Improving CNC Processes Using Computer Vision to Digitise Physical Objects

Master Thesis Group: HCC105F18
Supervisor: Timothy R. Merritt
Jakob Andersen, Jesper Ravn-Nielsen & Thomas Kærgaard
{jaande13,jravnn13,tkarga13}@student.aau.dk
Computer Science Aalborg University
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AALBORG UNIVERSITY
STUDENT REPORT

Summary

Computer numerical control(CNC) machines such as milling machines, and cutting machines like laser, knife and water jet cutters has become increasingly popular for architects and businesses to have in-house. With more people of diverse skills operating fabrication machines, it begs to question whether the human-computer interface of these machines can be improved, in particular the interaction between the user and the tools that are used to create models. During our thesis we studied whether this interaction can be improved, and if so, how can it be improved. Our thesis is separated into two parts, spanning a total of two semesters.

The first part is a pre-thesis study called Condor: Rhinoceros3D Plugin for Material Reuse, in which we studied how to assist architects in reducing material waste, by cutting models from scrap materials, instead of using brand new materials. During the study, we developed a plugin for the popular computer assisted design(CAD) program Rhinoceros3D called Condor. With an overhead image of the scrap material, Condor uses computer vision algorithms to capture contours of scrap materials. The contours can then be used as a reference to nest the models for cutting. We conducted a user study at Aarhus School of Architecture to evaluate Condors ability to assist architects in reusing scrap materials, to gather insights of how and if the architects at the school currently reuse scrap materials, what kind of features they found desirable in such a system and the current process they use to reuse materials.

During the study we found that the student architects rarely reuse scrap material. Their traditional method of reusing scrap material, consists of trying to fit one model at a time through trial and error. In the study we found that they preferred to use the Condor system to assist them in nesting models onto scrap material compared to the traditional method, when they need to nest more than one model. In the study we measured the time users spent nesting models onto scrap material using their original method of nesting, and compared it to using Condor. We found that on average, the user is 1.59 times faster using Condor than the traditional method.

In our thesis we collaborated with Zünd Skandinavien ApS to investigate how to assist users in obtaining contours from objects, as well as other use cases for such a solution. During the thesis we developed CopyCut!, a software solution that is able to retrieve the contours from an overhead image of objects. The contours are then exported in a DXF file format, that can be used to cut out the contours with a CNC machine.

To evaluate CopyCut! we conducted an expert review of CopyCut! with people from the leadership at Zünd. We were told that the typical client, that would benefit from a system such as CopyCut!, would most likely have little to no skills regarding CNC machines or CAD software, thus it is very important that the user interface is simple and quick to use. The experts commented that the technical accuracy of a contour extraction system is very important. They told us that an error of 0.2mm in the upholstery industry is quite normal and that in a general use case the error should not exceed 1mm.

We evaluated the technical accuracy of CopyCut! by placing nine different A4 papers on our setup and calculated the errors of the extracted contours by looking at the difference between the physical objects and the generated contours and found that the average error of CopyCut! is 4.14mm. This

large error is due to the image being warped from lens distortion. When correcting the image for lens distortion, we get an average error of 1.16mm.

To receive feedback on how CopyCut! could be used as a creative tool, we conducted a small co-design session with interaction design students. We found that CopyCut! was easy to use, and was well suited for rapid prototyping, and for creating 2D objects. In the co-design session we found that 5/7 participants that rated themselves as inexperienced with a CNC machine, could see themselves use CopyCut! in the future, while 2/7 could maybe see themselves use CopyCut! in the future. When looking at all the interaction design students, 5/9 participants could see themselves use CopyCut! in the future, while 4/9 could maybe see themselves use CopyCut! in the future.

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1 Introduction

Computer numerical control(CNC) machines such as milling machines, and cutting machines like laser, knife and water jet cutters has become increasingly popular for architects and businesses to have in-house. With more people of diverse skills operating fabrication machines, it begs to question whether the human-computer interface of these machines can be improved, in particular the interaction between the user and the tools that are used to create models. During our thesis we studied whether this interaction can be improved, and if so, how can it be improved. Our thesis is separated into two parts, spanning a total of two semesters.

The first part is a pre-thesis study called Condor: Rhinoceros3D Plugin for Material Reuse, in which we studied how to assist architects in reducing material waste, by cutting models from scrap materials, instead of using brand new materials. During the study, we developed a plugin for the popular computer assisted design(CAD) program Rhinoceros3D called Condor. With an overhead image of the scrap material, Condor uses computer vision algorithms to capture contours of scrap materials. The contours can then be used as a reference to nest the models for cutting. We conducted a user study at Aarhus School of Architecture to evaluate Condors ability to assist architects in reusing scrap materials, to gather insights of how and if the architects at the school currently reuse scrap materials, what kind of features they found desirable in such a system and the current process they use to reuse materials.

During the study we found that the student architects rarely reuse scrap material. Their traditional method of reusing scrap material, consists of trying to fit one model at a time through trial and error. In the study we found that they preferred to use the Condor system to assist them in nesting models onto scrap material compared to the traditional method, when they need to nest more than one model. In the study we measured the time users spent nesting models onto scrap material using their original method of nesting, and compared it to using Condor. We found that on average, the user is 1.59 times faster using Condor than the traditional method.

After the pre-thesis study we contacted Zünd Skandinavien ApS to inquire about a potential collaboration. They expressed, that their customers need a system that is able to capture the contours of an object, such that they become able to recreate the original object with little to no time spent using a CAD program.

In our thesis we collaborated with Zünd to investigate how to assist users in obtaining contours from objects, as well as other use cases for such a solution. During the thesis we developed CopyCut!, a software solution that is able to retrieve the contours from an overhead image of objects. The contours are then exported in a DXF file format, that can be used to cut out the contours with a CNC machine.

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In the following section we will describe our research contributions. Afterwards we will discuss how our work with Zünd has been, how our research contributes to the field, interesting results and possible limitations. Lastly we will discuss possible future work and conclude on both Condor and CopyCut!. Our papers, Condor: Rhinoceros3D Plugin for Material Reuse and CopyCut!: Using Computer Vision for Digitising Physical Objects can be found as appendices 1 and 2.

2 Research Contributions

In [5] they describes seven typical research contribution categories for HCI, which we will use to categorise our contributions. Using their definitions, both Condor and CopyCut! are artefact contributions. [5] describe artefacts as "Artefacts [...] reveal new possibilities, enable new explorations, facilitate new insights or compel us to consider new possible futures". These contributions are provided by our two systems and the workflow introduced with them. Additionally we have collected empirical data through studies of the two systems. Empirical data either "[...] tells us about how people use a system", or "[...] tells us about people" [5]. Below we will describe the contributions in more detail. The contributions are split into two sections. The first section will describe the research contributions of Condor: Rhinoceros3D Plugin for Material Reuse, while the second section will describe the research contributions of CopyCut!: Using Computer Vision for Digitising Physical Objects.

2.1 Contributions of Condor

The contributions of Condor: Rhinoceros3D Plugin for Material Reuse is threefold. The first and largest contribution of this paper is the Condor plugin for Rhinoceros3D. It allows users to quickly nest models onto scrap material compared to the traditional method of nesting. Condor [2] is publicly available with support for both Mac and Windows. The second contribution is the workflow that assists users in reusing scrap material. This process serves as a platform for future development of tools, whose purpose is to assist the user in nesting models onto scrap material. The third and final contribution is the empirical data collected during the study. This data sheds light on the current process of reusing scrap material, challenges that the architects saw with a nesting tool such as Condor, and in some cases how to fix these shortcomings. Additionally, this data contains the opinions of architectural students and teachers on additional features, such as a common library for scrap material, and a mobile version of Condor.

2.2 Contributions of CopyCut!

The contributions of CopyCut!: Using Computer Vision for Digitising Physical Objects for Editing and CNC Cutting is threefold. The first and and most important contribution is the open source software CopyCut! [1]. It first and foremost allows users to capture the contours of physical objects, that can then be used to create a physical copy, but CopyCut! also enables other use cases. The second contribution is the workflow of digitising physical objects for editing and CNC cutting, an investigation of the use cases made possible with CopyCut! as well as the challenges that may arise for these use cases with suggestions on how to alleviate these challenges. The third and final contribution is the empirical data, this is both the technical accuracy of CopyCut! that can be used to benchmark future systems and the data gathered from the expert review and co-design session, that can be used as insights for future developments.

3 Discussion

In this section we will discuss working with Zünd, how our work contributes to the research community, surprising results of the studies and what limitations our work has.

3.1 Working with Zünd

Working with Zünd presented both opportunities and difficulties. Zünd possessed a real world problem from one or more of their customers, and knowledge about those customers and what their needs might be for an application. They provided real use case examples in the form of images of templates from the upholstery industry on a machine bed, giving us good real examples to work from. Most importantly, they provided us with a CNC machine, the tools for it and the camera we used for CopyCut!.

When we started our collaboration with Zünd on the CopyCut! project, we did not meet to discuss the direction of the project until a month after the project started. We tried to utilise this spare time by exploring and prototyping for different directions, however once the final direction was decided at the first meeting, we had to discard some of the work that we had done. For future projects we suggests that the initial meeting between the collaborators happen a lot sooner, such that the direction of the project can be established, thus avoiding additional work that will eventually be discarded. If it is impossible for the collaborators to meet early in the course of the project to discuss the direction of the project, we suggests that all partners of the collaboration drafts initial directions and then decide on one of the directions through email. While this suggestion still facilitates some work that will be discarded, the amount of work will still be reduced to rough ideas, instead of the functional prototypes that we developed.

We had hopes that by collaborating with Zünd, we could get more access to the CNC machine or in some degree incorporate our solution with theirs. We could for instance, quickly cut models by directly communicating with the CNC machine, or at least avoid the extra step of importing

DXF files manually. During our study of Condor we encountered a problem, since the CNC software does not take the scrap material into consideration, when trying to place the origin of the machine. To be able to cut from scrap materials, it was necessary to make a small dot representing the lower right corner of the scrap material to keep the origin with regards to the scrap. The little dot had to be assigned to a tool for it to work, which is not a preferable solution, as it was only meant as a reference. This could be avoided if we had direct communication with the CNC machine by making sure to keep the origin at the same point, as if the scrap material was there. Alternatively the CNC machine could have a feature to take a contour into account for positioning, but without cutting it.

As part of the collaboration with Zünd, we conducted an expert review to evaluate CopyCut!. In the expert review we received essential feedback on the technical accuracy required in different industries. During the review we also tested examples of real use cases from some of their clients, which helped us identify some limits of CopyCut!. In addition to discovering some limitations of CopyCut!, these examples also confirmed that some of the use cases we have listed are relevant to the industry, such as creating contours from pencil drawings.

Zünd was interested in continuing to work with us, indicating that they see the potential and quality in our work. Although we are not going to take them up on their offer, we would encourage others to work with companies to get experience on how it is to work with companies. Working with companies also gives a feeling of importance and value to the work you do, since it provides a solution for a real problem that real people have.

3.2 Contribution to the research community

Our research contributes to the research community with our artefacts and workflows as examples of solutions that extract contours, as well as the information we have gained during our studies of the two systems, which future research can build upon.

While others provide standalone solutions, we looked at the possibility of making a plugin for Rhino3D, which provides a familiar work space for the architects to nest models in. We also contribute with quantitative data that shows the potential in reducing time for nesting. We provide qualitative feedback from architect students and teachers on reusing scrap material, how they prefer to work and possible future research to consider.

In the study of CopyCut! we show the technical accuracy of a system, that only uses a camera and algorithms, which is missing from CopyCAD [3] and WireMolding [6]. We describe several challenges that we encountered and possible workarounds or solutions for them, such that other researcher does not have to find out themselves and can focus on solving them from the start. We have compiled a set of use cases for CopyCut! with examples, which shows the potential of using software to expand the use of CNC machines and change the way we work with CNC machines and models. Through an expert review and a co-design session we provide qualitative feedback on what users would like for a system such as CopyCut!. We also provide an example of a solution that only requires a camera and can be setup with a regular CNC machine and is thus fairly easy to set up.

Our research involves small studies that were used to give initial insights on how our solutions might be useful to designers. However, the adoption of these technologies, as well as how it might change the workflow, is unclear. This should be studied as a longitudinal study by deploying the solutions into organisations.

3.3 Results

In this section we will discuss surprising results that we have gathered throughout the thesis. These results are not necessarily the main findings of the two papers, but rather results that differed from the initial hypothesis, or results that are peculiar.

In our studies we sometimes received peculiar responses to questions asked in interviews or questionnaires. The most curious and sometimes frustrating type of responses, were linked to the materials used in our studies. During the evaluation of Condor and CopyCut! we used cardboard as material to showcase the solutions and for the students to try the system. This lead to confusion, since some of the participants believed that the systems could only function with cardboard as material, and thus were unable to see past any use case involving cardboard. Even when we specified that the system would work with any kind of material, the participants had a hard time letting go of the notion that the system only works with cardboard. To remedy this in future investigations, we believe it is necessary to use different materials for the tests, such that the participants get an immediate sense of the value of the system, rather than relying on the participants being able to use their imagination. Using expensive materials for testing might be an expensive endeavour, therefore a good compromise might be to present a good variety of examples made from different materials before the test starts. This way the participants are immediately introduced to the fact that it is not only cardboard that can be used with the system.

During the user study of Condor, we found it surprising that the students were not too keen on the idea of a shared library for all their scrap material. They suspected that their peers would not follow the new system based on the fact that their current system of storing material was a mess. Furthermore, the students expressed that they were very reluctant to share their materials with other students, except students from their own work group. Surprisingly, through the interviews some of the participants suggested that the library idea should instead pivot towards a personal library that could keep track of the user's personal library of material. They responded that a shared library is more suited for the industry, since all materials are owned by the company.

Some participants during the Condor study suggested that they would like to see a feature that would be able to cut out large rectangles of unused material from scrap material. This is an interesting idea, since it would allow the users to quickly generate material for later use, that does not require the user to nest their designs, like they would if they were using Condor. This suggestion will also reduce the space needed to store scrap materials. While this idea will be more convenient for the user, it will, however, not utilise the maximum amount of scrap material, thus this becomes a balancing act between convenience and efficiency.

In the co-design session for CopyCut! the interaction design students generally found that the scenario most useful was rapid prototyping. Since CopyCut! was originally designed to replicate objects with high fidelity, we find it interesting that the participants found that CopyCut! most useful when rapidly producing prototypes. We suspect that this result might be due to the fact that all the participants were interaction design students and thus normally work with prototyping. Some of the students also suggested that they would be able to use CopyCut! to generate low fidelity paper prototypes for their mobile applications.

3.4 Possible Limitations of Our Work

We believe our work with Condor and CopyCut! provides valuable contributions to the research community. We are, however, aware that there may be some possible limitations of our work, which we will address in this section.

In Condor we conducted the study using the basic functionality of Condor. One might argue that we should have included the advanced functionality in the study. While including the advanced functionality in the study might help get a more in depth evaluation, we believe that the duration of the study would become too long, leaving the participants fatigued, which would potentially lead to inaccurate results. We believe that the basic scenario would avoid leaving the participants fatigued, while still evaluating the most important parts of the process: capturing contours, nesting in Rhino3D and cutting the models from scrap material.

During the evaluation of CopyCut! we conducted a co-design session with nine interaction design students separated in two groups. It might be argued, that nine interaction design students is too few, and it would be better to have participants with a variety of backgrounds to ensure different perspectives and creativity levels. While nine interaction design students, might not be enough to draw final conclusions, we believe that nine participants are enough to gather initial ideas and opinions that can be used as a platform for further investigations into topics such as user interface, workflow and technical performance. Additionally, the duration of these sessions can be questioned, however we think that 30 minutes were enough to gather the initial opinions of the participants.

4 Future Work

We will now discuss possible future work for research in systems for CNC machines and computer vision.

The study conducted on Condor was an artificial scenario that only tested the basic functionality of Condor. A more complete study with the whole workflow might provide more information on how users would use Condor and how it would fit into the architects overall workflow. Preferably, such a study would have architects use Condor in a natural context and use actual examples of their work. Not only could this present design issues, but also materials and use cases that are problematic which would require additional functionality or improvements to the software or setup.

While we discuss the workspace location of Condor, we do not have a study with different setups. From our study it seems that people prefer different setups, but a proper study could perhaps provide more substantial data on what workspace location different users prefer and what the advantages and limitations each setup brings. This could also be relevant for the setup of CopyCut!.

When producing contours of objects using Condor, the diagonal lines were jagged, whereas CopyCut! makes vectors and thus avoids this issue. It is not strictly necessary to avoid jagged lines in Condor, since the contours are only meant as a reference for nesting. However, we expect that, introducing vectorised contours will increase the technical accuracy, and in turn reduce the number of nesting errors.

It could be interesting to look more into lens distortion. Lens distortion limits the technical accuracy possible to achieve through computer vision using cameras. We tried Adobe Lightroom to correct the lens distortion and on average CopyCut! was 3.57 times more accurate than when using a warped image. There exists libraries such as [4] for lens correction, which may perform different to Adobe Lightroom. OpenCV has a camera calibration algorithm that uses a chessboard pattern to unwarp images, but we failed to make a calibration that did not make the image quality worse. To make computer vision solutions such as Condor and CopyCut! more accurate, we need more research on how to remove lens distortion.

5 Conclusion

In our thesis we have investigated two systems for CNC machines, Condor and CopyCut!. Both had the aim to research how to enable users of CNC machines and reduce time spent. We will here bring our concluding thoughts on our thesis.

In Condor: Rhinoceros3D Plugin for Material Reuse, we introduced Condor, a publicly available system for reusing scrap materials. In the study of Condor we show that we are able to reduce the time spent on reusing scrap materials, and through interviews we found that it is possible to encourage more reuse by making it more convenient. We collected data on how architect students and teachers currently reuse scrap materials, which can be used to understand their workflow, as well as the participants ideas and opinions on possible future work. In CopyCut!: Using Computer Vision for Digitising Physical Objects, we introduced CopyCut!, an open source solution for extracting contours from objects, allowing users to save time on converting designs to vectors. We collected feedback on CopyCut! through an expert review with Zünd and a co-design session with interaction design students. Apart from the intended functionality of replicating objects, we also show several other ways to use CopyCut!. We have looked at and compiled a list of challenges we encountered in our study of CopyCut!, wherein lens distortion is the most troublesome without any immediate solution that corrects distortion completely. With CopyCut! we achieved a minimum accuracy error of 0.02mm, an average of 4.14mm and a maximum of 9.21mm. Using Adobe Lightroom to remove distortion, we achieve the same minimum of 0.02mm, but an average of 1.16mm and maximum of 2.89mm. Although we have not tested the technical accuracy of Condor, we suspect it is slightly worse than CopyCut!, due to a lower quality camera and jagged contours. Both systems perform best at the centre of the camera where the lens distortion is smallest.

We have contributed with two artefacts for CNC machines, Condor and CopyCut!. Through our studies of the systems we collected empirical data and shown that systems for CNC machines can introduce new workflows, that can reduce time spent on tasks, enable new techniques and improve the way people work with CNC machines.

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Appendices

Condor: Rhinoceros3D Plugin for Material Reuse

Jakob Andersen
Department of Computer Science
Aalborg University
jaande13@student.aau.dk

Jesper Ravn-Nielsen
Department of Computer Science
Aalborg University
jravnn13@student.aau.dk

Thomas Egon Kaergaard
Department of Computer Science
Aalborg University
tkarga13@student.aau.dk

ABSTRACT
Architects rapidly go through materials to build quality models, explore designs and constructing formworks, creating large amounts of scrap materials that are difficult to reuse, and thus either end up wasting storage or get thrown out. We present Condor, a publicly available plugin for Rhinoceros5(Rhino3D), that with a webcam can find the contours of a scrap material and bring them into Rhino3D for easy nesting of models, before exporting them into the cutting software. Condor differentiates from similar projects in that it takes advantage of the users familiarity with the CAD program Rhino3D. It allows users to spend time nesting models onto scrap material, at their personal computer, rather than occupying a CNC machine and waste time not cutting. We conducted a user study at Aarhus School of Architecture, involving students and employees. The study showed that the participants found the plugin intuitive and simple to use, and would prefer to work with scrap materials using it over the traditional work process. Through interviews with the participants, we found problems with the current process of reuse at the school and ideas for improving the plugin or other solutions that could increase scrap usage.

Author Keywords
Computer vision; reuse; scrap material; CNC cutting; nesting; Rhino3D; Rhinoceros5

INTRODUCTION
CNC machines has become an increasingly popular tool for architects to build quality models, explore designs and construct formworks. CNC machines such as milling machines, laser, water jet, and knife cutters, all have in common that they are subtractive production tools that remove material from the original piece. It is nearly impossible to nest models in such way that a whole sheet of material is used, these kind of tools will inevitably leave pieces of scrap material. The software for these machines, however, are suited towards using whole sheets of material for each job. This is fine when cutting multiple model parts at the same time. Tight nesting is advantageous when the same models are cut repeatedly, since any savings will be multiplied. Hacker space, Fab Labs, and architects do not necessarily use an entire piece of material for their models, which leaves scrap materials with parts that are not always easy to reuse for another project. Therefore architects often decides to use a fresh material instead of taking the time and effort on reusing, thus creating more scrap materials.

Previous research [11, 12, 15] has been investigating how to reduce the efforts of reusing scrap material. [8, 11, 15] investigates the possibilities of projecting a visual guidance onto the scrap material. While [12] focuses on a more traditional screen-based solution. [11, 15] investigate the possibilities of having a separate work space where [8, 12] is having the work space on the CNC machine. [12] introduces an alternative nesting technique using physics and rigid bodies, while [15] investigates AR markers, an android app and a mouse to interact with the models.

None of the research has investigated the possibility of making a solution aimed at the main platforms of computer-aided design(CAD) program, which is a tool architects use in their everyday work. Neither have they made their software available to the public

In this paper we introduce a plugin for Rhinoceros 5(Rhino3D) called Condor that is able to assist the users in nesting 2D CAD models onto scrap materials, based on an image of the scrap material. Condor is available through `www.food4rhino.com/app/condor`, where it is possible to read more and see videos of the plugin. We evaluate the functionality of Condor, and finally, we conduct interviews to investigate challenges and future possibilities within the field of reusing scrap material.

Contributions
Our contribution is threefold.

- Condor: a plugin for Rhino3D that assist architects in nesting models on scrap material.
- A process in which users will be able to reuse scrap material.
- Insights into current challenges and possible solutions when reusing scrap material.

RELATED WORK
Schneiderman [13] discusses the possibilities, benefits and drawbacks of direct manipulation of virtual artefacts and getting instant feedback from the system, such that any small mistake can be corrected immediately. Much research has already been done on how to help users in cutting models

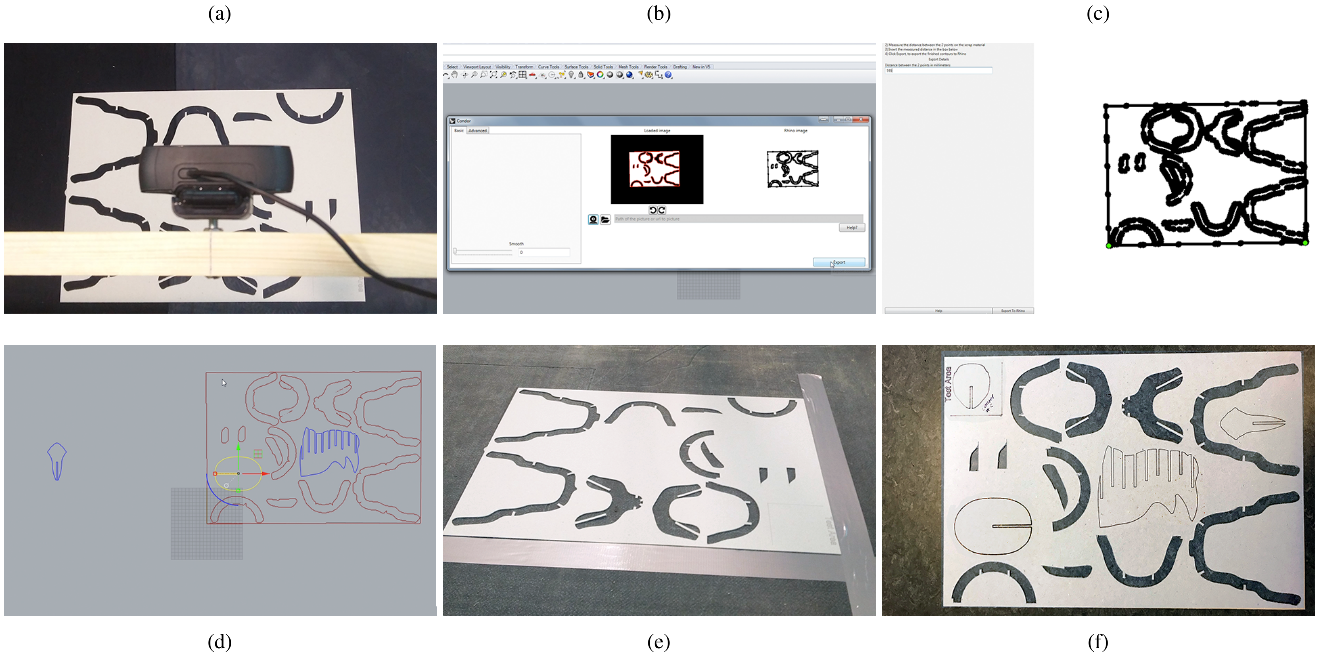

Figure 1: Pictures a-f show the process of using Condor. (a) Depicts the point of view of the webcam. (b) Shows the Condor plugin after the contours of the image has been found. (c)The export screen of Condor. Note the two small green dots, which will be aligned with the X-axis in Rhino3D. (d) Shows nesting of models inside the contours in Rhino3D. (e) Material placed on the CNC machine, using tape to align correctly. (f) Material with the models drawn on it.

and reusing scrap materials by giving immediate feedback to the user [10, 11, 12, 14, 15]. Others studies [4, 5, 7, 9] have investigated the automation of nesting models onto materials

We have decided to focus on direct manipulation of virtual artefacts, and have categorised the related work into the categories based on: Visualisation, work space and interaction.

Visualisation

When using CNC machines, users lack easy confirmation that models are placed correctly before cutting [15]. Papers such as [11, 15] investigates solutions that introduces visual guidance via projection of models onto the scrap material. With projection, users are able to see if their models are able to fit on the chosen scrap material, or if the model is exported with the right settings. VAL [15] created a prototype where the users are able to establish, whether their models are the correct size and make last minute adjustments before going to the laser cutter. They found that the users has increased confidence, that the cutting job would have the correct scale, size, and placement by visually confirming their setting using the prototype. In ProjecTables [11] a system was introduced with a projector installed above the work space, used as a visual aid for the user to nest models onto scrap materials. When the system was tested against the traditional method, that users normally used for nesting, it was found that using the ProjecTable system is up to 30 times faster.

Work Space

We define a work space as the allocated area for nesting the models on scrap material. In the different research papers mentioned, there are two different approaches to where the work space can be.

The first approach is to use the CNC machine itself as a work space [8, 10, 12, 15].

In PacCam [12] they have mounted a webcam above the cutting area of the laser cutter. By taking a picture before and after placing the material, and using background subtraction, they are able to isolate the contours of the material. The contours are used to nest the model parts within their program. They are able to map coordinates of contours and models between PacCam and the CNC laser, which allows them to send cutting instructions directly to the laser cutter using the Qt printer driver.

CopyCAD [8] is a system for integrating physical models into CAD software. A camera is mounted above the machine bed to capture the outlines of the physical model. A projector is installed next to the camera, to project the outlines of the physical model onto the bed. After the contours of the model is captured, the model can be removed from the bed. Modification of contours can be done using fingers or a specially marked pen.

VAL [15] has a projector, which projects the model parts down onto the work area of the CNC machine. This helps visualize the models for the users in a 1:1 scale on the work area, such that the users can perform last minute corrections before cutting. In their study they found that novice users, with current practices, spend approximately 35% of the total time in the precutting phase and they argue that social pressure from people waiting in queue rarely gives an occasion to cut out single items. As a solution they were suggested by a user, to have a separate precut space. A prototype of the separate work space were created and tested. They argue that having a separate work space had potential to reduce the idle time of the laser cutter significantly.

A separate area from the CNC machines work area is used in [11].

ProjecTables [11] has a separate table, used to nest models onto scrap materials, thus reducing time spent at the CNC table. After nesting, the user moves the materials to the CNC machine, where ProjecTables is able to match the materials from the precut table to the materials on the CNC, creating a smooth transition between the precut work space and the CNC cutter.

Interaction

When nesting models for CNC machines many different interaction techniques have been investigated. Both [11, 15] found that users prefer the mouse rather than directly manipulating objects. VAL [15] evaluated interactions using AR-Media for Google SketchUp with an AR pen, an Android app using Bluetooth and finally using a mouse. VAL [15] lists the three main reasons as 1) familiarity with the mouse. 2) users did not want to reach into the work area of the CNC cutter. 3) the mouse offer more possible interactions.

ProjecTables [11] allows users to move the scrap material even after it was placed. This allowed a more tangible interaction with the material. Although nesting of models was still done with mouse, the result was projected on top of the material. Some of their participants expressed, that they would have preferred a screen-based interface and use of a CAD program like Rhino3D for better control and options. ProjecTables [11] theorise that the mouse interaction may feel disconnected from the projection. They suggests to either implementing touch based interaction to give a more intuitive interaction together with the tangible experience gained from the projection, or alternatively making an screen-based interface with mouse input.

MARCut [10] uses markers for a tangible experience such that users can operate a laser cutter by adding different markers to the material. MARCut supports different actions, all represented with a different marker. Some markers designate where the laser should cut or engrave. Other markers are instructions such as copy and paste of engravings, material indicators, or indicator of the number of operation. They detect markers with a webcam, and then translates operations from the marker to the laser cutter. Like the AR marker in VAL, the markers specify where the model will be cut, thus making it more intuitive than setting the origin manually through the cutting software.

PacCam [12] used a screen-based interface and interaction with either mouse, pen or single hand multi-touch, but do not report any preference of interaction. PacCam [12] uses rigid body simulation for nesting models onto the captured material. They evaluated three ways to nest: using traditional rotation with handles, fluid dragging and fluid dragging with collision snapping. They found that collision snapping performed better than traditional nesting using rotation and translation.

RESEARCH PROBLEM

The research mentioned in the previous section has investigated different interactions, work spaces, and visualisation methods.

While there has been studies focusing on how to increase productivity and visualise the desired cut-outs. There has been no study focused on productivity and visualisation, for a virtual environment using a dedicated work space away from the CNC machine to nest models onto a scrap material.

Another common theme in the research is that they make a standalone solution. As suggested by an user in [11], we think it is worth while to investigate the possibility of incorporating a system into a CAD program that architects and designers already are familiar with, and use everyday.

In this paper we will therefore produce and evaluate a system, with a separate work space, that helps architects and designers in reusing scrap materials by incorporating it with a CAD program.

METHOD

Artefact

We made a plugin for the CAD software Rhino3D named Condor. Using a webcam, Condor is able to take a picture of a material and find the contours, which can be used to nest model parts inside the Rhino3D environment. The plugin uses computer vision algorithms from Emgu [1], a multi platform .Net wrapper for the OpenCV [2] library to find contours.

Using a webcam as seen on figure 1a, and the computer vision algorithms from Emgu, the plugin is able to process the image to find contours as shown by the red lines on figure 1b. The contours can then be exported into Rhino3D as polylines, where they are place in a separate layer, making it easy to differentiate between the models and the found contours. When exporting the contours from the plugin. The user is asked to select two points indicated by the green dots on figure 1c, which will be aligned to the x-axis in the Rhino3D environment. This is done to make it easier to place the material correctly on the CNC machine. After exporting the contours, they can be used as reference to nest the models the user wants to cut from the scrap, as seen on figure 1d. Both contours and models, can then be exported to the cutting software, where the models can be cut, and the user can see the contours as a guide for placing the scrap material correctly on the CNC machine.

We made a basic and an advanced tap for the plugin. In the basic tab the plugin uses predefined algorithms and parameters seen on figure 1b. If the basic tap is not able to find adequate contours, the user can switch to the advanced tap. Under the advanced tap the user can choose which algorithms to use and is able to change the parameters and execution order to find the best result.

To make it easy and intuitive to choose what algorithms to apply to an image, we made two lists containing active and inactive algorithms. The user can drag and drop the algorithms between the active and inactive list to get the desired result. Once a change to the active list is detected the algorithms are applied to the image captured in a top to bottom manner. As a final step contour detection is applied to the image.

It is possible to open a window with settings for an particular algorithm. Here users can change parameters, if applicable, and get immediate feedback on how the algorithm changes the image. For instance, in the settings for binary threshold, the user can change the threshold with a slider.

"Object selection" is a slightly different method from algorithms such as binary threshold. The algorithm behind "object selection" is watershed. Here users can draw on the image, to manually separate background from material. This method requires more user input compared to the others, but is more effective on images with a noisy background or can be used as an addition, to detect imperfections on the material.

For a better understanding of how the advanced tap and methods works, we will refer to the videos we have made available on Food4Rhino [6].

Experiment

The goal for our study is to evaluate our plugin, and get insights into how architects current work process of reusing scrap material. Furthermore we want to investigate their wishes for reuse of material and how to better facilitate reuse of material.

To evaluate the plugin we created a scrap material in cardboard which participants had to reuse using the plugin. To compare the plugin we included a task, which we believe to represent how architects work when reusing scrap material.

To test the primary usability of Condor, we have chosen to only focus on the basic use case, thus we only focus on the basic tab of condor in the experiment.

Experiment Setup

Figure 2 shows our setup at Aarhus School of Architecture. The CNC machine used was a Zünd G3 M2500, equipped with a pen for drawing. For the evaluation of the tasks, we found that drawing instead of cutting was beneficial for evaluating the results, and had no effect on the results. The necessary setup for Condor to work was placed next to the machine. We used two tripods holding a wooden beam to mount the camera. It is important that the camera points straight down to avoid warping the image. We placed black cloth on the floor to achieve high contrast between the material and background, such that the algorithms of the basic tap could find contours easily. Likewise when placing the scarp material it should be placed in the center of the cameras perspective to reduce the warp on the image. In this configuration of the setup, the floor was used to place the material on, however, it could have been placed on a table instead, if it is possible to mount the camera properly. The camera used for the setup was a Logitech C930e (1920x1080). For convenience we did not use a separate computer by the work space, but chose to use the computer used for the CNC machine.

For each task, the participants used the scrap material shown on figure 1e. It is a grey 1mm cardboard with a size of an A2

Figure 2: The experimental setup at Aarhus School of Architecture.

sheet. The intent was to have a real looking scrap, which is inefficiently nested, but with realism in mind.

The models, the users had to nest for both tasks, are shown on figure 3. The models were created using Slicer [3] for Fusion360 using their sample rhino model. These models were chosen such that we have different sizes and shapes. A small model(1) easy to place. A medium sized model(2), that has a simple shape, but is too big to fit everywhere. Finally there is a big model(3), that has an irregular shape, fits few places and is hard to fit correctly. Our intentions with these shapes were to catch the different situations participants would encounter when reusing scrap, and to look for differences in nesting them using the two tasks.

Independent variables

For this experiment, we have one independent variable with two levels, using our plugin or the normal method using the built in software.

Experimental measures

The dependant variables are, errors in terms of accuracy, and time in terms of efficiency. When looking at the independent variable, we wanted to see if there was any significant difference in both errors made and time taken. We consider errors to be when the participant drew outside the material. For time we

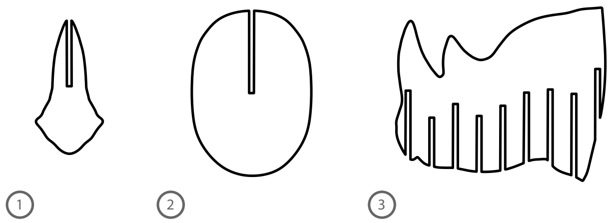

Figure 3: The models used in both tasks.

wanted to measure time spent on different goals, like overall time spent and time spent nesting each model.

Task 1
In task 1 the participants had to reuse the given scrap material using Cut it!, the cutting software used on Zünd machines. The task started in Rhino3D with the models loaded. The participants were allowed to rotate and move the models around, if they wished to do so. When ready, they exported the models to Cut it!, where they had to fit the models onto the scrap material, by moving the laser equipped on the machine, to make sure the models fit. They were allowed to draw one model or several models at a time, if they wished to do so.

Task 2
In task 2 the participants used Condor. Here they also started in Rhino3D with the models loaded. Participants then had to open the plugin, take a picture of the scrap using the webcam as shown on figure 1a. This would give them the contours of the scrap seen on figure 1b. They then had to export the contours to Rhino3D. In Rhino3D they nested the models within the contours found like seen on figure 1d. Here they were also allowed to rotate the models if they found it necessary. When done, they exported it to Cut it!, placed the material on the machine like on figure 1e and let the machine draw all models at once.

On the machine used for the study, there was no easy way to ascertain that the material was placed correctly. As a simple solution, we opted to place tape on the mat as seen on figure 1e. In the task the participants had to set the origin point of the machine to the lower right corner of the material.

Questionnaire
The participants were asked to fill out a short questionnaire to get some statistical information about the participants demographics, as well as their experience with Cut it! and Rhino3D, and how often they used these programs.

Interview
We conducted a semi structured interview, where the participants were asked about their experiences with reuse of scrap materials. The exercises served as a platform to talk about inefficiencies in reusing scrap materials, what worked well and what did not work well using the plugin, and how it could be improved to better facilitate their work process.

The participants were encouraged to come up with ideas that would make them more likely to reuse scrap materials, whether it would be through software or not. When a participant did not have anymore ideas or failed to suggest any, they were presented our own ideas and what other participants mentioned, to get their opinion on those.

Experimental procedure
The participants were told roughly what they would be doing before signing a consent form. In the beginning of the experiment, we emphasised to the participants, that we did not make any of the software nor were we associated with it in any way. This was done to avoid creating any bias. We used within group, therefore we randomised the order of the tasks to avoid any learning effect.

For each task we first guided the participant through a simple example before beginning the real task. This ensured that the participant knew the goal of the task, and could be used to brush up on the software. For the guided example, they used the same piece of material as they would for the real tasks, but confined to a test area seen in the upper left corner on figure 1f.

After completing both tasks, the participants were asked to fill out the questionnaire, and finally we conducted the semi structured interview.

Data analysis
Data was gathered using screen recording, video recording, notes, questionnaire and interview.

Time measurements was found by looking at the screen recording and video recording captured with a GoPro Hero 5. The GoPro was mounted on a wall, overlooking the experiment. We placed the GoPro out of sight, in hopes that it would be inconspicuous to the users.

We agreed beforehand on what should be measured, and then each individually calculated the times. Afterwards we compared our times and looked further into the edge cases to agree on a common time. After agreement on all times, we used the average for analysis. Likewise, the interviews were coded separately, and then compared.

RESULTS
We recruited 10 participants of which 3 were female. 2 were employees at the school and 8 were students. Participants were between 20 and 49 years old ($M = 26.3$, $SD = 8.5$). All were recruited from Aarhus School of Architecture. The participants were compensated with a meal ticket to the canteen on campus, valued at 38 DKK.

We had 6 participants doing task 1 first and 4 doing task 2 first. Using an independent-sample T-test, it suggest that, on average, participants starting with task 2 ($M = 265$, $SD = 70.65$) were faster in task 2, than participants that started with task 1 ($M = 280.83$, $SD = 49.61$). However this difference was not significant $t(8) = .42, p > .6$. Furthermore participants starting with task 2 ($M = 383.25$, $SD = 87.60$) were on average faster in task 1, than participants starting with task 1 ($M = 469,83$, $SD = 116.95$). However this difference was also not significant $t(8) = 1.26, p > .2$.

Data	Mean	SD	t	df	p
Total time used on task 1	435.20	110.254	5.987	9	0.000206
Total time used on task 2	274.50	55.660			
Time used to place all models in task 1	188.50	78.441	7.725	9	0.000029
Time used to place all models in task 2	39.30	27.382			
Time used on placing model 1 in task 1	40.30	13.961	8.209	9	0.000018
Time used on placing model 1 in task 2	11.60	11.587			
Time used on placing model 2 in task 1	53,80	34,282	4,222	9	0,002231
Time used on placing model 2 in task 2	9,10	6,454			
Time used on placing model 3 in task 1	94.40	51.364	5.940	9	0.000218
Time used on placing model 3 in task 2	18.60	16.480			

Table 1: Statistical results on the collected data. Each row is a seperate paired-sample T-test. All show a significant difference between task 1 and task 2.

We used paired-sample T-test to test whether there is a significant difference in the total time spent on the two tasks. The results show that on average, participants were significantly faster in task 2 ($M = 274.5, SD = 55.66$) than in task 1 ($M = 435.2, SD = 11.254$), $t(9) = 5.987, p < 0.05$. Table 1 show all the results we calculated, all shows that task 2 is significantly faster than task 1. On figure 4 is shown a boxplot over total time used for task 1 and task 2. We can see that the total time for task 2 is generally lower than task 1, and that the variance in task 1 is much greater than the variance of task 2.

Looking at the total time spent on the two tasks we can see that task 2 is on average 1.58 times faster than task 1. The participants also nested the models 4.79 times faster in task 2 than task 1. Nesting the individual models, model 2 was the model with the highest difference in average nesting time with task 2 being 5.91 times faster than task 1. When the participants were nesting model 3 they were 5.08 times faster in task 2 than task 1. Lastly, when nesting model 1, the participants were on average 3.47 times faster in task 2, than in task 1.

We created the models such that, the difficulty increases from model 1 to model 3 such that $1 < 2 < 3$. As intended in task 1, model 1 is 1.33 times faster to nest than model 2 and model 2 is 1.75 times faster to nest than model 3 in task 1. However, this does not hold for task 2, where model 2 is 1.27 times faster to place than model 1, and model 1 is 1.60 faster than model 3. Thus we have the relations $2 < 1 < 3$.

We used a Pearson product-moment correlation coefficients to see if there were any correlation between the participants perceived experience with Rhino3D or Cut it!, and the total time of each task. We also tested if there were any correlation between the participants frequency of using Rhino3D or Cut it!, and the total time of each task. The tests showed that neither the experience level nor the frequency of the participants using Cut it! or Rhino3D had any correlation with the total time for each task.

Errors

Under the study we found three errors occured in task 1, and three errors in task 2. We considered a drawing of a model to be an error, when the drawing went outside the scrap material. The three errors done in task one, can be contributed to that the participants did not test thoroughly enough with the laser, to ensure that models fit the selected area. Two of the errors using Condor is due to the participants nesting the models at the very limit of the contours, causing them to draw on the edge. This makes it such that, a slight offset of the origin or a slight distortion from the image taken will cause an error in drawing. The last error with Condor had a greater degree of error and cannot be contributed to an offset of origin, but rather that the image had a high level of distortion.

Observations

For participants doing task 1 first, we noticed some tried to cut all models at the same time. We believe this is due to the participants not knowing the exact size of the models compared to the size of the scrap.

When doing task 1, some participants choose to rotate models in Rhino3D, while others rotated when necessary in Cut it!. The advantage of rotating the models in Rhino3D is that it is possible to rotate any degree, while Cut it! only allows 90 degree rotations.

Participant 9 did task 1 a bit different from the others. Under task 1 he replicated the process from Condor. Knowing the measurements of the scrap, he made a rectangle in Rhino3D. He then nested the three model parts, while looking at the scrap lying on the machine as reference. He exported the models and used the laser on the machine to check if all the models fit, which he did not need to do when using Condor. He admitted, that he had never tried to reuse a scrap material on the machine before, and he found the plugins method to be more intuitive after having seen it, and thus decided to try emulating Condor. The participant spent roughly the same amount of time as when he used the plugin. He spent a bit more time nesting the models, since he had to reference the real scrap to the rectangle in Rhino3D.

Interviews

In the interview we found that all participants(except participant 9) currently reuse materials roughly in the same way as in task 1. Some mentioned they would choose to cut out the models by hand rather than use the machine. One participant also re-purposed cheap materials such as cardboard as disposable plates. They also confirmed that the scrap material we used

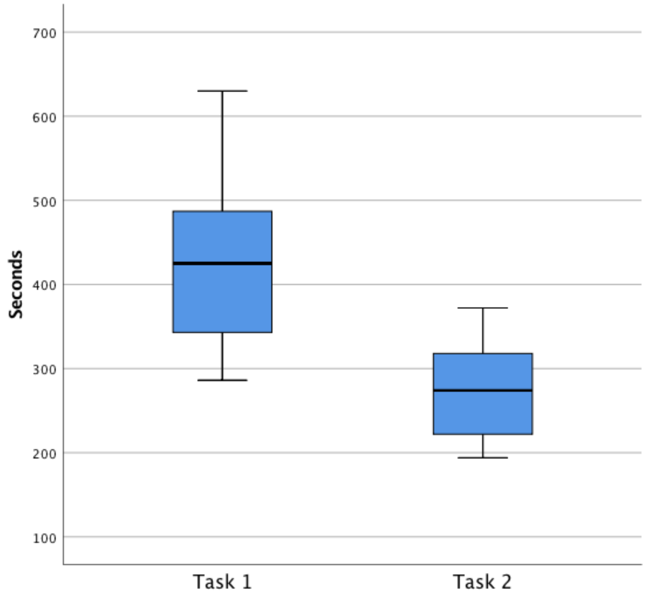

Figure 4: Box plot for total time used in both tasks.
Task 1:(Min:194, Q_1:222, Median:274, Q_3:318, Max:372)
Task 2:(Min:286, Q_1:343, Median:425, Q_3:487, Max:630)

was representative for a typical scrap material, that could be found in the workshop. The models were also representative with shapes and sizes they normally would cut themselves.

Not surprisingly, people decided whether or not to reuse scrap material based on the cost of the material, the effort it takes to reuse it, available storage space, and for some participants, the need to be sustainable. It is different for each person what matters most. One participant, for instance, never saved scrap materials unless he knew that he would be able to use the scrap in the near future. He did, however, save expensive materials like acrylic, though. For another participant, sustainability was a major concern.

Some suggested that it would give a better flow to have the setup on the machine itself, such that the camera would be placed over the CNC machine, and then the CNC bed would be used as a bed for scanning the scrap material. However, some participants commented that they preferred a separate workstation due to the fact that the students have to pay for each minute they occupy the machine. One participant thought the idea of a separate worktable was good, but wished for the origin to be found automatically when the material is placed on the machine.

We found that participants would prefer to use Condor when cutting more than one model, and if there are many holes in the material. Several commented that they liked being able to nest their models using the contours as a reference in a CAD environment they are familiar with.

Some of the participants believed Condor would make them more inclined to reuse scrap materials they normally would not consider reusing, due to the effort required by their current techniques.

The participants were both positive, but also sceptical about the idea of some kind of material library. The participants commented that the current storage system has little structure, and normally, they simply put their material onto a random shelf and attach a note with their contact information. The participants doubted that the students would be able to change their habits to become more organised, and would instead continue to use the shelves without using the library system.

Both participant 1, who was an employee at the school, and other participants commented that students mostly use cardboard, and they believed that the effort to save a cardboard material in a library system would be too much of an effort relative to its cost.

The participants expressed that they were very reluctant to share their personal materials with other students except for people inside their work groups. Instead they suggested that the library should be a personal catalogue, of the materials the student owns themselves. Some participants also noted that a library system would be better suited for industrial use, where the materials are owned by the business, and not by the individuals.

When discussing the idea of a mobile application that could scan the contours of the material, most participants thought that it would be a useful feature, a few participants even suggested this use case themselves. Some participants had a few concerns about using a mobile phone to capture the contours. One participant was worried that the background of the image would interfere. Another participant would not be inclined to use a mobile phone, if one had to stand over the scrap material to capture a birds eye view image of the scrap material. One participant referred to an experimental system [14], that is able to take a picture of a scrap material, and then use the phone to see if the models would fit the scrap material.

One participant suggested that Condor should be extended such that, it is able to communicate directly to the CNC machine. This was suggested such that the use of Cut it! would be avoided.

Several participants suggested different flavours of auto nesting. Some suggested that Condor should automatically place all models onto the scrap material. Some suggested that Condor should be able to make suggestions to where the models could be placed, and then the user would have to accept the suggestions, or manually move them either due to poor placement, or because the suggested location is on top of an imperfection in the material.

Some of the participants told us, that when they had cut something, they often cut off parts that are of no value for reuse, before storing the material for later use. We thus asked them whether a software solution, which automatically found usable areas of the scrap and discarded the rest would be useful. Most participants would like a rectangle, where they could specify a minimum size, as to not get a lot of too small pieces. One participant wished for a more free form solution, because she thought a lot of scrap would go to waste by only cutting out rectangles.

DISCUSSION

Visualisation & Interaction

The participants in our study uses Cut it! no more than a few times a month or a few times a year. We also saw under the experiment, that almost all the participants needed a quick brush up on how to use Cut it!. In comparison all participants use Rhino3D everyday or a few times a week.

Our solution attempts to draw on users familiarity of Rhino3D on a regular monitor with mouse input, whereas other research like [11, 12] make standalone solutions, where their goal is to make intuitive interactions and visualisation to help users. A downside of our approach is that it consists of three different programs, if we count Condor as one by itself.

Work Space

In [15] they mention that when there is a queue to the CNC machine, people tend not to cut out single models at the time due to the social pressure. They suggested to make a separate work space, so they would not occupy the CNC machine and instead reduce the idle time at the CNC machine. Furthermore, in our interview one of the participants told us that they pay for every minute spend on the machine, so having a dedicated area for nesting the models will not only alleviate the social pressure, but also save the students money in the process. [15] mentions that users spend roughly 9 to 35% of their time in the precut phase, depending on their skill level. Thus a separate work space should reduce idle time spend on precut at the CNC machine, and as a consequence students can save money.

One of the benefits with a separate work space is that, it is possible to have multiple users work in parallel. This can be achieved by having the users bring their own laptops, and connect the camera to the computer, take a picture and sit at their own desk. The users can then nest the models at their own pace, without feeling the social pressure of a queue.

Many expressed that they would prefer to have a table close to the machine to have a good workflow. In our study the camera was placed next to the machine, and not next to the controls, therefore participants had to walk, to the computer to capture the image, and then retrieve the material to place it on the CNC machine. If the work space has to be close to the machine for a good work flow, the better solution would likely be as done by [12] and use the machine bed itself. However, by having the work space on the CNC machine, we lose the prospect of reducing idle time and social pressure mentioned before.

Work Process

We found that the assumption about the students current workflow for reusing scrap material was confirmed in the interviews we conducted. With the current workflow it is only possible under special circumstances to nest and cut multiple parts at once. This creates two different problems. The first problem is each time a model is nested and ready to be cut the CNC has to warm up, this overhead is present each time models are cut separately. The second problem is that when nesting multiple models on a single scrap material, there may only be one specific way for all to fit. Keeping track on the optimal nesting strategy for the given scrap material might be hard, and invites irreversible errors, by cutting out models in sub optimal places.

The students currently avoid these problems, by only nesting models on the edges of the materials, or by finding a square where all the models can fit. This means they never nest their models between holes in the materials, that are too small to fit all the models. Thus there is a lot of wasted material.

Condor alleviates these problems by giving the user an overview over all the models they have to fit, and allows the user to try different configurations of nesting before settling on a final version. Additionally the Rhino3D environment allows for more control, like free rotation of objects compared to the fixed 90 degree rotations in Cut it!. This could be circumvented by physically rotating the material, however during the experiment no one did this. This aligns with what [15] reported, that the users did not like to interact with the material once it is placed on the machine. This feature enables even more possibilities for different nesting configurations. Furthermore Condor allows for all the models to be cut at once, rather than one at the time, and thus reducing the overhead.

Participant 9 showed it is possible to do this without Condor, but we would argue that it would not be feasible or worth the trouble in the general case since it is likely very prone to errors.

LIMITATIONS & FUTURE WORK

Without a more throughout study, we cannot validate whether participants would actually continue to use Condor. Likewise we cannot say how much Condor can improve reuse without knowing how much is wasted currently and doing a study where Condor is deployed for a longer period of time.

We had 10 participants, which is on the lower scale for quantitative data, however, we did find Condor to be significantly faster, making it probable to be true for higher number of participants. We find that 10 is enough for a qualitative study to get feedback, which is similar to [11] with 10 and [12] with 12 participants. We did not get the full spectrum of experience levels, having no self perceived experts. In the questionnaire the participants placed themselves relatively low when reporting their own experience. After observing the participants, we believe that some of the participants placed themselves lower than their true experience level. Thus it is possible that there are correlations, that we were not able to find.

The participants are mainly students and all are from Aarhus School of Architecture, therefore we cannot say how Condor would be received in a different setting, like industrial or a very different type of school.

As a future study it would be interesting to test a scenario where participants prepare at a separate table using their own laptop to evaluate whether it reduces social pressure or how it could reduce idle time of the CNC machine as described in [15].

As of now the camera has to be placed perfectly to ensure good images without distortion. For easier setup and consistently accurate images, the camera should be calibrated like [11, 12]. We are currently using tape to assist in placing the scrap material on the machine. A solution for this is the automatic recognition of the material as done in [11], this will however increase the cost of the setup.

Condor could potentially extend into the direction of replicating or modifying models like [8], however, it would require higher quality contours than what we find now. The contours we find are jagged due to how we find them. This is not a major problem when they are only used as reference when nesting.

Currently users have to reference between the contours in Rhino3D and the real material to spot imperfections, that may be relevant when cutting. Solutions include [12] where they import an image of the materials surface into their program or using visual projection like [11, 15].

We have shown an interface alternative to visual projection used in [11]. We can not tell whether it is a better solution since we did not test a version with visual projection. It could be interesting to compare the two and perhaps look for a hybrid solution that incorporates both projector and screen based visuals.

It would be interesting to investigate the library system further. As the interviews suggested some participants were supportive of the system, and some were sceptic. Further studies should be done to conclude if and how such a system should be implemented. An industrial context could also be considered, as suggested by some of the participants.

To avoid a stationary setup to capture the contours of a scrap material, a mobile application could be introduced. Similarly to [14], the application should be able to capture the contours and save them in cloud storage. The user can then access the cloud storage on a computer, and begin the nesting process.

Lastly, an improvement to workflow could be to communicate directly with the CNC machine like [11, 12]. This way it may be able to remove the need of cutting software such as Cut it!. It might also be possible to make a cloud based solution to smooth the transition going from personal computers to the CNC machine, queuing print jobs similar to a regular printer.

CONCLUSION

We have presented Condor, a screen based plugin for Rhino3D that assists architects in nesting models onto scrap materials, by using computer vision to find contours of a scrap material. A user study was conducted, which demonstrated that using Condor is significantly faster at reusing scrap than the traditional method. A semi-structured interview was conducted to verify assumptions of current practices, to collect personal opinions about Condor, thoughts about further improvement to Condor and general needs in regards to reusing scrap material. We found that participants preferred to use Condor for reusing scrap materials. Most of the participants also thought that, they would be more likely to reuse scrap materials more often in the future, if they had access to Condor.

Our solution alters the current process for reusing scrap material, into a new process, which decreases the time spent trying to nest models onto scrap materials. Furthermore, this study has gathered information that can be used as a base for further development in the field of reusing scrap material.

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CopyCut!: Using Computer Vision for Digitising Physical Objects for Editing and CNC Cutting

Jakob Andersen
Department of Computer Science
Aalborg University
jaande13@student.aau.dk

Jesper Ravn-Nielsen
Department of Computer Science
Aalborg University
jravnn13@student.aau.dk

Thomas Egon Kaergaard
Department of Computer Science
Aalborg University
tkarga13@student.aau.dk

ABSTRACT
When working with CNC machines, there is sometimes a need to replicate an already existing object. In the upholstery industry it is normal to have handmade templates, thus there is no CAD file available to cut with a CNC machine. Recreating objects without the original file can be a difficult and time consuming process that involves tracing an object in a CAD program. Additionally, not all who works with CNC machines are necessarily apt at using CAD programs. We present CopyCut!, a system that allows users to copy existing objects or create new objects from sketches. CopyCut! extracts contours from images captured using a camera mounted above a CNC machine, and converts them into vector format, allowing users to use them in CAD programs or with the CNC machine. CopyCut! thus creates a new process for copying objects and allows for creative ways of using objects and sketches to create new products. CopyCut! differs from other similar work in that it allows much larger work area than those described in the related work, and does not use any specialised equipment. CopyCut! is a simple addition to an industrial CNC machine, meaning it can be set up and used without changing expensive equipment. We also describe several creative ways to use CopyCut! beyond copying of objects. To evaluate CopyCut! we tested the accuracy and conducted both an expert review and a co-design session. The system has an minimum accuracy error of 0.2 millimetres in the centre of the work area, but worse further away due to camera lens distortion. The expert review and co-design session gave us feedback on the usefulness of CopyCut! and possible improvements.

Author Keywords
Computer vision; Contour detection; Assistive Computer-aided Design(CAD);

INTRODUCTION
Computers are used increasingly for many tasks. For architects and designers, software can enable them to create new constructs or designs they were not able to do before [5]. Kolarevic [5] talks about the implications of digital fabrication using CNC machines. He mentions the return of the term "master builders", who are not only able to design, but also fabricate. In the industrial age, architects and designers drew plans and specifications for buildings and models, which were then given to masons, carpenters or other experts to build from. With the introduction of CNC machines and computer-aided design (CAD), it is increasingly possible and required for architects and designers to be part of the whole process, from design to construction. This allows for time savings by reducing the amount of information that needs to be communicated through drawings and documents. CNC interfaces or software can assist architects and designers in many ways that allow for time savings or enables new techniques. Software can be used to automatically convert a model into 2D parts that can be fabricated by a CNC machine, or it can be used to create new shapes and forms that would otherwise be impossible or unmanageable to do. It is therefore important to research how to support and enable architects and designers with new techniques and improvements, to allow them to work with new ways to design and fabricate and further their industry.

In this study we have collaborated with Zünd Skandinavien ApS [4]. Zünd sells and develops CNC machines, interfaces and software. They have much to gain from software with new techniques that can expand their business to new markets. For instance, they have software that assists in nesting models onto textile and leather, and software for creating packaging and display stands. Some of their costumers have a need to quickly acquire vector files of existing objects, but do not have the original file. The environment that models are build in, are typically in a computer aided design(CAD) tool, where it can be time consuming for the user to replicate or modify an object. Additionally, those that work with CNC machine, may not be designers or skilled at using CAD tools. Even though CAD tools are becoming more available and easier to use, it can still be slow or complicated to copy a physical object by hand. It is therefore interesting to find out how to best support creation of models from physical objects.

Much research has investigated how to improve interaction with CNC machines by going beyond the 2D screen and CAD programs. New techniques and software can allow users to extract contours from objects [8, 9, 20] for different uses or provide feedback on models in the physical world to give an idea of the size and shape when fabricated [16, 17, 19]. It is also possible to automate some processes that would otherwise be time consuming or complicated [6, 12].

In our research, we introduce CopyCut!, a system that uses computer vision with a consumer DSLR camera to convert raster images of objects to high quality vectors. We show how CopyCut! can be used to replicate objects and enable several creative ways to work with CNC machines. We provide CopyCut! as open source, such that others can use it as a tool, as inspiration or to further their own work.

In this paper we describe the core technologies of CopyCut!, as well as the design decisions made throughout the design of the system. Furthermore we explain the versatility of CopyCut! by describing different use cases that it is able to assist in. We then evaluate the technical accuracy of CopyCut! by measuring its ability to replicate A4 papers. Next we conduct an expert review to evaluate the potential of CopyCut! in an industrial setting. Lastly we conduct a co-design session with interaction design students to explore what use cases they found useful as well as general feedback for CopyCut!.

Contributions

The contributions of this paper is threefold:

- CopyCut!, an open source solution [3] for extracting contours and exporting them to a DXF format.
- A workflow for digitising physical objects for editing and CNC cutting, as well as several use cases and challenges of the system.
- Empirical data on technical accuracy of the system and feedback from an expert review and a co-design session.

RELATED WORK

Much research has already been done on how to improve the process of designing models and using CNC machines. Related work can be put into three categories, Augmented Design and Fabrication Tools, Material Detection and Preparing Files for CNC Cutting.

Augmented Design and Fabrication Tools

The following research introduces tools that allows designers and architects to save time or create new techniques that allows them to work in new creative ways.

WireMolding: 3D Modeling Approach Involving Molding with Wire [20] propose a work process using wire to capture contours. First the user physically designs the desired shape of the model in 2D with a piece of wire. Afterwards a picture is taken of the wire, from which contours are extracted and converted into SVG format. The SVG file can then be brought into a 3D modelling software.

Logic Trace Digitizing System [9] is a commercial available product, that enables the user to trace physical objects with a magnetically tipped pen on a digitizing tablet to produce digital copies of the physical objects. A model can either be drawn in free hand, or by describing the shape in lines and arcs. The lines can be described by marking the start and end point with the pen, while an arc can be described by the start and end point along with the apex of the arc.

CopyCAD: Remixing Physical Objects With Copy and Paste From the Real World [8] introduces a technique that allows users to copy contours of objects or sketches and cut them using a CNC machine. The contours can be modified by changing, deleting or adding to them using fingers or a special pen. CopyCAD also provides users with projected feedback of the object.

Reprise [6] and AutoConnect [12] are two examples where 3D models are partially auto generated. Reprise can be used to augment tools with for instance handholds for a better grib. AutoConnect can create 3D connections between two objects. For instance it is able to make a smartphone mount for a bike. Both require 3D models of the tool or two parts to be connected. Both solutions also have a database of premade designs from which the user can chose the best for the given problem. The problem is thus reduced from complex 3D modelling in a CAD program, to choosing from some auto generated options and using sliders to make adjustments.

SPATA: Spatio-Tangible Tools for Fabrication-Aware Design [19] adapts two traditional measurement tools, calipers and protractors, to integrate with virtual design environments. These tools are developed with bidirectional value transfer, which enables both the user to send the measurements from the tools to the CAD software, but also the opposite way. This enables the user to experience a more tangible design experience.

ProjecTables [16] provides alternative visual feedback of models. ProjecTables uses projection for nesting of models and allows users to see the size, shape and where the models will be cut on the CNC bed. This allows for visual feedback onto the material used to cut from, making it possible to validate the result before cutting.

PacCam [17] uses a webcam to capture materials, which are used to nest models onto. They conducted a study in which they asked participants to nest physical objects to get inspiration on how to design interactions for nesting. Different interaction techniques were developed as well as three types of input in the form of multi-touch, pen or mouse. They also introduced rigid body simulation to simulate physical nesting. Their system is able to send coordinates directly to a connected CNC machine to cut out the nested models.

Material Detection

Contour detection is useful to avoid tracing objects manually in a CAD program or solutions like Logic Trace Digitizing System [9]. Material detection is not only useful for replicating, but can also be used to nest materials on scrap materials, where it is very time consuming to do so with the normal CNC interface [2, 16, 17]. A common way to capture the contours of an physical object or sketch is by using an image of the material taken from a birds-eye-view with a camera mounted above [2, 8, 16, 17] or with a handheld smartphone [20]. Contours can be captured by putting the image through computer vision algorithms to extract the contours. [8, 16, 17] uses background subtraction to get rid of the background in the image while highlighting the materials, this is done by first taking an image of the background and afterwards taking an image of the materials with the same background. [2] does not use background subtraction, but instead enables the user to either pick and choose from different algorithms to produce the best possible contours from a single image, or go with a predetermined selection of algorithms to generate the contours from the image.

Preparing Files for CNC Cutting

As mentioned in Material Detection, using images to detect contours is a common approach. Normal camera images are captured as raster graphics and is used in software such as [7, 11], which converts raster images into G-code (instructions for CNC machines), however, these solutions only focus on engraving.

However, for CNC cutting it is not sufficient to use raster images. Contours taken directly from raster images will be jagged due to pixels, and thus be a poor representation of the real contours, which usually consists of straight lines and curves. For CNC machines with blade tools, it will also result in a lot of knife up and down instructions where the blade punches out the model rather than cut it, which slows down the process significantly.

There is thus a need to convert raster images into vector formats, such as SVG or DXF, which gives higher quality contours that are also scaleable without losing quality. Converting raster images to vectors is a developed field of study with different commercially available products and libraries. [8,17,20] all convert contours to vectors before cutting or importing them into a CAD program.

Similarly, Adobe Capture [1] is a mobile application from Adobe Creative Cloud to assist designers with different task as taking a picture and convert it to a vector image or recognise font types.

Potrace: a polygon-based tracing algorithm [18] is an algorithm which uses polygons as an intermediate step for converting raster images to vectors. There are many difficulties in tracing a raster image and creating a good representation to the original. Challenges include deciding when there should be straight lines, curves or corners and finding the best representation of the original. Potrace provide a solutions to all those, and has several parameters, which can be fine tuned to create the best result. Potrace is both implemented as a standalone converter but is also available as libraries in several languages and is integrated into software such as Inkscape [10].

RESEARCH PROBLEM

While there has been extensive research on replicating objects [8, 9, 20], there does not seem to be sufficient focus on large work areas without the use of special equipment. There is also no reported metrics of accuracy for the systems in the related research apart from Logic Trace Digitizing System [9].

Although these solutions appear to work well, it begs the question how it is possible to develop a highly accurate solution with a large work area and minimal amount of electronics to digitise physical objects for editing and CNC cutting.

COPYCUT! SYSTEM

In this section we present CopyCut!, a solution that is able to detect contours of objects and drawings and convert them to vectors.

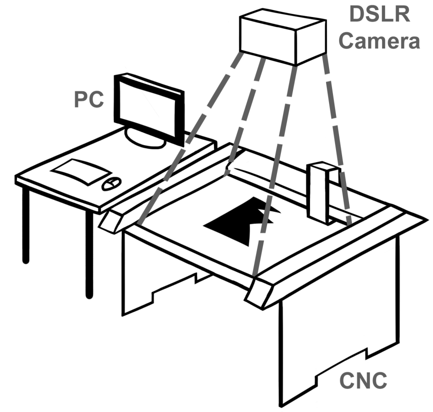

Figure 1: System Setup of CopyCut!

To detect contours we created the system setup for CopyCut! seen on figure 1. A Canon EOS 700D was mounted over the bed of a S3 M-800 CNC cutter from Zünd Skandinavien ApS. To insure that we get the most accurate images we levelled the camera with a spirit level. Both the CNC cutter and the camera was connected to a desktop computer with CopyCut! installed. To use the system, we designed the user interface shown on figure 2.

When designing the interface we had a few goals in mind. We need to provide relevant feedback to the user during the process, such that the user can correctly decide on the next step. We should ensure that we provide the necessary functionality, that allows users to extract high quality contours. We must ensure a good workflow that allows users to quickly accomplish their tasks.

Feedback

The majority of the screen real estate is occupied by three images. These images are used to give visual feedback to the user about intermediate results and how the final contours will look. On all the images, the user is able to use the scroll wheel to zoom in to get a more detailed view.

Window A on figure 2, shows the original image as it is, without any manipulation. We have chosen to include the original image, such that the user can make sure that the input image is of a decent quality. If the original image was not included in the user interface, it could be hard to determine whether the low quality contours were due to a low quality image, or bad settings.

Window B on figure 2, shows a manipulated version of the original image. These manipulations corresponds to the settings in the settings panel on the left side of the user interface. This image gives the user feedback about how the settings changes the image before trying to extract contours and vectorise them.

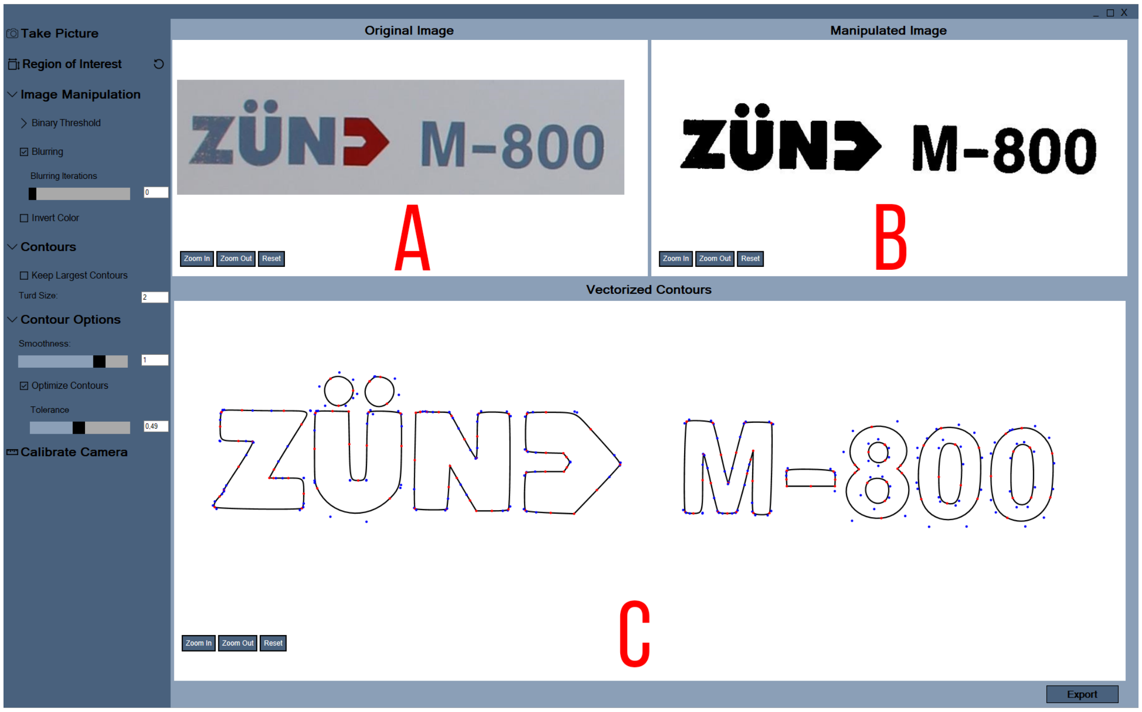

Figure 2: The main user interface for CopyCut!. A) Shows the original image. B) Shows a manipulated version of the original image C) Shows a vectorised image of the extracted contours from the manipulated image

Window C on figure 2, is a vectorised image of the contours extracted from the manipulated image. This image accurately displays the contours that the user will get. In addition to the contours, the image also contains the control points of the contours. The reasoning behind adding the control points, is so that the user can make informed decisions on how the contours are constructed, and whether CopyCut! should try and reduce the amount of control points.

Functionality

The left panel of the interface is used to display the settings available to the user, and is where the main interaction with the software takes place. We have arranged the settings in three categories: *Image Manipulation*, *Contours*, and *Contour Options*. These categories can be expanded to show the different settings, as shown on figure 2. In addition to the categories of settings, there are three buttons: *Take Picture*, *Region of Interest*, and *Calibrate Camera*. *Region of Interest* is used to limit the area of the image that CopyCut! finds contours in. This also reduces the size of the image, making it faster to process.

The functions under the image manipulation category and the *Keep Largest Contours* function from the Contours category uses the open source computer vision library, OpenCV [14]. These methods are applied to the original image in raster format. The rest of the functions from the *Contour* and *Contour Options* category, are settings that are used to generate the vector image using the library, Potrace [15]. Potrace takes the raster image resulting from OpenCV and creates a vector image containing corners and Bézier curves.

To make sure that the resulting vector image contains the right dimensions, the user can click on the *Calibrate Camera* button and start a procedure that calculates the ratio of pixels per millimetre(PPM). The procedure requires the user to place an A4 piece of paper onto the work area. The ratio is calculated by comparing the length of the diagonal of the detected paper with the real diagonal of an A4 paper. We chose to calculate the PPM from an A4 piece of paper since it is of known dimensions and is readily available.

The *Export* button is located in the bottom right corner. When the user presses this button the contours are saved at a selected destination as a DXF file. As of now, the contours can only be exported in a DXF file format.

Workflow

Figure 3 shows the workflow of copying an object using CopyCut!. Steps 1-5 is the process of creating vectors from existing objects using CopyCut!. At step 3 the user can fine tune the settings for the given task if necessary.

After the systems has taken a photo, the computer vision actions are run. The time taken to update the images is based on the settings and can vary greatly depending on the size of the image and the settings selected. To inform the user about the progress, we have included a progress bar and the mouse will indicate that the program is computing the new contours. It is made such that the user can still change parameters while the program is updating. Any parameter changes will cause the program to cancel its current update, and re-run the computer vision actions and the Potrace algorithm with the new parameters. We have opted for this design choice, to avoid

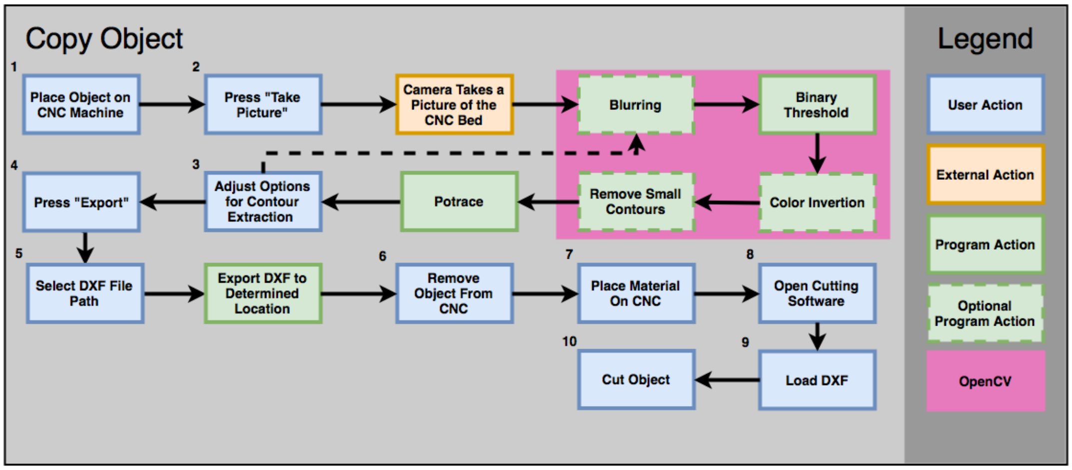

Figure 3: Flow diagram that shows the workflow for copying an object with CopyCut!

an explicit update button, that the user would have to press each time feedback is needed. We have arranged the settings in such a way that the user would normally go through them from top to bottom. However, due to how the settings interact with each other, the user might have to go back and forth between settings to some degree, to achieve the best results. To make the information more manageable, the settings can be collapsed. For settings with intervals, we have included sliders to make them easy to change and know the limits, but we also allow the user to input a specific number in a text box.

When the user is satisfied with the contours and have selected the file path, a DXF file with the final contours is created. In steps 6-10 the user proceeds to cut the file using the native cutting software. The workflow diagram shows the basic use case of replicating an object with CopyCut!, but there may be additional steps like preparing an object, such as a drawing before hand.

Use Cases

In this section we will demonstrate the versatility of CopyCut! by describing different use cases, however it is not meant as an exhaustive list. We have divided the use cases into several general categories, each with one or more examples.

Copying Objects

A user has a worn car mat he wishes to replace, but he does not have the original CAD file, and can thus not make a new one. Using CopyCut!, he takes a picture of the mat, which gives him a DXF file representing the car mats contour. With the DXF file of the car mat he is able to cut out a new mat with a CNC cutter. By saving the DXF file it also enables him to cut more mats in the future.

Model building

A user wants to create a soda can dispenser, such that she always gets the coldest can from her fridge. She is, however, not entirely sure on what design would work best for her. To test the different ideas she quickly draws the designs onto paper and uses CopyCut! to extract the contours for cutting. After cutting the initials designs, she picks one of the designs to further iterate on. However, the design does not quite suit her needs, so she uses the papers with the initial design, and tweaks it further to her liking. When she is satisfied with her design, she once again uses CopyCut! to extract the contours, but this time she uses the contours as a base for 3D models, such that she can 3D print the final solution.

In another case, an architect firm needs to design a new up-and-coming part of a city. With multiple architects on the project, they find it hard to quickly communicate and conceptualise their ideas. To combat this the architects draws the facades of their building designs, and extracts the contours of the facades using CopyCut!. They can then use the extracted contours to cut out their designs and assemble the facades of the designs to create a mock up model. This allows them to quickly communicate their ideas internally, and collectively iterate on each others ideas.

Adjusting Existing Objects

In this case the user has a car mat, which is not only worn, but also damaged by having some parts torn off. He therefore wants to make a new car mat. Similar to the copying use case, he takes a picture of the torn car mat. Luckily he knows how the car mat should look like, so he imports the DXF into a CAD program, where he can modify the contour until it looks like the original car mat before it was torn. When he has corrected the damage, he can start cutting his new car mat.

Alternatively, if the user does not feel confident in his CAD skills, he can place the mat on a large piece of paper. By using a pen to outline the correct shape, where the mat is damaged, he can then take a picture of the mat and the drawn correction. When he is satisfied with the result, he extracts the contour of the mat, but where the damaged part is replaced by the drawing.

The user from before is finally done with her design of a soda dispenser, and is ready to 3D print her final design. However, just before she is about to print the soda dispenser, she discovers that one of the sides of the dispenser is too big for the 3D printer. Instead of scaling the model, such that it fits the 3D printer, she splits the model in two pieces with a connecting puzzle joint, by drawing the puzzle connection onto the design. This enables her to print the long side in two parts and then connecting them together afterwards.

Tracing

A user wants to create a pelican case for some fragile equipment he needs to transport. He takes the items and put them on a piece of paper, such that they are placed as they should be in the case. Using a pen, he can draw around the items and use CopyCut! to extract the contours from the drawing. He then proceeds by importing the contours into a CAD program, where he fits them inside a box that represents the foam in the physical case. By subtracting the contours of the items from the box, he gets the 3D model of the foam which can be used to fabricate the pelican case.

Another user is browsing images of her childhood home, and stumbles upon an old physical picture of a great oak tree from their yard. Wanting to keep the memories alive, she decides that she wants a metal cutout of the tree. Using a marker to draw the outlines of the tree onto a transparent plastic sheet, it is possible for her to use CopyCut! to get the contours of her drawing as a DXF file. The DXF file can then be used to cut the metal with a CNC machine, giving her a lasting memory of her childhood.

Vectorisation

A designer has drawn a logo for a company by hand. Now he wants to digitise it, such that it can be used for documents, websites and 3D printing. The designer places the drawn logo on the CNC bed to get the contours with CopyCut! as a DXF file. The vectors can then be made into a 3D object in a CAD program for 3D printing, or made into a logo in Adobe Illustrator or similar software.

The designer has a range of custom icons he has made through the years when creating paper prototypes of user interface. Instead of drawing them by hand every time, he would like to have stencils to speed up the process and still make good quality icons for his work. He therefore draws each icon as a stencil and uses CopyCut! to get the contours. He then cuts out a small sheet of metal with all the stencils. Now he can save time, but still make quality icons by using his stencils. Additionally, he can use the scanned stencils to create icons, with Adobe Illustrator or similar software, so he can use the custom icons, for instance in a mobile application.

RESULTS

Our evaluation of the CopyCut! system consists of three parts. We look at the technical accuracy of the system, conduct an expert review and finally a co-design session.

Technical Accuracy

We evaluated the technical accuracy of the system using nine A4 papers placed on the machine bed, since they have a known size and shape. The placements of the papers are shown in figure 4, where the blue centre piece is the paper used for calibrating the scale of the system. The rest of the bed is filled with papers to test a more general accuracy. To calculate the technical accuracy of CopyCut!, we compare each side of the extracted contours, with the true dimensions of the paper. The technical accuracy can be seen in table 1. With the current solution, the image will be slightly warped due to distortion from the camera lens. Therefore we have included accuracies for the same image, that has been unwarped by the lens correction feature from Adobe Lightroom.

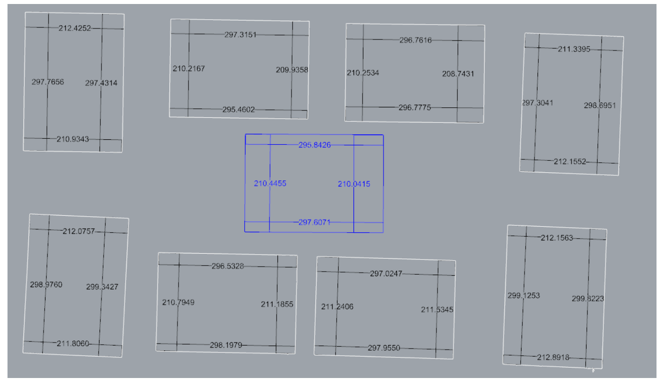

Figure 4: Setup for calculating accuracy as seen in Rhino3D after contour extraction. The blue rectangle is the paper used for getting the correct pixel/mm ratio.

	Without lens correction	With lens correction
Min	0.02	0.02
Max	9.21	2.89
Average	4.14	1.16
Median	3.75	1.17

Table 1: Minimum, maximum, average and median error in millimetres without and with lens correction of the image.

As seen in table 1 there is no difference in the minimum error. This is because, the centre of the image is least affected by distortion, thus the centre paper from both the warped and unwarped image will have the same accuracy. Furthermore the ratio of pixel per millimetre is calibrated from this paper, which will cause the least amount of error from scaling on the centre paper.

There is however still a small error on the centre papers. This is possibly due to an inaccuracy introduced by OpenCV's contour detection, where the contours found tend to be slightly skewed, compared to the real object. This small error of the centre paper can be reduced by increasing the PPM. Maximum, average and median all have a clear difference. As seen in table 1, unwarping the image, improves the accuracy significantly.

In addition to testing the accuracy of CopyCut!, we also tested its ability to extract contours from drawings. In our tests we have been able to detect contours drawn with a regular ballpoint pen with both blue and black ink on white paper. In our setup the camera is 178cm above the bed. If the distance is greater, it may be necessary to use a wider pen, or use optical zoom to see the drawings.

Expert Review

We evaluated the potential of CopyCut! by doing an expert review with people from the leadership at Zünd Skandinavien

ApS. They have expert knowledge about the domain and potential customers that could use CopyCut!. We introduced them to CopyCut! and allowed them to use it, both with prepared examples and their own. During the process they provided feedback in regards to CopyCut! and the problem domain. Afterwards we conducted a semi-structured interview for additional feedback, to discuss the problem domain and potential use cases.

The three different images shown in the user interface were appreciated for the valuable information they give. It was suggested to have the original image underlying the resulting vectors, such that it is possible to see how well the vectors fit the original objects, and to more easily see how parameters transform the objects in the image to vectors.

They commented that the users of the system will be people with little to no skills regarding CNC machines and CAD software. Therefore it is important that the program is simple and quick to use. They noted that to get a good result, it is necessary to change parameters back and forth which may be difficult and time consuming. Currently we save settings, such that if the user finds a set of good settings for a job, the user do not have to redo the settings. It was suggested that instead of saving just one set of settings, profiles should be implemented, such that multiple sets of settings can be saved without overwriting each other. Profiles could for example be optimised for capturing contours of drawings or dark materials. They also suggested that in addition to premade profiles, the user should be able to create their own custom profiles. To help users with a quick start, it was suggested to initially show a number of results from different profiles, to allow the user to easier see what works best for the given image, and afterwards tweak the settings of one of the premade profiles to optimise the result.

An important aspect of the solution, is its ability to replicate contours accurately. We were told that an error of 0.2mm is normal for the textile upholstery industry, and that in the general case, 1mm would be the upper limit. CopyCut! is currently only able to achieve this in the centre of the camera, and when the object is not too large.

During the expert review, they wanted to test some use cases from their customers, of which some of them caused problems. In one use case, they wanted to extract the contours of an object with rough edges. This caused the resulting vectors to be jagged. The contours represented the object correctly, however, they wanted straight edges for cutting. The smoothing and optimisation of the contours was not able to overcome this criteria, without a significant reduction in accuracy. Due to the nature of the material, it was not possible to simply trace the edges with a pen, since the drawn lines also became jagged. However, this can be achieved by tracing the contours on a transparent piece of plastic on top of the object, and then proceed to extract the contours from the sheet of plastic.

In a different use case, they wanted to capture the contours of a pencil drawing. CopyCut! was not able to get the entire contour due to a few faint pencil lines. By retracing the faintest pencil lines, CopyCut! was able to capture the contours. The pencil drawing did not always have clean lines due to small mistakes created while drawing. CopyCut! was able to detect these small juts, however, this was not the desired outcome. Again this can be remedied by tracing the drawing with clean lines.

Due to these problems it was requested to have functionality, that allows users to edit vectors in CopyCut!. They suggested that the user should be able to manipulate and delete control points, such that they are able to repair the contours to achieve the desired result.

Co-Design Session

To get feedback on how CopyCut! can prove useful outside of copying objects, we conducted a small co-design session. We had two groups, one group of four and one group of five participants, six male and three female, age 22-27. All participants were students studying interaction design. From the session we received feedback on CopyCut! and the use cases. Two artefacts were produced during the study.

We presented CopyCut! to each group, as well as some examples of the use cases presented in the Use Cases section. Afterwards they were encouraged to try out CopyCut! and discuss possible use cases. The participants were asked to fill out a questionnaire after the session. In the questionnaire the participants reported their thoughts on CopyCut! and the use cases they found most and least interesting during the session.

The most popular use case amongst the participants, is to use CopyCut! as a tool for prototyping because the participants found it to be fast and thus well suited for rapid prototyping. Many liked the possibility of transforming quick sketches into physical prototypes. One example given was drawing and cutting cloth for sewing, much like an example we received from Zünd of a textile company wanting to cut cloth in the shape of handmade templates.

The use case seen as least useful were artistic in nature where a painting was traced and cut out in steel. The participants thought it was a very niche use case and could not see themselves using CopyCut! in this manner.

The questionnaire also revealed that the participants with the least amount of experience with CNC cutters (rated themselves 1 or 2 out of 5) also rated themselves more likely to use CopyCut! in the future (5/7 yes and 2/7 maybe). In total we found that five would most likely use CopyCut! in the future, while four would maybe use CopyCut! in the future.

The benefits of CopyCut! were listed as easy to use, good for rapid prototyping and recreating 2D objects. However, the participants expressed a need for support of 3D objects. Furthermore, the participants voiced their desire to be able to edit the vectors, similar to what the experts expressed. Lastly the participants responded that the workflow needs to be more intuitive. They commented that more icons and better descriptions would make it easier to grasp the functionality.

During the study, participants created two artefacts. One participant wanted to create a plane out of cardboard. He proceeded to draw the plane parts onto a piece of paper. The plane consisted of 2 parts, the wings and the body, as seen in figure 5a. The plane created from the drawing is shown in figure 5b. An interesting note about the construction of the plane, is that the line splitting the wings was a mistake, so the participant used paper scraps to cover it before taking a picture. This shows that users are not limited to drawing with a pen or single objects, but can also use multiple objects together to create something new.

Another participant wanted to create a physical copy of their mascot from their project. She drew their mascot on a paper, shown in figure 5c, and used CopyCut! to capture the contours of the mascot. The resulting cut out was, however, not as desired, since the top of the figure was cut off, due to the line going across the top of the mascot, as shown in figure 5d.

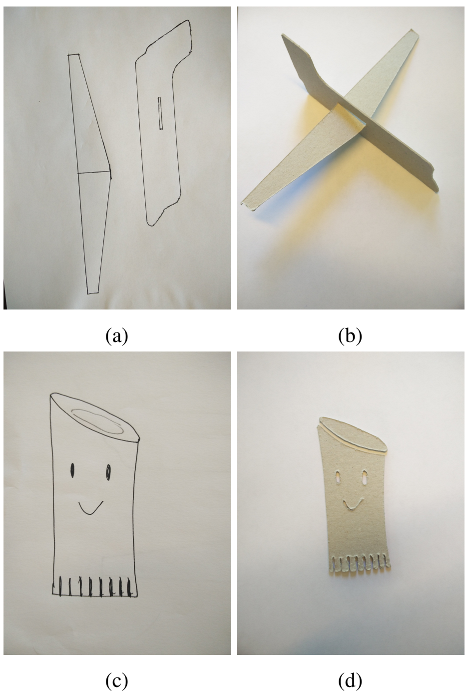

Figure 5: (a) Hand drawn parts of a plane. (b) Resulting plane from contours extracted from figure. (c) Drawing of a mascot. (d) Resulting cardboard cutout from figure.

Challenges

When using a camera to capture contours, there are several challenges that can be present. Unfortunately if the image quality is poor, it is not always possible to alleviate it through software alone. In general, if the extracted contours are sub optimal, a possible solution to many problems, is to draw the outline of the object and use that to capture the contour instead. This may introduce inaccuracy, but we expect it will be negligible in most cases. Another solution is to repair found contours in a CAD program, which may give better results than drawing by hand, but may take a longer time. In this section we describe the problems that we have experienced during the development of CopyCut!, and possible ways to combat or circumvent them. The problems belong to one of three categories: Environment and Objects, Image Quality or Software.

Environment and Objects

Contrasting background is important, as without it, detection of objects can be impossible. The solution is to use either a darker or lighter background than the object. In case of multiple objects, it may be necessary to split them into groups of light and dark colour. In our study we have been able to create high contrast by using a white foam board when trying to detect dark objects, and using the dark bed of the CNC machine in any other case.

Shadows can be a problem for objects that are not flat. If shadows are prominent, they may flood the image, and be detected as part of the object. This can be solved by having a lighting setup that eliminates shadows.

Glare can be a problem when there is strong direct light and materials have a reflective surface, for example polished metal or smooth plastic. Glare will cause light to flood the image similar to shadows, making it impossible to find the correct contour of the object. There are several different solutions to eliminate glare. A solution to avoid glare and also remove shadows, could be to eliminate overhead lighting and use a lightbox as bed for objects, this, however, is a more extensive solution. A more simplistic solution could be to sand the shiny object to scatter the light, or by coating the object in matte paint.

Image Quality

Camera and image quality is important to get accurate contours. Cameras with higher resolution gives higher PPM ratios, which allows for higher precision. PPM can simply be raised by using a camera with a higher resolution, therefore we consider lens distortion a bigger problem for the image quality. We have investigated camera calibration to improve the accuracy for more precise measurements, however, we could not achieve good lens correction. While it may be possible to make use of software to combat lens distortion, we found that the centre of the image is still usable as long as the camera is level. To assist in this, there exists spirit levels that can be attached to cameras. There will still, however, be some slight warp in the image the further the object is from the centre of the image.

Software

When drawing on white paper with a black pen and both the inside and outside of the drawing is white, similar to figure 5a and 5c, the program assumes that the drawn lines are objects, resulting in a contour on each side of the line in the CAD file. To avoid this, one can infill with black, such that the entire object is black. In Figure 5a both the wing and body of the plane should be entirely black. Another route is to cut out the drawings by hand, such that it has a uniform colour, and then using the cut out, like one would with a normal object. The simplest solution is to delete one of the contours in a CAD program. However, in some cases, we found that this double line artefact could be used as an artistic tool.

DISCUSSION

We will now discuss the results from the co-design session, expert review and the technical accuracy of CopyCut!. Finally we will compare CopyCut! to related work and discuss the differences.

Co-Design Session

It is interesting that participants of the co-design session, who see themselves as experienced with CAD software and CNC machines, are more uncertain of whether CopyCut! will be useful to them. We expected experienced participants would be able to see CopyCut! as both a shortcut for obtaining contours of objects and as a tool for creative applications that was not possible before. Instead it may be that novices are more interested in CopyCut! because they see it as a way to avoid using CAD programs. It would be interesting to investigate this further.

Interface Design

Getting the right balance between simplicity and enough complexity to get the job done is a challenge. From our expert review, we were told that typical users of the system would have little skill. At the same time, the task of capturing contours is not so simple, that it can always be achieved by one click alone. We have more functionality than, for instance Adobe Capture [1], which increases complexity, but also enables CopyCut! to get more versatile results than Adobe Capture.

In Condor [2], tabs were used to separate basic functionality from advanced settings. The advanced tab uses drag and drop as a way to make it possible for users to customise the order as well as the inclusion or exclusion of functions. Options for each function would be accessed by clicking on a function, which would bring up a window with settings and before and after images. Compared to Condor, we have tried to simplify the interface. Everything you might change is visible from the start, and not hidden in other tabs or windows. While it may be overwhelming to have all the options at once, it is rarely possible to avoid changing some of the parameters, and those not used can be hidden by collapsing the menus. In the best case scenario, where nothing needs to be changed, the user can get away with only clicking the Take Picture and Export button. Condor has a window for each settings, showing parameters and the image before and after the setting is applied. CopyCut! does not have this feature, meaning it is not as clear to see what one setting does, isolated from other settings. We believe that it is better to keep the settings available at all times, to allow an overview and quick switching between settings. However, further investigation into the user interface of contour extraction applications is needed to draw any conclusion.

In [6, 12] they provide users with multiple generated previews of settings, such that users can choose the one that fits their needs best. [6] also allows for further customisation from the chosen setting. We could also generate setting variations by sampling different combinations or design profiles for users to browse, such that users can quickly get an overview and thus reduce the time spent on adjusting settings. This feature was also requested in our expert review.

System Accuracy

CopyCut! is not able to get perfect replication, even with the unwarped image. While some of the error in the accuracy is introduced by computer vision, most of the error is due to the lens of the camera, especially as we move away from the centre of the field of view. Even using the lens correction functionality from Adobe Lightroom is not enough to perfectly correct the error. High end cameras will likely suffer less from warp, and some also include built-in lens correction into the camera, but whether they will produce a perfectly unwarped image, is unknown. To further reduce the error we got, it may be necessary to, not only look at warp, but also look further into improving computer vision beyond what OpenCV provides.

As mentioned previously, capturing lines drawn with a pen yields two lines. This may be a good feature for artistic purposes, but a nuisance when it is not wanted, for instance in high accuracy replications of models. There are ways to remove them, like infilling or deleting one contour. Rather than removing the double line artefact completely, we think, that keeping this artefact, enables some artistic possibilities that may not have been possible without. In the future there should possibly be an option that specifies, whether doubles lines should be enabled, as well as the distance between the lines etc.

Comparison to Similar Research

In this section we will compare related work to CopyCut! and discuss the differences and what impact they have.

WireModeling [20] uses wires instead of drawings. This gives a more tangible experience, and is more forgiving to mistakes. When sketching or tracing with a pen, it is easy to make small mistakes that are irreversible, potentially requiring a complete redo. Using wires is most likely not a perfect solution, for instance, wires may have trouble with very fine details and sharp angles. CopyCut! can in some cases have trouble representing sharp angles due to pixellation, but using a wire introduces an additional generation between the real object and the image, where some details may be lost.

In CopyCAD [8] they have a 640x480 pixel camera and approximately 3.8 pixels per millimetre for a 150x100mm work area. In our current setup we have a 1170x800mm work area, using a camera with 4608x3456 resolution and roughly 2.4 PPM. CopyCAD also allows users to move, delete and resize individual contours, but what seems to be a more requested feature in our studies, is to be able to manipulate the vectors freely. The level of control requested ranges from being able to select and modify individual points, to targeting whole segments. For instance, individual points could be dragged to fix small errors in the contour, while a segment of points could be converted into one straight line. It is important to note, that this can be done in a CAD program, but that including this functionality, can improve the workflow.

Unfortunately, neither CopyCAD nor WireModeling report any accuracy metric we can compare to CopyCut!, but Logic Trace Digitizing System [9] reports an accuracy of 0.01mm and 0.005mm depending on the product. This is a lot better than what we have achieved with computer vision.However, they also rely on tangible interaction, which can be intuitive and easy to learn for inexperienced users, but there is also risk of the user making mistakes while tracing. Their solution also require specialised equipment, whereas ours only needs a mounted camera. Furthermore the user input it takes to create contours with Logic Trace Digitizing System scales linearly with the complexity and the number of models, because the contours have to be traced by hand. With CopyCut! the input is the same regardless of the number and complexity, since CopyCut! can generate several models at once. This saving in input translates directly to time saved.

LIMITATIONS & FUTURE WORK

With our implementation of CopyCut! we found possible limitations regarding vector optimisation, lens distortion and technical accuracy. In this section we will describe these limitations and possible future work.

While we do have limitations that affect the accuracy of the system, it is limited to areas outside the centre of the work area. We expect our system performs similar to CopyCAD [8] and WireMolding [20] when we limit the work area to the same as them. Loss of accuracy for the rest of the work area is problematic, but can possibly still be used for tasks that does not require perfect replication. For instance, replicating a car mat is more forgiving, and can perhaps be adjusted by hand if necessary.

We have both examples where CopyCut! creates perfect contours, but also ones where it struggles. We see two ways to improve the contours produced by CopyCut!. One way to continue is to look further into algorithms that can extract contours and optimise vectors. Another possibility is to interact more with the user, since humans are better at recognising how the result should be compared to computer vision. The disadvantage of including the user more, is that it will slow down the process compared to if everything is done by the computer. It may, however, be necessary to involve the user to achieve the best results. The question is then, how to best facilitate this interaction. We could go in the direction of [8, 9, 19] and include tangible interaction, or avoid extra equipment and create a simple CAD-like environment.

As of now the images that are captured in the current setup suffer from a slightly warped image from the lens of the camera, which in turn affects the accuracy of CopyCut!. Removing the warp caused by the lens will therefore directly increase the accuracy of CopyCut!. One possibility is to use the camera calibration of OpenCV [14] to address the warpage of the image. Another solution is to use the open source library Lensfun [13]. This library has a database containing lens corrections for a large collection of lenses. Using this library will likely make it possible to remove much of the warp thus may be a good way to improve the technical accuracy.

In the expert review, they mentioned that an error margin of under 1mm is acceptable. We are only able to operate within this margin in the centre of the image. Even with a library such as Lensfun, we expect that there will still be some amount of distortion. One solution suggested in our expert review, is to divide the image into grids. Correcting the warp for individual grids may give better results than trying to correct the whole image at once. Relying on users to correct lens distortion may be a simpler approach than trying to develop an algorithm, but there needs to be an investigation on how such an interaction could happen.

Our expert reviewers and participants commented that more icons and better descriptions would make it easier to grasp the functionality. As further work, we would like to interact with the end users directly and conduct user studies to improve the interface and interaction, such that we can better facilitate the users needs. We believe a worthwhile next step would be to make more and better icons and names, which can quickly give a user an idea of what a setting does. To show the effect of changing settings, we could look into using the original image as an underlying background for the resulting contours, or perhaps show the previous contour together with the new contour. A more extensive and expensive expansion could be to introduce a projector to project the contours down onto the bed in real size as done in [8, 16]. This could allow users to get a better feel for how the contours will actually look like when cut, and perhaps allow users to make small adjustments to counter warp. During the co-design session, we did not gain any new use cases, only new examples. The sessions were short and we only had interaction design students as participants, however, we still believe it provides initial feedback on CopyCut! as a creative tool. Further studies could be conducted on how to apply CopyCut! in creative ways. For such studies, it would be interesting to expose participants to CopyCut! for a longer time period and to a larger variety of people from different professions.

CONCLUSION

We have presented CopyCut!, an open source system aimed to assist in replicating objects using a CNC machine. CopyCut! uses computer vision and raster-to-vector conversion to capture contours from images. We found that our system is able to achieve a minimum accuracy error of 0.02 millimetres. The accuracy does, however, degrade the further the contour is from the centre of the camera's field of view. To help users get better results and for further research, we have compiled a list of challenges that we encountered when using CopyCut!. We conducted an expert review with a company and a co-design session with interaction design students. From the expert review we collected qualitative feedback on design and functionality, and what is needed for it to be useful in industry. From the co-design session we gathered creative feedback on how CopyCut! can be used outside of our original scope of replicating objects. Our system contributes with a workflow that speeds up the process of replicating objects and enables several creative ways to use CNC machines.

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