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FROM HAND-DRAWN SKETCHING TO LASER CUTTING - A PROOF OF CONCEPT PROTOTYPE AND PILOT STUDY

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ABSTRACT

Sketching ideas and building physical prototypes are common in early stage product development. They are used for learning, testing ideas, proving concepts and sharing knowledge. Laser cutting is a popular tool for making physical prototypes due to its accuracy, robustness and speed. Computer aided design and vector graphics software are the main tools used for designing parts for laser cutting. Several sketch-based interfaces have been developed to support the process, using tools such as stylus pens with intuitive sketch-like commands.

A proof-of-concept prototype for capturing a hand drawn sketch and converting it to a laser cuttable file has been developed. In this pilot study we attempt to discover when drawing design by hand on paper can be better or more efficient than conventional methods, for developing physical prototypes with laser cutting in the context of early stage product development. This includes testing the accuracy of the tool, a pilot experiment comparing drawing speed and accuracy, example use cases utilizing pencil and paper, and a simple design challenge experiment.

Keywords: Early design phases, Conceptual design, Design process, Sketching, Laser cutting

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1   INTRODUCTION

Prototyping is a common activity in early stage Product Development (PD). Prototypes are used by designers to learn, discover, generate, and refine designs (Lim *et al.*, 2008), and can serve as a medium for transferring and sharing knowledge within multidisciplinary teams and stakeholders. Prototypes attempt to approximate parts of the final product (Ulrich and Eppinger, 2012) and can take many forms including tangible artifacts, sketches and Computer Aided Design (CAD) models. Designing, building and testing prototypes is an essential part of the wayfaring model presented by Steinert and Leifer (2012) when attempting to find radical innovations in a large design space. Building prototypes can also lead to discovering unknown unknowns (Gerstenberg *et al.*, 2015).

To reduce both time and cost, low-fidelity prototypes can be made such as (hand drawn) sketches and cardboard models. Bao *et al.* (2018) compared the use of sketching, physical prototyping and their interplay in early stage product design. They found sketching to increase the generation and diversity of ideas, being a likely contributor to higher novelty of the final design. Physical prototyping increased the generation of more feasible designs due to early testing of ideas. In their experiment, the interplay of both sketching and prototyping generated the most creative ideas indicating an increase in idea generation efficacy. Using sketching on paper to directly make physical parts, not only as separate tools, is an approach less commonly explored in literature. Using sketching in combination with 2D manufacturing machines is possible, such as laser cutters and PCB-mills.

The extensive use of laser cutting in a yearly project based graduate course (Slåttsveen *et al.*, 2018) has shown to benefit the production of physical prototypes in terms of accuracy, robustness and speed. Laser cutting is especially useful for making robust physical objects with materials such as Medium Density Fiberboard (MDF) and acrylic glass. Simple shapes can be cut quickly and then assembled to make 3D objects. Making 3D objects without the need for assembly has also been achieved by Mueller *et al.* (2013). Shape changing interfaces (living hinges) with repeating patterns can efficiently be prototyped using a laser cutter (Jensen *et al.*, 2017). Accuracy is provided through software by defining dimensions to the design. However, the process of generating designs for utilizing laser cutting in PD can be cumbersome in some scenarios, especially if the shapes are organic, the designer is not familiar with the required software, or if the part must fit with other physical objects. CAD and software in general will also remove the designer further away from the work piece, restricting them to a static 2D screen and digital input, potentially limiting creative thinking.

In this paper, we explore how drawing by hand on paper using common drawing tools (denoted as sketching) can be used to produce laser cut designs, and attempt to discover its potential benefits during physical prototyping in the context of early stage PD. Although sketching is practically ubiquitous, it is not obvious if this approach is faster or simpler than other methods in every case, or if it can produce functional prototypes when accuracy can be crucial. The proof-of-concept tool used throughout this paper is implemented by Kohtala *et al.* (2018), which captures an image of the sketch and converts it to a laser cuttable file. In this pilot study, mostly qualitative data is explored and discussed, based on several potential use cases, pilot experiments, and user feedback. The main question we explore is: when is drawing designs for laser cutting by hand on paper better or more efficient than conventional methods (software), in the context of early stage PD and prototyping?

2   SKETCHING TO PHYSICAL ARTIFACTS

Some of the most common tools for making designs for laser cutting are CAD software such as Siemens NX, Autodesk Fusion 360 and Solidworks, and vector graphics software such as Inkscape, CorelDRAW and Adobe Illustrator. Each of these methods are primarily used through the common pointing and clicking interface with a mouse and keyboard. In this chapter, we will present hand drawn sketch-based approaches for generating designs for laser cutting. We will then present our method, how it is different and hypothesize about its potential benefits.

2.1 Existing sketch-based methods

Several sketching tools or methods that can be used for laser cutting has been developed in the past. ParSketch is an application developed by Naya *et al.* (2007) that integrates a sketching interface to a commercial 2D parametric engine commonly used in CAD software. The application can recognize

freehand strokes on a Tablet-PC screen and then clean and convert them into typical geometries such as lines, arcs, and circles. It can also recognize gestures to for example remove certain lines or to apply dimensions to lines using technical drawing conventions.

Inspired by the abovementioned application, Johnson *et al.* (2012) created Sketch It, Make It (SIMI), which is an interactive sketch-based modelling tool using a stylus pen with an optional button. Rough input from the user is recognized after a certain time interval (900ms or when the button is pressed). The recognized inputs are then converted to vector graphics and segmented into dots, lines, elliptical arcs, and splines. The user can edit the geometry with sketch-based commands, such as drawing a half-square symbol near an intersection of two lines to make them right angled and erasing a line by scratching it out. Its intuitive user interface makes it a suitable tool for non-experts, generating refined designs through a constraint-based approach.

Mueller *et al.* (2012) have developed a method based on interactive fabrication. Their interactive drafting table, called constructable (interactive construction), allows the user to draw directly on the workpiece placed inside a laser cutter using laser pointers. The pointer path is tracked, then it is beautified before being cut with the high-powered laser. The part is created directly, providing physical output after each editing step. The method can use constraints to produce functional mechanical devices, such as cogwheels and boxes, in addition to allowing the use of freehand drawing without constraints. It uses different laser pointers for different functions, to for example make edges round or add special patterns (living hinge patterns) to make the material flexible in some regions.

These are some of the many sketch-based approaches that can aid the development of designs for laser cutting. However, we had trouble finding research on the simple case of drawing on paper to directly make laser cut objects. A similar approach has been developed by a company where a material with a drawing on it can be put inside the laser cutter and be cut directly (Sketch & Cut – Your drawing automatically cut by laser!, 2014). Converting line-drawings from paper to vector graphics has been used for archiving technical drawings and topographic contour maps, or when designers in the field of visual arts want to digitalize their drawings. We will explore this approach for making physical prototypes with a laser cutter.

2.2 The proposed method

The approach explored in this paper does not focus on integrating and interfacing sketch-based methods with computer tools. We simply draw freely on a normal piece of paper, using common drawing tools such as pencils and rulers, and then convert the drawing to a laser cuttable file. To make the process as fast and effortless as possible for the potential users, the capturing and conversion of the sketch can be fully automated. Currently, the vector file must be manually sent to the laser cutter (Gravograph), although it should be possible to automate this using a different laser cutter (e.g. Epilog). Minimal refinements are made to the drawing to preserve the actual sketch that is created by the designer, only a simulated Bezier algorithm is applied when generating the vectors to smooth out small and sudden changes in the vectors.

The tool used, as introduced in Kohtala *et al.* (2018), consists of a booth where the sketch is placed, and a Logitech C920e web camera for capturing the sketch. The image is first processed using OpenCV (OpenCV about, 2017) to create a bitmap using a threshold, then vectorized with a freeware called KVEC (KK-Software, 2010), and finally the output is sent to a shared folder on a computer connected to the laser cutter. The file can simply be dragged and dropped into the laser cutter software before sending it to the laser cutter.

2.3 Why draw on paper

We do not expect the proposed method to as effortlessly produce refined designs compared to the aforementioned methods. However, what is good enough to produce a functional prototype can vary. Furthermore, by drawing on paper and not being constricted to a screen, different possibilities exists where paper can be utilized to help generate the desired design. The main question to ask is therefore when this approach can be better or more efficient than conventional methods in the context of early stage PD and prototyping using laser cutting. To address this question, we will experiment with using hand drawn sketches to produce physical parts. We will consider the accuracy, speed and effort of using this approach and the functionality of the physical output, and then discuss the potential benefits and drawbacks compared to using common design tools.

We hypothesize that this method will allow novice users to more effortlessly utilize laser cutting to make functional prototypes. For experienced users of software and laser cutting, we hypothesize that the method will increase the speed of generating some designs, especially when the shapes are simple and organic but does not require repeating patterns and high precision. We also hypothesize that the accuracy of drawing by hand is acceptable for many low-fidelity prototyping efforts. We will explore how the drawing medium (paper) and other objects can be integrated with the design process. If designing a functional prototype becomes more effortless, thus also reducing speed, more prototype iterations can be generated in the same amount of time. A correlation between more iterations and better performance has been demonstrated by Dow *et al.* (2009), suggesting that rapid iterations yields better design insights.

3 EXPERIMENTING WITH SKETCHING TO LASER CUTTING

A qualitative approach is used in this pilot study to explore and discuss several potential use cases, conduct simple pilot experiments and get user feedback from engineering design practitioners as well as non-engineers. The laser cutter used in this paper (Gravograph) is placed in a prototyping laboratory where mostly mechanical engineering students and graduates are designing, building and testing prototypes. Both experienced and novice users of the laser cutter were asked to participate in simple experiments in situ, to then observe, ask and discuss the method compared to their normal approach. Individuals with no background in engineering, design or arts has also participated to experiment with non-experts.

This section will describe how we have experimented with four main aspects of the system: the accuracy of the tool, a pilot experiment from Kohtala (2018) comparing drawing speed and accuracy, example use cases utilizing pencil and paper, and a simple design challenge experiment. Some use cases are explored by the authors through practical examples to discover applications where drawing by hand can be superior to using common software tools. One of these cases were made into a simple design challenge that participants were asked to try out, in order to observe and discuss their performance using the tool compared to how they would normally solve it. The results are presented in the next section.

3.1 Accuracy of the tool

The system used for capturing a hand drawn sketch on paper and converting it to a laser cuttable file was built as a proof-of-concept prototype that is simple to use. This system has consequently used a webcam for capturing the sketch, which is both simple to use with computer programming through OpenCV and fast to set up. Even good webcams are often limited in quality, and the Logitech C920e used for this system is limited to capturing 1920x1080 pixel images. The webcam is placed approximately 0.8 meters directly above the table where the sketch is captured.

The system has worked well as a proof-of-concept but has some drawbacks in resolution and quality compared to other hardware. We have therefore compared the same drawing captured with this system, an image scanner and a higher resolution camera. The drawing contains lines, a circle, square, cross, and a line decreasing in strength, drawn with a pencil, compass and ruler. When converting the captured image to a bitmap format, the threshold has been manually adjusted for the experiments in this paper, to reduce noise before the lines are traced by KVEC. Noise will still frequently remain around the edge of the paper, which must be manually removed before laser cutting the design.

The end goal of the capturing method is to generate an image of the sketch that includes all the features the designer intended to include, and that the tracing and vectorization algorithm can detect without including noise. It is thus beneficial to not detect weak lines, such as remaining pencil lines after attempting to remove them with an eraser.

3.2 Drawing speed and accuracy

In the pilot experiment conducted by Kohtala (2018), most of the 14 participants were mechanical engineering students in addition to a few non-engineering students. They were asked to draw a circle and rectangle as shown in Figure 1, first as accurately as they could within 5 minutes, then as fast as they could within 30 seconds. They had different drawing tools available during the task, such as pens, pencils, rulers and a compass. Time was measured, and the drawings were captured with the C920e webcam and converted to vector files before being measured using software. The diameter of the circle and all the sides and angles of the rectangle were measured to find the Standard Deviation (SD) from the given dimensions.

The aim of the pilot experiment was to get an estimate of how accurately users can draw by hand and how speed affects their drawing precision, in addition to discovering preferred drawing tools.
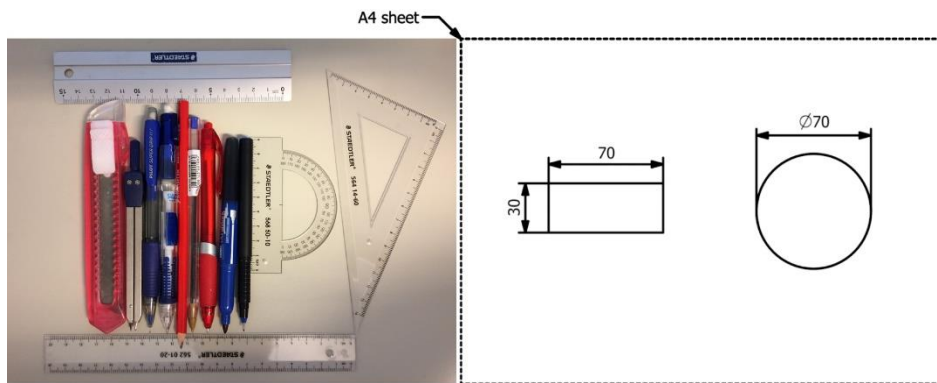

Figure 1: Tools available during the drawing experiment on the left, and drawing task on the right with dimensions in millimeters.

3.3 Utilizing pencil and paper

Some of the example use cases done with the system previously has demonstrated how a complex shape can be captured on paper using light-colored chalk, before drawing a design on top to fit the shape. In another example paper was placed on an existing structure to then be able to directly design the part where it will be placed. These examples are presented in Figure 2 below.
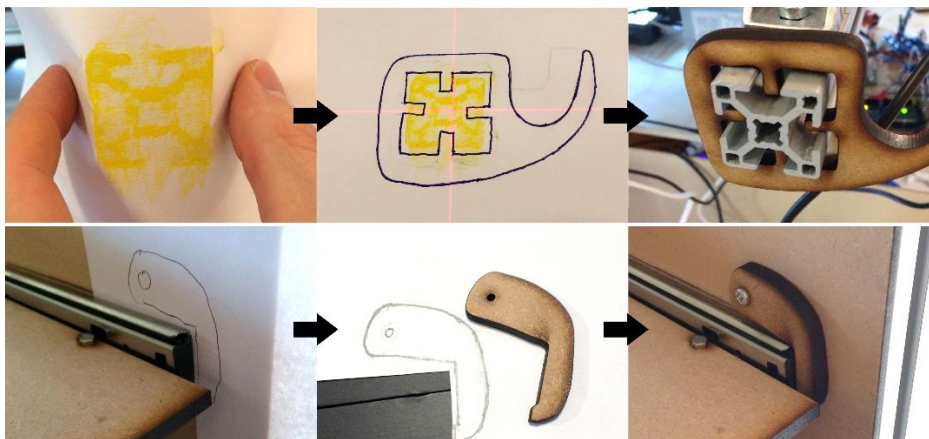

Figure 2: Examples using paper in the design process. On the top a hook for cables is adapted to a profile, and on the bottom a locking mechanism for a pull-out shelf.

We will explore other potential cases where we can take advantage of paper and simple drawing techniques when designing laser cut objects, that are difficult or impossible when constricted to a computer screen. One interesting opportunity is to use living hinges in the design, since paper is flexible and can represent how the design will behave before it is produced.

3.4 Design task

Based on a design found after exploring use cases, we asked people with different levels of experience with laser cutting and computer software to come up with a laser cut design to solve the design task. The task was to make a laser cut object that can hold a mobile phone upright at an angle between 0 and 90 degrees. It was an open problem with the only requirements being that they had to use the laser cutter, with 3mm and 6mm plates available, and they were only allowed to draw the design by hand on paper. They were provided normal A3 or A4 paper, a pencil with an eraser, a ruler and an iPhone 5s. They were also told that the design did not have to look perfect, and that time or any other final measurements would not be used as a metric to evaluate their performance, in order to encourage a natural process.
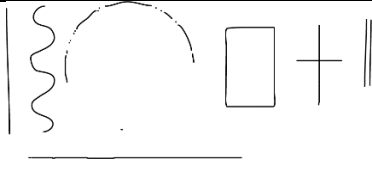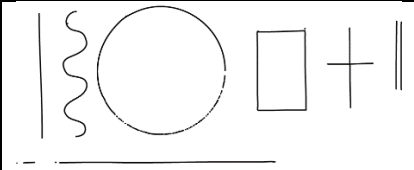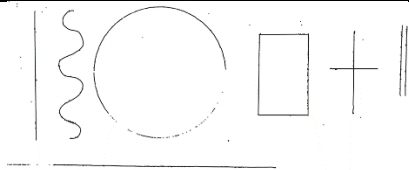
A total of 7 people participated, 3 of whom were natural science students, and the rest from mechanical engineering, some doing their master's and some having recently finished.

The aim of this task was to observe how they solved the problem and then provide some ideas on how they could have solved it, followed by a discussion on the practicality of the approach compared to their preferred method to get some new insights. They were also asked open ended questions about previous knowledge on laser cutting and software, and if they believe they could benefit from our approach in some scenarios.

4 RESULTS AND EXAMPLE USE CASES

4.1 Accuracy of the tool

Table 1: Comparing vectors generated from different capturing methods.

Logitech C920e 1920x1080 pixels ~0.8 meters from sketch 28 vectors	iPhone 5s 3264x2448 pixels ~0.4 meters from sketch 82 vectors	Scanner (Ricoh MP C6004) 4961x3508 pixels ~0.0 meters from sketch 419 vectors

With the program used for converting an image of a sketch to vector graphics, a high-resolution camera seems to provide the best results compared to the webcam and scanner (Table 1). With the webcam, it is difficult for the program to trace all the lines, while the scanner produces more noise. Using a low-resolution camera far away from the sketch will not capture all the details and results in some inaccurate vectors. A higher resolution close to the sketch will generate more accurate vectors but will also capture too much details resulting in many small vectors not part of the drawing. The circle was drawn using a compass with a lead tip, resulting in a weak drawing, and was difficult for each method to capture. Due to the nature of the camera lens, lines further away from the center can be distorted. The best results might therefore be achieved using a scanner to capture the sketch, then reduce the resolution or potentially implement a noise reduction method. However, using the Logitech has worked well enough for our purposes if the drawn lines are strong enough, and is thus used for the remainder of this paper.

4.2 Drawing speed and accuracy

When drawing a rectangle and circle with given dimensions accurately, the 14 participants from the pilot experiment (Kohtala, 2018) used on average 1 minute and 7 seconds, with an SD of roughly 1 minute. In terms of accuracy, the average SD of all the measurements in the drawings were 0.49 mm. When drawing fast, participants finished after 36 seconds on average with an SD of 10 seconds, and with an average SD of 1.27 mm in accuracy. Almost all participants chose to use a pencil, ruler and compass. The results are summarized in Table 2.

Table 2: Drawing speed versus accuracy, experiment results

	Average time (SD) [minutes: seconds]	Average SD from given dimensions [millimeters]
Draw accurately within 5 minutes	01: 07 (01: 02)	0.49
Draw accurately within 30 seconds	00: 36 (00: 10)	1.27

4.3 Utilizing pencil and paper

When trying to fit objects with a laser cut design, the common approach is to measure the object and use the measurements in the design or apply them as constraints. Using the object directly in the design process is usually simpler when drawing on paper, since putting the object on a screen and tracing it is not as feasible. We designed a stand for a mobile phone to demonstrate this simple concept (Figure 3).
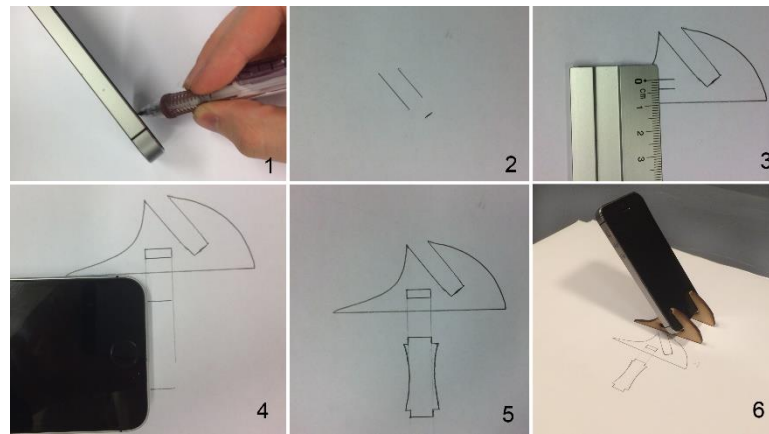
Figure 3: Sequential stages (1-6) for creating a stand for a mobile phone using hand drawing to laser cutting.

In the above figure, we captured the most important constraint in the first stage, both for fitting the phone in a notch and deciding the angle we wanted for the phone. From the second stage we can draw the overall shape by free hand, again using the phone to find the approximate center of mass so the bottom is long enough to counteract the torque. In stage 3 we had to measure a gap of 3mm for fitting a connection made of 3mm MDF. The phone was used in stage 4 to find the appropriate length for the connector. Weak straight lines were drawn from the connection hole, used as guides for drawing the connector with correct length and shape by free hand (stage 4-5). The main part was copied in the laser cutting software before it was cut. This simple approach for making a functional prototype required approximately 2 minutes of time. With the same design in mind, measuring the critical dimensions of the phone and using CAD lasted almost twice as long.

Making flexible parts from a stiff material like MDF is possible using living hinge patterns. We tried making a wristband from one piece of material using this approach. The easiest living hinge pattern which also yields the most deformation in one direction was used, based on the classical pattern or P1 in Jensen *et al.* (2017).
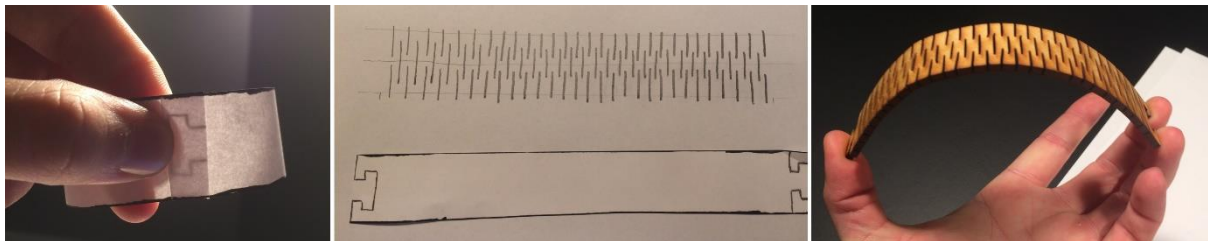

Figure 4: Hand drawn wrist band using living hinge patterns on MDF. The result on the right is too stiff and on the brink of breaking.

In Figure 4, we started by cutting a piece of paper representing the general shape we wanted to create, and to make sure it fits around the wrist. By drawing a connection mechanism at one end, it could be used at the other end to draw a corresponding inverse shape (left image in Figure 4). The living hinge pattern was drawn separately so it would not interfere with the edges. The final design was not flexible enough for bending around the wrist, but applying pre-made patterns to the design using software resolved the issue as shown in Figure 5.

Figure 5: Wristband made of MDF using pre-made living hinge patterns.

Drawing repeating patterns by hand can be cumbersome and inaccurate, but the general shape can quickly be prototyped with paper, to then mark the areas where bending is needed. Pre-made patterns can then be placed properly using software.

In another case, paper was placed at a shattered area of a motorcycle backlight lens to draw and capture the outline of the broken and lost piece. The drawing was then laser cut from acrylic glass and glued to the lens. By adapting paper with the environment, like the example shown previously in Figure 2, we can more efficiently capture organic shapes and use them in the design instead of using measuring tools.

4.4 Design task

By observing each participant draw a mobile stand, one of the most reoccurring approach was using the ruler more than we had found necessary (see Figure 3), however the participants were not able to contemplate about this approach as much as the authors have beforehand. It seemed that most participants that would normally use CAD software, and had some experience with laser cutting, used the same approach when drawing by hand. This resulted in more effort than necessary to make simple geometries (rectangles) with accurate measurements. Using already drawn shapes as guide for drawing corresponding parts, as shown at stage 4-5 in Figure 3, was not observed. Instead some participants drew the shape from scratch using a ruler to make them fit. This would be considered normal in software since measurements can simply be entered and matched, but cumbersome when drawing by hand.

Participants with no experience with laser cutting also used simple shapes but were even more careful and accurate, thus using more time than experienced users. This is expected considering they are unfamiliar with laser cutting and prototyping. They were still mostly able to produce a functional prototype with the laser cutter, without requiring any training. When asked how they would solve the problem under normal circumstances, they answered that a program such as Geogebra (an interactive math and geometry application) would be better since it can produce more accurate and faster output.

One of the most experienced participants (regularly using Inkscape) had also the most original idea. Having discussed living hinges before the task was given, the participant included them in the design. The drawing was too complex for the conversion program to get an accurate vector file, so parts of the design had to be manually traced (right image in Figure 6).
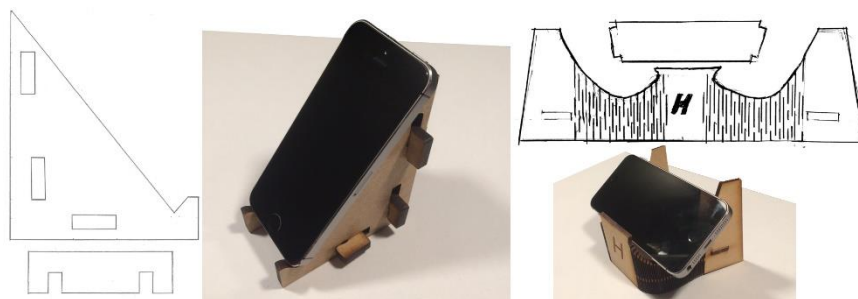

Figure 6: Two drawings and corresponding laser cut mobile stands from the experiment.

The left image in Figure 6 was made by a participant with no previous experience, although the design was based on another similar known design. The drawing was made using accurate measurements of the phone and using calculated dimensions for the parts, thus using over half an hour to finish. The mobile stand on the right in Figure 6 was made using mostly the phone itself as reference and finished quicker but with less accuracy.

5   DISCUSSION

A summary of the findings is presented in Table 3 below. Coming up with the best possible solution for capturing and converting hand drawings to vector files for laser cutting is beyond the scope of this paper. Using a normal scanner or high-resolution camera has shown potential to improve the accuracy of this method. However, a good starting point for making the process simple and automatic is using a webcam with OpenCV and KVEC.

With an accuracy between ± 0.49 and 1.27 mm, depending on drawing speed, we can argue that drawing by hand is acceptable for most rapid prototyping efforts using laser cutting. It is important to keep this in mind when designing connected parts, to make sure the parts fit. This can also result in

loose connections than can reduce the structural integrity of the final design and should therefore be carefully considered in some cases.

Since paper is light and flexible, and drawing by hand is considered ubiquitous, we found several use cases that has potential advantages over common computer software. Most of the participants that were asked to design a mobile stand used an approach similar to using CAD software, indicating fixation on familiar methods. Showing examples of the explored use cases might introduce new concepts and approaches for the designer but can also result in fixating on the presented examples. One of the explored use cases was to some degree mentioned by experienced participants as a useful supplement to using software, namely capturing geometries or dimensions from objects that are needed for the design without having to measure them directly. Even though inexperienced participants would prefer using a software that they believe would be more accurate and faster, they were still mostly able to produce functional prototypes using the laser cutter without any prior experience.

The size of the design is currently restricted to the paper size. This can be resolved using optical character recognition in the program to recognize and apply a scale factor written on the sketch. We have manually adjusted the threshold to reduce noise, due to variation in sketch quality and surrounding lighting, which should be automatically optimized in the future.

This pilot study has found many potential benefits for drawing designs by hand on paper when laser cutting physical prototypes. The approach has potential as a tool by itself or as a supplement to common methods, but the conclusions that can be drawn are limited as more quantitative and controlled experiments are needed to better understand to which extent the proposed method can support or improve the use of laser cutting, and to address some of the hypothesis proposed in the beginning of this paper. One interesting dimension to measure is the number of iterations created and the creativity of the output, compared to using common tools.

Table 3: Summary of findings.

Variables	Pros	Cons
Tool for capturing and converting a sketch	- Simple to implement and use - Can automatically capture and convert pencil sketches	- Presence of noise - Currently requires some manual cleaning of output
Drawing accuracy of potential users (see Table 2)	- Acceptable for most low-resolution prototyping efforts	- Limited accuracy, which can be critical for connected parts
Drawing speed (see Table 2)	- Fast way to draw and capture organic and complex shapes	- Slow to produce accurate shapes with dimensions
Sketching on paper	- Can directly utilize the physical environment in the design process - Can interact physically with the drawing medium (paper)	- Cannot directly apply dimensions or copy shapes
Novice designers	- Able to use laser cutting without training	- Can be slow due to uncertainty regarding accuracy
Experienced designers	- Able to capture organic shapes	- Can be slow when using familiar methods

6   CONCLUSION

The main question we have explored in this pilot study is when drawing designs for laser cutting by hand on paper can be better or more efficient than conventional methods (software), in the context of early stage PD and prototyping. The answer depends on the situation and experience of the user with regards to laser cutting and software. A small-scale experiment indicates that inexperienced users can produce functional prototypes with laser cutting without having to learn new software. Experienced software users seem to use a similar approach when drawing by hand, thus not utilizing some of the potential advantages of paper and pencil sketching. Some participants view the method as a helpful supplement to their normal software approach, by being able to capture shapes and dimensions from other objects that are cumbersome to measure directly.

Results from a pilot experiment has shown that people can draw with an accuracy we consider acceptable for most rapid prototyping efforts using laser cutting. The process of capturing and converting a sketch on paper to a vector graphics file can be improved by using a normal paper scanner but will require some adjustments to reduce noise.

Some of the explored use cases where drawing by hand on paper can be more practical than common tools include utilizing related objects in the design process, being able to bend paper to simulate how a flexible part should behave and be designed, and adapting paper with the environment to effortlessly capture complex and organic shapes into the design.

More quantitative research is required to better understand the potential advantages of paper and pencil sketching for producing physical prototypes with laser cutting, and when and to whom the benefits may apply.

REFERENCES

Bao, Q., Faas, D. and Yang, M. (2018), "Interplay of sketching & prototyping in early stage product design", *International Journal of Design Creativity and Innovation*, Vol. 6 No. 3-4, pp. 146–168.

Dow, S. P., Heddleston, K. and Klemmer, S. R. (2009), "The efficacy of prototyping under time constraints". *Proceedings of the seventh ACM conference on Creativity and cognition: ACM*, pp. 165–174, https://doi.org/10.1145/1640233.1640260

Gerstenberg, A., Sjöman, H., Reime, T., Abrahamsson, P. and Steinert, M. (2015), "A Simultaneous, Multidisciplinary Development and Design Journey–Reflections on Prototyping". *International Conference on Entertainment Computing: Springer*, pp. 409–416, https://doi.org/10.1007/978-3-319-24589-8_33

Jensen, M. B., Blindheim, J. and Steinert, M. (2017), "Prototyping shape-changing interfaces-An evaluation of living hinges' abilities to resemble organic, shape-changing interfaces". *DS 87-4 Proceedings of the 21st International Conference on Engineering Design (ICED 17)* Vol. 21-25.08.

Johnson, G., Gross, M., Do, E. Y.-L. and Hong, J. (2012), "Sketch it, make it: sketching precise drawings for laser cutting". *CHI'12 Extended Abstracts on Human Factors in Computing Systems: ACM*, pp. 1079–1082, https://doi.org/10.1145/2212776.2212390

KK-Software (2010), Available at: http://www.kvec.de/ (Accessed: November 6 2018).

Kohtala, S. M. I. (2018), "Methods for Augmenting Physical Prototype Activities in Early Stage Product Development-Development of a system designed to accelerate prototyping and learning in the early stages of product development." Master's thesis, NTNU.

Kohtala, S. M. I., Erichsen, J. A. B., Sjöman, H. and Steinert, M. (2018), "Augmenting Physical Prototype Activities in Early-Stage Product Development". *DS 91: Proceedings of NordDesign 2018*, Linköping, Sweden, 14th - 17th August 2018: The Design Society.

Lim, Y.-K., Stolterman, E. and Tenenberg, J. (2008), "The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas," *ACM Transactions on Computer-Human Interaction (TOCHI)*, Vol. 15 No. 2, pp. 7, https://doi.org/10.1145/1375761.1375762

Mueller, S., Kruck, B. and Baudisch, P. (2013), "LaserOrigami: laser-cutting 3D objects". *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: ACM*, pp. 2585–2592, https://doi.org/10.1145/2468356.2479544

Mueller, S., Lopes, P. and Baudisch, P. (2012), "Interactive construction: interactive fabrication of functional mechanical devices". *Proceedings of the 25th annual ACM symposium on User interface software and technology: ACM*, pp. 599–606, https://doi.org/10.1145/2380116.2380191

Naya, F., Contero, M. and Aleixos, N. (2007), "ParSketch: a sketch-based interface for a 2D parametric geometry editor". *International Conference on Human-Computer Interaction: Springer*, pp. 115–124, https://doi.org/10.1007/978-3-540-73107-8_13

OpenCV about (2017), Available at: https://opencv.org/about.html (Accessed: November 22 2017).

Sketch & Cut – Your drawing automatically cut by laser! (2014), Available at: https://www.studiodiip.com/2014/11/24/sketch-cut-your-drawing-automatically-cut-by-laser/ (Accessed: November 6 2018).

Slåttsveen, K., Kriesi, C., Steinert, M. and Aasland, K. E. (2018), "Experiences from a positivistic way of teaching in the fuzzy front end". *DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018)*, Dyson School of Engineering, Imperial College, London. 6th-7th September 2018, pp 694–699.

Steinert, M. and Leifer, L. J. (2012), "'Finding One's Way': Re-Discovering a Hunter-Gatherer Model based on Wayfaring", *International Journal of Engineering Education*, Vol. 28 No. 2, pp. 251.

Ulrich, K. T. and Eppinger, S. D. (2012), '*Product design and development, 2000*,' New York: MacGraw-Hill.