the SparkLaserCut tablet middleware interface and a laser-cut tangram-like puzzle example that was designed using the Bamboo Spark.

coordinates and the orientation of the notebook and classifies the strokes as specific button inputs or regular sketching lines. The algorithm assigns the strokes that were produced in a timely consecutive order to one of the laser-cutting mode properties. These settings include the layer mode, path width (e.g., cutting 0.015 mm) and color parameters (e.g., red: cutting or blue: engraving). Most of these settings are specific to the used laser-cutter machine and have, therefore, been incorporated in a tablet middleware application. Note that commenting is not included in the final generated laser-cutter file and is only viewable in the vector graphics file. The comment mode enables note-taking and parallel developing of a laser-cutting model without the need for changing the tool or interrupting the process in e.g., a meeting.

The goal is to make the entire processing steps more intuitive for novice laser-cutter users and provide a seamless user experience. We achieved better usability with a middleware application between the Bamboo Spark notebook and the laser-cutter machine controller. In our prototype, we implemented an Android application, that runs on a tablet mounted to our laser-cutter (c.f. Figure 2). For other machine applications, the middleware interface could easily be implemented in the laser-cutter controller itself. The middleware enables openness and flexibility as laser-cutter manufacturers just have to provide the defined Bluetooth interface to allow the integration of third-party sketching interfaces.

Once the user has sketched the design and is ready to process and manufacture a first prototype piece, the digital design files from the Bamboo Spark are wirelessly transferred to the laser-cutter controller with a press of the sync button. From there, the sketch data is automatically analyzed, optimized, and converted into a laser-cutter compatible format. The resulting file can optionally be viewed and manipulated (i.e., line beautification based on semantic analysis of sketches combined with adaptable beautification levels). To start the laser-cutting process, the user has to select the desired sketch and follow the standard laser-cutter operation procedure.

Using the Bamboo Spark notebook and the developed SparkLaserCut middleware, one can hand-sketch arbitrarily complex and creative figures using pen and paper and transfer the designs seamlessly and true to scale to a laser-cutter for prototype fabrication.

SPARKLASERCUT EVALUATION

To evaluate the benefits of our pen and paper approach for rapid prototyping with laser-cutters, we first, conducted a small-scale usability user study, comparing SparkLaserCut and traditional CAD tools, second, deployed the Bamboo Spark in the real-world prototyping design application to fabricate a tangram-like puzzle for a children behavior research project, and third, presented the final demonstrator of our system to the creative audience at a local maker fair.

Usability Study—SparkLaserCut and CAD Workflow

With a small-scale user study, we evaluated our sketching approach with novice users to gather their first opinion and impressions of the SparkLaserCut system in comparison to a more traditional vector-based CAD tool (e.g., Corel Draw or Adobe Illustrator). Three common laser-cutting design scenarios with different, rising complexity were covered in the study: (I) a basic geometric rectangle shape, (II) two rectangles with interleaving finger joint connection, and (III) complex, irregular and overlapping free-hand creative design. The three tasks were abstracted and categorized based on the most popular laser cutter designs on the online platform Thingiverse. We reviewed the top 1000 laser cut items with most likes and makes in the community and identified common design patterns (e.g., joints, complex shapes, or mechanics). We cumulated our statistical findings and abstracted the most commonly used design practices in three scenarios (I to III). Spark and Illustrator present different approaches on how to design the prototype. We compare the usability, intuitiveness, and efficiency of both approaches with three design tasks with raising complexity. Each task focuses on special design skills of the study participants. All scenarios had to be performed on both first, the Bamboo Spark with paper and pen and second, with the well known and commonly deployed vector-based graphic editor Adobe Illustrator. Before the study, a short introduction and how-to for the Adobe Illustrator application and the Bamboo Spark system was given to allow the participants to familiarize themselves with the provided tools, ensure a comparable level of expertise with the tools and to build evidence in order to cross-check the self-assess usability questionnaire. The study evaluation was focused on the overall usability and likeability of the provided design methods, as well as the perceived sensations of the novice users. Further, design time and sketch accuracy measurements were included in the evaluation as secondary means of comparison between the traditional CAD and the SparkLaserCut workflow. Participant feedback about the usability was collected with a Likert-type scale questionnaire and an additional poststudy, semi-structured interview session. The smallscale study was carried out with 15 students, who had a wide variety of study backgrounds, but limited experience with personal fabrication and related design tools.

Research Project Application—Designing a Tangram Puzzle

In an ongoing research project, we study the evolution of learning capabilities in combination with problem-solving strategies of preschool children over a more extended period of time. In one of the multiple conducted studies, the children were asked to solve custom tangram puzzles. In addition to the time it took each child to complete the puzzle, we observed their attention using eye-trackers, their emotions, general behavior, utilized approaches, and strategies to solve the puzzle. As a reward for the completion of the session, the children got to keep the puzzle game.

For the study, we needed to design and fabricate 35 custom tangram puzzle games (cf. Figure 1) with the help of a psychologist and the class teachers, thus, our system provided first, the more intuitive solution to permit parallel working on the design with people having a diverse, non-technical background and second, rapid fabrication of the needed customized tangram puzzles even integrating feedback that was gathered after each study iteration.

The specifications for the puzzles were outlined as 15×15 cm size, around 20 pieces in four to five different colors and arbitrary complex-shaped puzzle pieces. The individual puzzle games had to be manufactured at low cost and in a short turnaround time. We evaluated the time and cost of designing and manufacturing a puzzle with a 3D printer and a laser cutter. The tangram puzzle design for laser cutting was iteratively designed using the SparkLaserCut system, whereas the laser cutter concept sketches inspired the blueprints for the 3D printer and developed in Autodesk Fusion 360. An oneoff prototype puzzle was created with both fabrication methods to assess the time, cost, and quality aspects of the manufacturing processes as well as the potential to be used by the diverse study team members to adapt the prototypes and work in parallel.

Maker Fair—Meeting the Target Audience

As a follow-up to the lab-based study and to further review the usability, the potential and the usefulness of the pen and paper-based laser-cutting approach, getting it as close as possible to a possible target audience, we presented SparkLaserCut to visitors at a well-established maker fair where creative makers and rapid prototypers meet. Roughly 10 000 visitors over three days were joining the fair.

We demonstrated our system and let visitors try it out. Due to the uncontrollable nature of the event in terms of how much time people spent at our exhibition stand, we decided to interview them on the fly based on the developed user study questionnaire. Over the three exhibition days, we interviewed 53 people that spent on average 10 min at our booth. Interested visitors were introduced to the concept idea behind SparkLaserCut and invited to use and experiment with the prototype system. As part of the trial sessions, the visitors were actively engaged in an interview to collect personal feedback and their points of view on the SparkLaserCut system. From the evaluation of the interview notes, the interest and the need for this easy to use a laser-cutter design interface was clearly shown.

RESULTS AND DISCUSSION

User Study

The invited 15 "novice" study participants had a median age of 25 years, were 53.3% female (8) and 46.7% male (7). They were randomly selected with an open recruiting system. With a Likert-type scale questionnaire, we a-priori evaluated the general computer skills of the participants, their experience with graphical CAD tools and their interests in rapid prototyping and laser-cutting. The participants rated their computer skillset as average. None of the study participants had prior experience with specialized CAD software tools or the general laser cutting design and operation process, though six participants stated to have basic knowledge of some illustrating software.

Throughout the user study, three data parameters were collected for each of the two used design tools: (i) scenario editing time, (ii) sketch design accuracy and (iii) design tool usability. To evaluate statistically significant differences in editing time per scenario between the Bamboo Spark and Adobe Illustrator, the Wilcoxon signed-rank test was used due to the nonnormality of the data (tested with the Kolmogorov-Smirnov-Test and additionally backed by a sample size < 30). The statistical significance level was selected as $p < 0.05$. Results of the design task time comparison Bamboo Spark versus Adobe Illustrator are for the given scenarios: (I) $p = 0.607$; (II) $p = 56 \times 10^{-8}$, and (III) $p = 19 \times 10^{-9}$.

The mean completion time in scenario (I) was 45 seconds with the Bamboo Spark and 48 seconds using Adobe Illustrator. Scenario (I) was found easily doable with both input methodologies by the participants, backed by no statistically proven difference in the time data.

For the second given task (II), a significant difference was shown in the completion time, since the participants needed on average 145 seconds with the Bamboo Spark and 575 seconds with Adobe Illustrator. Time differences within the Bamboo Spark are explainable with the accuracy, and finesse participants drew the finger joints. Although participants needed more time with Adobe Illustrator, they managed to achieve better accuracy, mostly due to straight lines and the line snapping functionality (no holes in corners) of the computer vector graphic tool.

The third scenario (III) was completed on average in 205 seconds with the Bamboo Spark. Around 60% of the study participants reached the time limit of 900 seconds while trying to complete the sophisticated free-hand design in Adobe Illustrator. For this scenario, Adobe Illustrator would be the wrong choice for novice users. In comparison, using the Bamboo Spark participants could just put the object on the paper and trace it with the pen. Tracing the object was significantly faster and much more accurate than anything that was performed by the participants with Adobe Illustrator. This scenario impressively highlights the possibilities when sketching a free-hand form prototype with pen and paper, especially when a physical representation is available.

The accuracy classification of the sketched laser-cutting models is based on a simplified classification scheme with four classes (not matching, matching to a lesser extent, matching to a greater extent, full match). All sketches created by the study participants were evaluated by two independent judges with advanced backgrounds in CAD, by overlaying the study datasets and the reference scenario files in Adobe Illustrator. The task at hand was to identify general issues in the sketches and categorize their fit based on the four given categories. We chose to use the assessment of experts rather than relying on questionable and possibly imprecise mathematical approaches. The accuracy of the simple rectangular shape from the first scenario (I) was equivalently for both used design methods. In the second scenario (II), where detailed finger joints had to be precisely modeled, the evaluation favored Adobe Illustrator with a mean accuracy rating of 73%, whereas the Bamboo Spark sketches were only rated 31% accurate. The advantages of the

SparkLaserCut approach were clearly shown in the third scenario (III), where the Bamboo Spark achieved an average accuracy of 68%, whereas the Adobe Illustrator models were only judged to be 23% accurate. The free-hand modeling application cases, where a physical object was given to the study participants to replicate, revealed the full benefits of the paper and pen approach. The more complex the forms get in terms of being composed of nonstandard geometric shapes, the more beneficial the use of pen and paper for sketching gets. When a physical (but no digital) representation of the object is available, tracing it with pen and paper is significantly faster and more accurate than using a software tool (e.g., for a repairing task based on a broken piece).

Besides the quantifiable, metric results, we interviewed the study participants using a questionnaire about their opinion and practical, hands-on impressions when using the two input methodologies. The study participants rated the modeling speed of the SparkLaserCut system significantly higher compared to Adobe Illustrator. Furthermore, the learnability was said to be higher for the Bamboo Spark as it is easier to use, and a specialized tool compared to the multipurpose vector graphic tools. The haptic feedback of pen and paper and the experience sensations were rated very good and positive for the Bamboo Spark notebook. The design process with Adobe Illustrator was mostly described as frustrating and cumbersome in the overall handling by the novice users. With the Bamboo Spark, participants felt closely connected to what they had to model and could focus their attention on the task rather than being distracted by the overwhelming functionality and complexity of the CAD tools. Most participants identified the most significant drawback in the achievable accuracy with the included Bamboo Spark pen. The mechanical limitation of the standard ball pen with its large 1.25 mm tip leads to users stating that this tool is too imprecise for the shapes, and a finer pen (e.g., a pencil) was expected to be beneficial to raise precision. Additionally, participants were missing interactive feedback for the currently selected operational mode.

Tangram Puzzle—Application Case

The first concept design sketches of the puzzle were developed on the Bamboo Spark notebook during a project meeting. Different arrangements of layouts and puzzle piece configurations were conceptualized. After some iterations, the final design was derived on the Spark notebook and translated by a professional CAD designer for the 3D print. The Bamboo Spark has proven to be the superior design tool for the iterative rapid prototyping of the tangram puzzle. In terms of speed, flexibility, and adaptability, the traditional CAD solutions did not fit into the research focused rapid prototyping process and were cumbersome to work with for the novice users.

During a 15-minute project meeting regarding the tangram puzzle user study, five different variations of the puzzle were iteratively designed by the meeting participants using the Spark notebook. The final sketch file could be transferred effortlessly to the laser cutter and was ready to be manufactured in under a minute. In contrast, just the conversion process from the final SparkLaserCut sketch to a 3D model with professional CAD software took longer with around 18 min. This timeframe also includes the post-processing in the slicing software, which is needed for most standard 3D printers.

The next important factor is the actual time for the machining process. 3D printing one complete puzzle in one color with fast print settings took 2 h 35 min with our Ultimaker 3 printer. A complete tangram puzzle assembly with various colored pieced could be manufactured with the laser cutter in 5 min and 50 seconds. The quality and fit of the fast-printed parts from the Ultimaker 3 and the laser-cut parts are shown in Figure 3. Cost wise the 3D print is 0.89€ cheaper than the laser-cutter per puzzle (5.07€/4.18€) but with a significantly longer manufacturing time.

In conclusion, the SparkLaserCut system represents a more agile, time- and cost-effective solution in this use case application. The laser-cutter fabrication process is about 25 times faster. The accuracy and finish of the fast-printed parts are inferior to the laser-cut puzzle pieces. With the SparkLaserCut system, we were able to iteratively design, prototype, and manufacture the tangram puzzles needed for the user study within one working day.

Maker Faire

Besides the benefits of the SparkLaserCut system identified in the user study and the

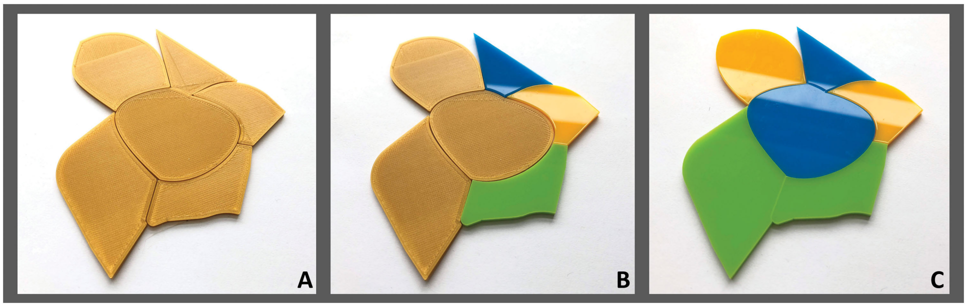

Figure 3. Comparison of the precision and finish quality differences between 3D printed puzzle pieces (A) and laser-cut tangram pieces (C). The 3D printed parts have a rougher finish and do not match the perfect fit of the laser-cut puzzle pieces.

tangram puzzle application case, further application cases have been clearly identified by the audience at the Maker Fair as:

- Preschools where simple parts of games that are lost (e.g., pieces of a puzzle, Connect Four, etc.) can be easily reproduced by tracing the surrounding boarders of the existing parts.
- Artists without CAD experience or empirical knowledge were impressed to use SparkLaserCut for engraving love-locks with your own handwriting. Until now it is sketched/drawn by the customer on paper and scanned into the computer and refined by hand. Our interface would speed up this specific process significantly.
- Hobby model makers mentioned they would not use SparkLaserCut for sophisticated highly-detailed models, but for fast and roughly design-drafts or non-visible support bracing parts in their models.
- Architects mentioned using SparkLaserCut for rough architectural models that are based on Styrofoam layers. Currently, each layer is manually derived per hand from the building plan and then stacked and glued.

General observations included the fast understanding of the sketch to laser-cutter concept, especially with our presented demo objects, and the out-of-the-box usage applications for the people. Novice users described the interface as intuitively and more precise, especially compared to traditional tablets and the relatively imprecise pen-based input options. Additionally, visitors mentioned that they can still feel the latency of the stroke generation, although it improved dramatically over the last years. Although these problems are based on the used technology, the pen and paper approach eliminates these kinds of problems.

SUMMARY AND CONCLUSION

We developed and fully implemented a pen and paper-based input methodology for rapid prototyping with a laser-cutter. The presented system streamlines the personal fabrication process with a laser-cutter by allowing users to hand-sketch objects on a paper notebook and directly send the cutting data to a laser-cutter for manufacturing. SparkLaserCut represents a minimalistic tool for all experience levels of rapid prototypers, that is non-stationary, makes the whole laser cutting process easier by abstracting the complex processing sequence, can be used in different environments, provides haptic pen and paper feeling, does not need bulky and expensive additional hardware that needs setup and maintenance and allows users to put their focus of attention on rapidly developing the prototype using a laser-cutter.

The system has been evaluated in a small user study with 15 participants, which highlighted the significant benefits of the pen and paper-based approach. SparkLaserCut has been successfully deployed in a research project to manufacture tangram puzzles. Furthermore, we presented it at a Maker Fair to get in-depth target audience feedback. From our field exploration deployments and the user study, we received highly positive feedback for the achieved effective, simplistic, and usable sketching process for laser-cutters. Users preferred to use pen and paper because of its haptic and simplicity for creative rapid prototyping.

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