Adaptation of the X-Carve to UT education

Bachelor Thesis

Adaptation of the X-Carve to UT education

Dylan Vogelsang
s1492748

Preface

Title:
Adaptation of the X-Carve to UT education

Student:
Dylan Vogelsang
s1492748
BSc Industrial Design Engineering

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Mr. G.M.Bonnema
Mr. R.G.J. Damgrave

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Summary

This thesis describes the process undertaken to give meaning to the task that was set for the bachelor assignment.
The assignment can be comprehensively described as: “Modifying the X-Carve CNC-milling machine to be used within educational tracks of the University of Twente”.

To fill in this assignment the X-Carve was researched in-depth. Starting with researching its current capabilities and possible future additions, as well as the current workflow. Through this, several aspects with room for addition and improvement became clear.
The X-Carve provides a user-friendly carving experience out of the box. But to improve the X-Carves current capabilities and adhere to the assignment, improvements and changes were needed.

These changes have been divided in two areas:
- Workflow enhancement
- Mechanical enhancement

Both areas were looked at separately, and ideas for enhancement of both were generated.
The workflow enhancement focusses on providing a comprehensive and enabling workflow for the user. Providing them with information in real-time or eliminating difficult aspects to make the X-Carve more useable for even the least experienced user.
The mechanical enhancement focusses on providing the X-Carve with greater accuracy, as this was an aspect found to be lacking during the orientation.

Comparing both aspects, the decision was made to continue with workflow enhancement. As, no matter how accurate the X-Carve would be, working with it for most users would be rather difficult without a proper workflow.
The problem stated to be solved with the workflow enhancement was:
“The (3D carving aspect of the) X-Carve is difficult to utilise and grasp for new users with no previous experience in CNC-machining and the workflow lacks streamlining and clarity.”
To find the idea which would offer the best possibility in solving this problem, the generated ideas for workflow enhancement were compared once more and eventually several were combined to form the idea of an interactive manual.

This interactive manual was then developed by researching and contemplating the interface needed to distract the user as little as possible, so they can focus on working with the X-Carve. While also offering enough flexibility that it could be used by both experienced and completely new users.
To provide cross-platform flexibility in usage of the manual and provide possibilities for eventual expansion, the manual was created as a web-app. Through this the manual will be able to communicate with the X-Carve, be accessible to the user regardless of location and provide for easy expansion and editing in the future.

The content for the manual was chosen to be a combination of text, images and videos, to provide an efficient and comprehensive method for offering information to the user.
The final product was tested with several users, and their experiences and comments were used to evaluate the manual and provide several recommendations.

The final product can be found in the HTML folder by opening the index.html file.
Or by logging in to http://www.8trackdesign.nl/Handleiding and logging in with the credentials:

username: BachelorThesis.8trackdesign
password: XCarveIM

Introduction

It seems like yesterday that I started Industrial Design Engineering at the University of Twente. Just like all the first year students cycling by my balcony as I write this introduction.
Three years have gone by quickly, I have learned quite a lot and this thesis is one of the final steps towards my Bachelor's degree.

In this thesis you will find the process I went through the last three months in order to give meaning to the task I was set by Roy Damgrave and the UT. This assignment can be comprehensively described as: "Modifying the X-Carve CNC-milling machine to be used within educational tracks of the University of Twente". As will become clear throughout this thesis, this can be interpreted in many different ways. Eventually, all the orientation, research and preparation have come together into a finished product. This thesis clarifies the process leading towards this product. I hope you enjoy reading it.

Dylan Vogelsang

Orientation on the X-Carve

This section shortly describes what the X-Carve is, what it can do, and what it could be used for.

The X-Carve *(Figure 01)* is a Do It Yourself (DIY) CNC-milling machine. It comes at relatively low cost for the features it offers (3-axis milling up to 800mm x 800mm x 100mm) and it is fully open source. This means that all the CAD-information used in designing and constructing the device is readily available, making it very easy to adapt the X-Carve to individual needs, or even fabricate a new part in case of a breakdown.
This in turn means that it is not a large problem when something breaks, as parts are cheap and readily available, making the X-Carve ideal for use by students who are not experienced enough to use a more expensive, full scale CNC-milling machine.

Figure 01 - The X-Carve

There are some drawbacks to the X-Carve, however. The first being that at this moment the software natively used with the X-Carve only supports 2.5D carving. To achieve true 3D carving one needs a whole suite of software to convert a 3D model to G-Code and send it to the X-Carve. Which is a fairly complex process.

The X-Carve should not be treated as a high-accuracy machine like the 5-axis CNC-machine or the laser cutter already available in the workshop in the Horst. It offers an accuracy which is large enough to carve aesthetically acceptable 3D models. It should, however not be seen as a competitor or replacement for the machines mentioned above, which both cost at least a tenfold of the X-Carve.
In short, the X-Carve is an excellent tool which is easy to maintain, adapt and expand and use, even when the user has little experience.

Before defining a target group and actually thinking about adaptation of the X-Carve a good step to take is researching what the X-Carves weak and strong points are and in which other ways it could be used in the future.

To do this a list of (future) possibilities has been made and Norbert (head of the UT workshop) has been interviewed about the X-Carve. Also, research into the workflow nad accuracy of the X-Carve has been done in the workshop itself. This chapter provides an overview of the research done into the X-Carve and the insights gained from it.

(Future) Possibilities for the X-Carve

The X-Carve is a CNC-machine. Basically, this means that the machine is directed by a controller or computer which reads G-Code, or machine language. This controller then tells the X-Carve where to move, how fast it should move there and which path it should follow to get to its destination.
The X-Carve is meant to be used as a milling machine. But, taking the concept of the machine to a level at which one thinks of it as just a machine controlled by a computer, which can move a tool holder along three axes, opens up a whole new range of possibilities. These possibilities, along with the ones already offered by the X-Carve will be discussed in this section.
The possibilities which will be treated are:

- G-Code and project integration
- Rapid Prototyping of a (CAD) model
- Virtual Clay model to physical model
- Embroidering or engraving
- Cutting vinyl/fabric/carbon fibre/stickers

G-Code and project integration

Solidworks and any other CAD-modelling programme, is able to generate G-code through an extension known as CAM (Computer Aided Manufacturing). This extension, known as CAMWorks, is able to load a specific tool library and calculate a path, including z-depth and rotation, for a CNC machine. A good form of integration of the X-carve into the educational programme within the UT could be its integration into the CAMWorks tutorial provided to the first-year students.
At the moment the students go through the CAMWorks tutorial and then head down to the workshop to see the CNC machines work from G-code, which then continues to be a rather vague and arbitrary concept.
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It might be much more interesting to students to design a simple shape themselves, export it to G-code and input it into the X-carve to have it produce the desired shape. Through this, a better understanding of the link between CAD, CAM and G-Code could be achieved, enabling students to make use of this in later projects.
Using the X-carve in projects throughout the educational track would be a great addition to the tools which students already have access to. However, not every student has as much experience with or understanding about CNC-machines. This means that, should this idea be implemented, it is very important that the X-carve is easy to work with, while it should also offer enough possibilities for a more advanced user.
There are several possible software suites which could be used to generate G-Code, besides CAM-Works. These are discussed in the workflow research later on.

Rapid Prototyping of a (CAD) model

Generally, when creating a concept visualisation, students tend to make a drawing or create a CAD-model. This drawing or model is then taken to the workshop and a model is created, mostly by hand. Small form variations are hard to achieve, especially using harder materials such as Polyurethane.

At this moment Rapid Prototyping is generally done with easy to work with materials, like paper, tape and cardboard *(Figure 02)*.
When making use of the X-Carve, students can get their rapid prototype models to be much closer to the way they have actually designed them with a minimal amount of effort.
Encouraging, for example, much more expansive form studies. They would just simply be able to generate G-Code from their model and, within a short time, create a large range of differentiated models.

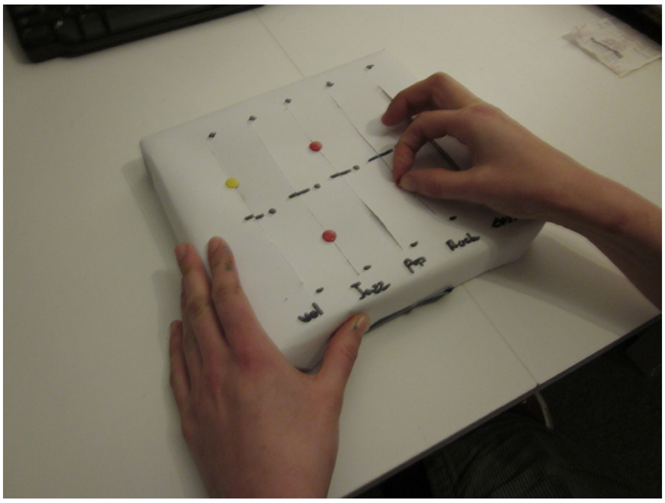

Figure 02 - An example of a paper protoype

Figure 03 - A haptic feedback used for virtual claying

Virtual clay model to physical model

An underused technology within the educational programme is the haptic feedback clay modelling available in the VR-lab (*Figure 03)*. At this moment it is not much more than a nice gadget for playing around with on open days. It could however, with the addition of the X-carve, be integrated into the educational programme.

The general idea is that the modelling procedure with the virtual clay is a very natural way to obtain shapes, just like claying in real life.
However, converting these shapes to a CAD-model and then CNC producing or even 3D printing them is a rather daunting and complicated process. Further complicated by the complexity of the machines involved and the possibility of breaking something expensive if the code is even slightly off.
The X-carve could offer the possibility to directly export the 3D clay models and carve these out of a piece of wood or plastic easily and cheaply. Plus, if something breaks, it is cheap to replace.
In short, it enables the students within the Engineering tracks to experiment with different shapes much more easily, leading to much more freedom in design and form factors.

Embroidering or engraving

CNC, in its most basic form, is a path following method. This means that when a path in the form of text or an illustration is provided, it can also be used to engrave a piece of material.
This could be done in several ways: Either by using an engraving mill, which can be placed in the existing mill used by the X-Carve. It might also be possible to provide an attachment for an engraving laser in the X-Carve (one such attachment can be seen in *(Figure 04)*) meaning that laser engraving could become a possibility.
But, this option would require extensive modification, as laser engraving is a technique which has its own unique set of requirements.
A modification which would be less extensive is embroidering. This could be done by replacing the wasteboard with a softer material and telling the X-Carve which path to follow and at which points it should thread the needle.

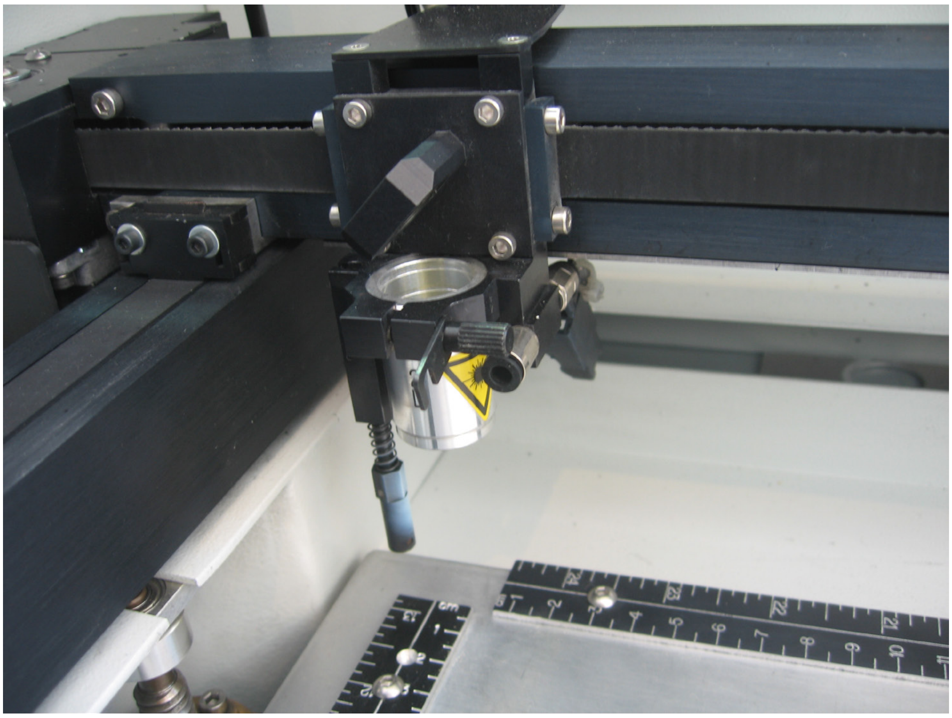

Figure 04 - An example of a laser engraver

Cutting vinyl/fabric/carbin fibre/stickers

Most modern day composite, fabric or leather cutting to patterns is done using computer controlled “plotters”.
Plotters, bluntly said, are not much more than a cutting wheel which follows a certain path to cut a shape out of the material which is under it. With a cutting wheel which is able to rotate to a certain angle on the Z-axis, by replacing the existing mill with a stepper motor, the X-carve would be able to achieve this same feat rather easily. This means that it might also be used for cutting out sewing patterns or even composite sheets, aiding in research into composites, depending on the required accuracy. With some work, even stickers might be a possibility, further expanding on the possibilities available to students independently of the workshop (employees).

Interview with Norbert (UT Workshop)

To get a better idea of the usability of the X-Carve as described by professionals (the UT Workshop employees), Norbert was interviewed about the possibilities and drawbacks he sees with the X-Carve.

Norbert stated that the accuracy of the X-Carve is lacking. It is fine for the general applications within the Industrial Design Engineering field, and possibly the Biomedical Engineering track, but it lacks the precision required for use within the Mechanical Engineering track.

There are several reasons for this:

- The rubber belts which the machine uses to translate along the X and Y-axis are rather stretchable, meaning that they stretch when a force is applied, leading to a less accurate system.
- The motors used in the X-carve do not possess a built-in encoder, which means that there is an open loop system. Combine this with unwanted rotation of the portal along the Z-axis and quite a bit of accuracy is lost, especially under heavier workloads, such as high milling and surface speeds.
- Milling a piece of wood, especially compressed fibre sheet, produces a lot of dust which ends up on the guide rails further reducing the accuracy of the machine due to slippage of the belts.

According to Norbert CAMWorks is not the ideal candidate for usage with the X-Carve as it requires a separate postprocessing encoder to put out G-Code in a format readable to the X-Carve.
Norbert thinks the X-Carve could well be used already, but in order to function more accurately some of these problems need to be addressed.

Interim conclusion

As can be seen from the previous pages, the X-Carve is a machine which already offers interesting possibilities. And, with a bit of work, it could be developed into a machine capable of doing a whole range of different tasks. It does however, have a drawback. Mainly in the fact that it is not as accurate as is to be expected from a CNC-machine, and that the current 3D carving workflow is rather complex according to Norbert. Both these aspects will be assessed later on in this chapter.

Workshop Research

To get an idea what the X-Carve can do and how easy it is to work with, some research in the UT workshop was done by working with the X-Carve and testing how accurate it actually was.
According to both Roy and Norbert, a good way to get an idea of the capabilities and accuracy of the X-carve is to have it produce a couple of artefacts.
These artefacts can then be measured and compared to the model to determine how accurate the carving process was.

First, research was done pretending to be a new user who had never used a CNC-machine or G-Code of any form. The experiences and insights gained from this can be found in *Appendix X1.*

The second bit of research focussed on testing accuracy on the X, Y and Z-axis.
The first thing to be tested was the X/Y accuracy of the machine. This was done by having the machine carve some circles to measure the accuracy when moving along both axes simultaneously.
Squares were used to measure accuracy on a single axis. Both the squares and circles were given an exact dimension through Easel.
These shapes were then measured using callipers *(Figures 05 and 06)* to determine the maximum discrepancy between the model and the actual result. Leading to the following results, taken from 3 measurements each:

Shape	**Average Size (mm)**	**On path correction**	**Final Result**
Square 50x50mm	54.1x 53.7y	(¼*25.4)/2 = 3.2	50.9x 50.5y
Circle 53mm diameter	56.6x 56.3y	(¼*25.4)/2 = 3.2	53.1x 53.4y

As can be seen from the results, the accuracy of the X-Carve is rather variable.
For example, the accuracy in the y direction when milling a circle was as specified: 0.1mm. The X-axis, however, seems to suffer from a larger loss of accuracy in general.
A good explanation for this is that the Y-axis translation uses two belts, making it less prone to slipping than the X-axis, which only uses one.
Another explanation is the high surface speed at which the X-Carve was milling: 1000mm/min. This means the non-encoded stepper motors have to carry out commands quickly, making the rubber belt slip if it is not exactly tight enough.

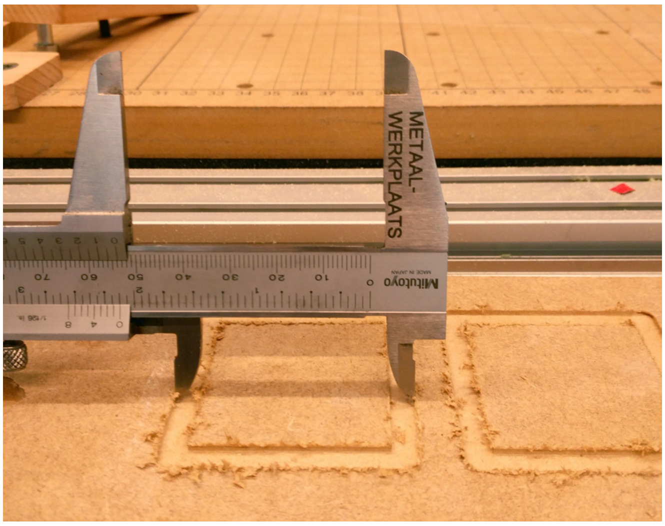

Figure 05 - Measuring the square carve

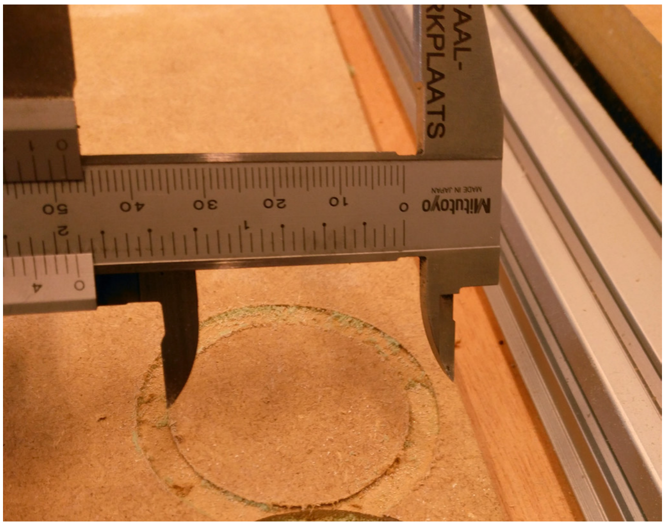

Figure 06 - Measuring the circular carve

To test Z-axis accuracy, a stepped model resembling stairs can be carved and then measured to determine how accurate the X-Carves stepdown along the Z-axis is.

This led to the discovery of a rather major flaw. When milling at high surface speeds (>250 mm/min) the X-Carves stepper motors have to carry out movement commands very quickly when the model is small.
This leads to slip when the belts are not tightened properly. The X-Carve quickly offsets its bearings and possibly ends up milling thin air instead of the model.

Accuracy along the Z-axis in general was good however. A small part of the stairs was carved and then given another pass with the same mill. This left only some very slight marks where the mill went into the material deeper than before, as can be seen in *Figure 07.*

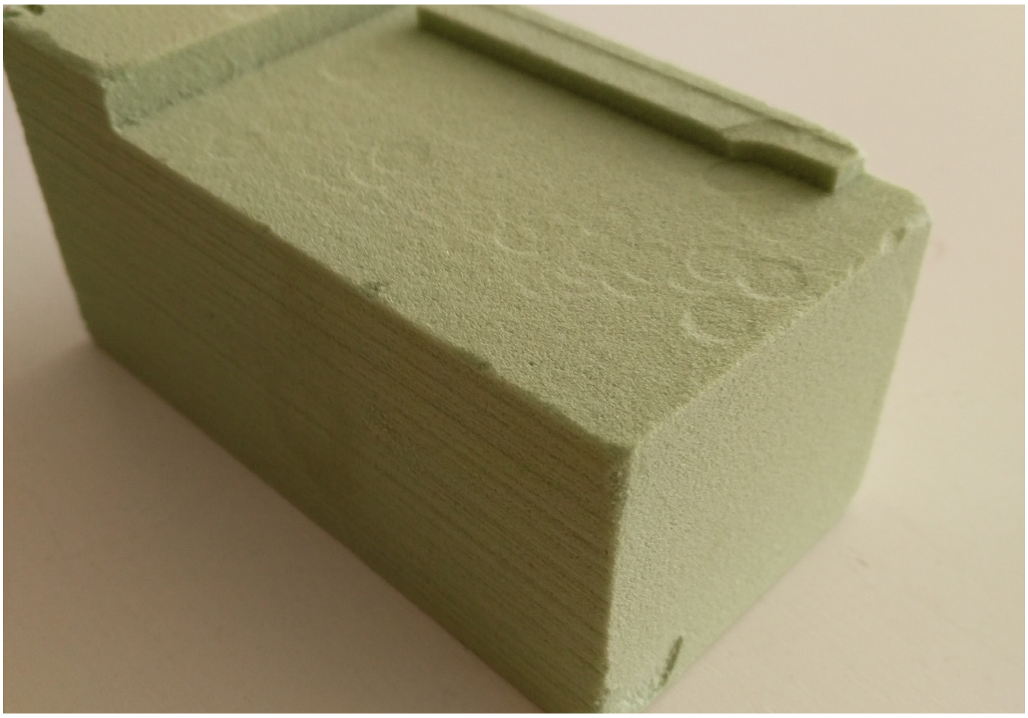

Figure 07 - Flat surface carved by the X-Carve

All in all, the loss of accuracy on 2.5D is something which is non-ideal, but not noticeable from an aesthetic point of view. It is, however, a discrepancy which is too large to make the X-Carve a useable tool in the production of highly accurate prototypes without the need for some form of post-processing.
Accuracy on the Z-axis, as far as this could be properly measured, seemed to be good. This is most likely due to the fact that a lead screw provides Z translation, combined with a properly tight belt of a type which does not as easily slip.
Concluding, the X-Carve lacks in accuracy for producing highly accurate prototypes. This same lack in accuracy is seen when milling in 3D while using high movement and surface speeds. This leads to slip on the belts providing X and Y translation, leading to a loss of accuracy.
As it is, the X-Carve is usable at lower surface speeds. Higher surface speeds result in a loss of accuracy and should be avoided.

Workflow Research

As stated in *Appendix X1*, The X-Carve lacks a clear workflow when being used for actual 3D-carving. To get a better idea of the steps required to convert either a freeform or feature-based model to a G-Code file readable by the X-Carve and the software which can be used for this, a small experiment was conducted.

A model was created in SolidWorks (feature based) and Blender 3D (freeform surface modeller) and tested with various CAM-enabled software.
The full report of this test can be found in *Appendix X2.*

The conclusion which can be drawn from the workflow research is that there are several well-functioning combinations of software. Of which at this moment the combination of Blender3D/Solidworks with Fusion360 and ChiliPeppr seems to be the simplest and fully free one, as well as offering more possibilities to the advanced user.
This then, is the workflow which will be used throughout the rest of the process.

Target Group

To get a better understanding of the general direction to be taken in the assignment, a target group needs to be defined to be able to make a more focused effort into integrating the X-Carve into the educational tracks. The target group using the X-Carve can be a rather broad one. Ranging from students in general to students of a specific study track. To make it possible to undertake an analysis of the target group it should be narrowed down to a more specific set of subjects. This means taking a look at the functionality offered by the X-Carve offers and which users would be interested in this particular functionality.
As described before, the X-Carve is an easily adaptable tool, be it lacking in accuracy for certain applications.
A good start in choosing a more focused target group would be to divide the broad range of “students” into several smaller groups according to study direction. These will all have to be students who might need to use the X-Carve throughout the course of their studies.
This limits us to the students in the Engineering tracks: Biomedical Engineering, Industrial Design Engineering and Mechanical Engineering. Each of these study tracks will have different requirements when using the X-Carve, as can be seen in the table below.

Track	Required Accuracy (mm)	Milling Directions	Typical Project Dimensions (mm)	Speed vs Accuracy
BME	0.05<x<0.01	2D, 2.5D, 3D	500x500x100	Speed+Accuracy
IDE	0.1<x<0.01	2D, 2.5D, 3D	150x150x100	Speed/Accuracy
ME	x<0.01	2D, 2.5D, 3D	150x150x100	Accuracy

A short explanation of the stated values is in order for each of the tracks:

According to an interviewed BME student and personal experience coming from Roy Damgrave, the X-Carve has been and can be used to carve out a replica of a certain body part, for example a bone. Which is where the set dimensions are derived from, although certain body parts might be larger. This can then be used in research purposes and forms of protoyping. This does mean that a certain accuracy is required to be reached as the margins within the human body are relatively small. The X-Carve is not able to offer these accuracies at the moment. However, for prototyping certain ideas the X-Carve would be ideal.

IDE: Similar to BME in that the X-Carve could mainly be used for Rapid Prototyping of ideas and models. However, when creating a final model accuracy might be favoured over speed. The accuracy stated to be reached by the X-Carve would be enough to at least achieve the visual details required by such a model.

ME: In the mechanical engineering track the focus would not lie on the prototyping or creation of complex curved shapes. If the X-Carve were to be used it would be a very useful tool for milling parts required for certain machinery which might otherwise take a lot of time and effort to make. However, the lack of accuracy of the X-Carve means that there will always have to be a manual form of post-processing. Making this kind of usage rather labour intensive still.

Already a pattern starts to emerge. Due to its capabilities and open-endedness the X-Carve can prove to be a great tool in prototyping. It would however, lack in the department of actual parts or components manufacturing.

As the desired accuracy for the ME track is much more readily delivered by the laser cutting machine, among others, it is logical to exclude this track from the target group.
However, keeping this group in mind while working will still be good practice. The more focussed target group then, will consist of the BME and IDE track.
This means that further focus will mainly be on the prototyping possibilities the X-Carve offers. Be it Rapid Protoyping or creation of aesthetical or functional prototypes.

Conclusion

As can be deduced from the analysis undertaken in the previous pages, the X-Carve is a very good and capable piece of equipment, all be it a bit lacking on certain fronts.
From the research committed in the workshop and into the workflow of actually carving a 3D model, the following can be concluded:

- The X-Carve is already well developed when it comes to 2D and 2.5D carving. It is still lacking however in a comprehensive or well documented workflow regarding 3D carving.
- The X-carve lacks in accuracy when it concerns highly detailed or precise carving operations and high surface speeds.
- The X-Carve offers enough accuracy to comply with most demands regarding purely aesthetic carving.
- The X-Carve is a tool which, in its current form, will mainly be used by the IDE and, in a lesser amount, by the BME track.

A good place to start integrating the X-carve into the educational track of IDE and possibly BME would be to make its operation more fool proof and user friendly.
Providing a clear and easy workflow for whichever function is required, including certain safeguards to protect the user and the machine.
Mechanically the accuracy might be improved to achieve high accuracy results at high surface speeds.
In the next chapter possibilities for both workflow enhancement and physical enhancement will be discussed.

Workflow Enhancement

As stated, the workflow offered by the X-Carve could be much more streamlined and insightful. In this chapter several ideas will be generated by looking at existing methods, or coming up with new ones.

Comprehensive Software Suite

As has been seen during the analysis, the Easel software the X-Carve provides does a very good job of providing a closed interface which guides the user through the milling process step by step.
All the while it makes sure that the user can't accidentally do something wrong by providing dialogs, clearly set out steps and set-ups, up to the point that it actually asks if your project turned out like it should and, if not, providing you with a list of troubleshooting options.
The downside of this system though, is that it does not (yet) support full 3D carving. Which is one of the features of the X-Carve we are particularly interested in.

This means that the same amount of guidance and safeguarding falls away when using the X-Carve for said 3D-carving. While this might not be a problem to the more advanced user, the less experienced user might have trouble setting everything up correctly and in doing so might accidentally damage something, which could have been avoided.
To provide this same amount of guidance and control over the situation a software suite could be assembled consisting of several programmes working together through a shared interface to produce the desired result.
Figure 08 provides a flowchart of how this software could be tasked to work together.

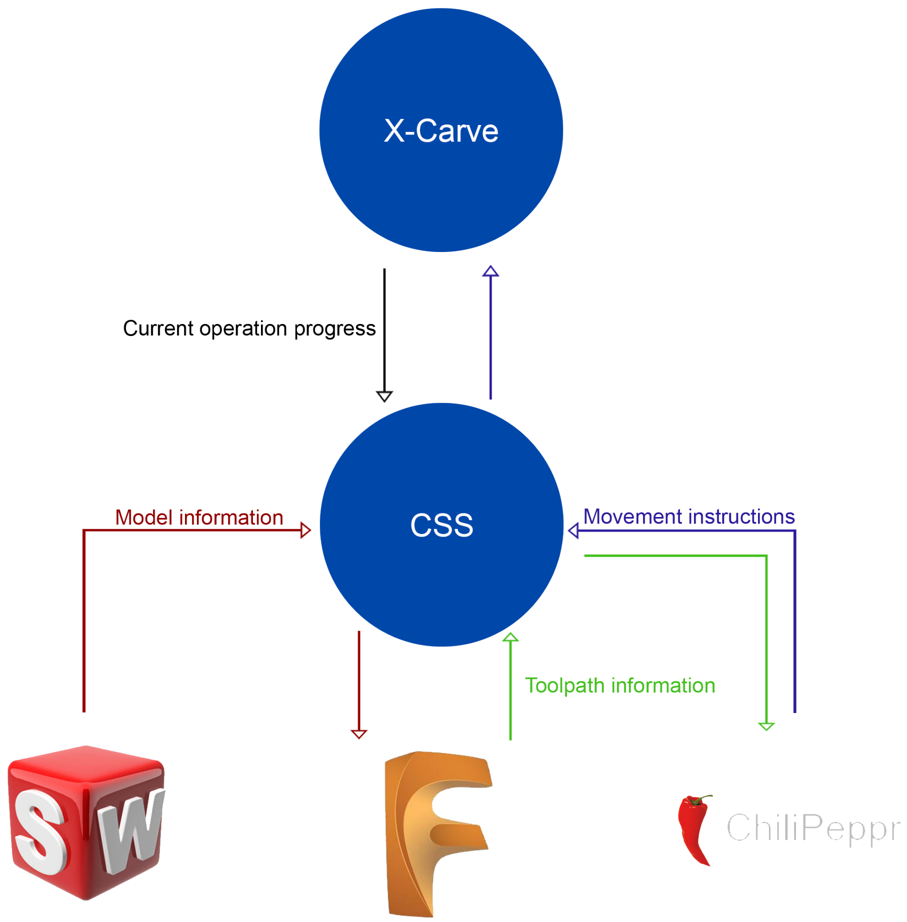

Figure 08 - Comprehensive software suite flowchart

Manual

A manual is a tried and true method for putting across knowledge. Sadly, it is also one of the least interactive and most distracting ways. Usually, when a written or video manual is involved, it requires constant switching between the manual and the task at hand, not allowing one to fully focus on the task they are completing.

It is, however, still one of the most effective ways of looking up knowledge. This is true for beginners and experts alike. Especially the last group will find it easy to have something to look up certain specifics of doing a task when they already know the general procedure.
A standard manual or tutorial is usually provided on paper or PDF. Sometimes it is provided in a video format, already making it more interactive to the user as the author or what could be called teacher or lecturer is actually audible and perhaps even visible.

Still, even this is a rather static way of bringing across knowledge. Something which just cannot be completely avoided with any form of manual or tutorial.
Taking from the research conducted by *Kuipers and Tieleman, 2015*[1] during their minor at the UT, it might be a very good option to provide the user of the X-Carve with an interactive manual in which he or she can select their level of expertise.
Depending on the selection the user is guided through the entire process step by step or left to their own depending on their skill level.
In this way the less experienced user is provided with the support and guidance needed to successfully complete their task, while the more advanced user is able to navigate through the manual freely to look up just that specific piece of knowledge they need.
Making the manual interactive also opens up a broad spectrum of possibilities regarding videos, links and moving images. All of which are generally much clearer than a fixed image with a piece of text next to it.

Live instruction feed

The third idea is a kind of combination of the previous two. A live instruction feed, which, depending on where the user is in the process of carving a 3D model, would display the instructions or steps required to be taken at that exact moment.
This brings us to the subject of AR (Augmented Reality). As this live instruction feed might be projected into some form of Google glass the user has to wear while working (they need eye protection anyways). It might even be projected onto the working surface of the X-Carve while the user is working.
The mindmap in *Figure 09* displays several ways to bring across this live instruction feed. Either externally or through some form of AR.

Augmented Reality

Continuing on the Augmented Reality idea, this can be expanded to include more than just instructions of what to do.
AR offers a lot of possibilities regarding visualisation of what the user or machine is doing. For example, the G-Code which is used to carve the final 3D model basically contains every instruction needed to generate a toolpath. This way, using AR it might actually be able to project the current project status onto the workpiece the user is working on.
Another possibility is projecting where the stock to be carved should go on the work surface of the X-Carve. It might even be possible to point out the exact zero even when part of the stock has been carved away, making re-zeroing the machine much easier.
Figure 10 shows some of the possibilities thought about.

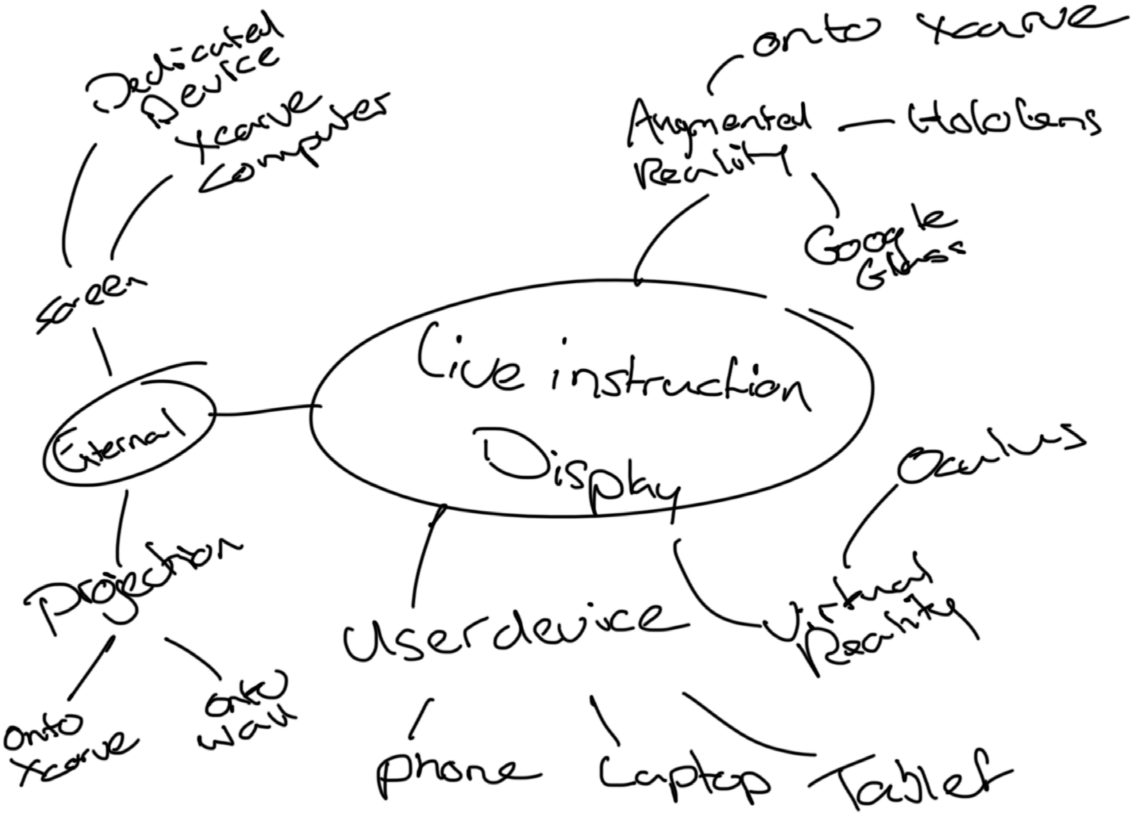

Figure 09 - Live Instruction Feed Mindmap

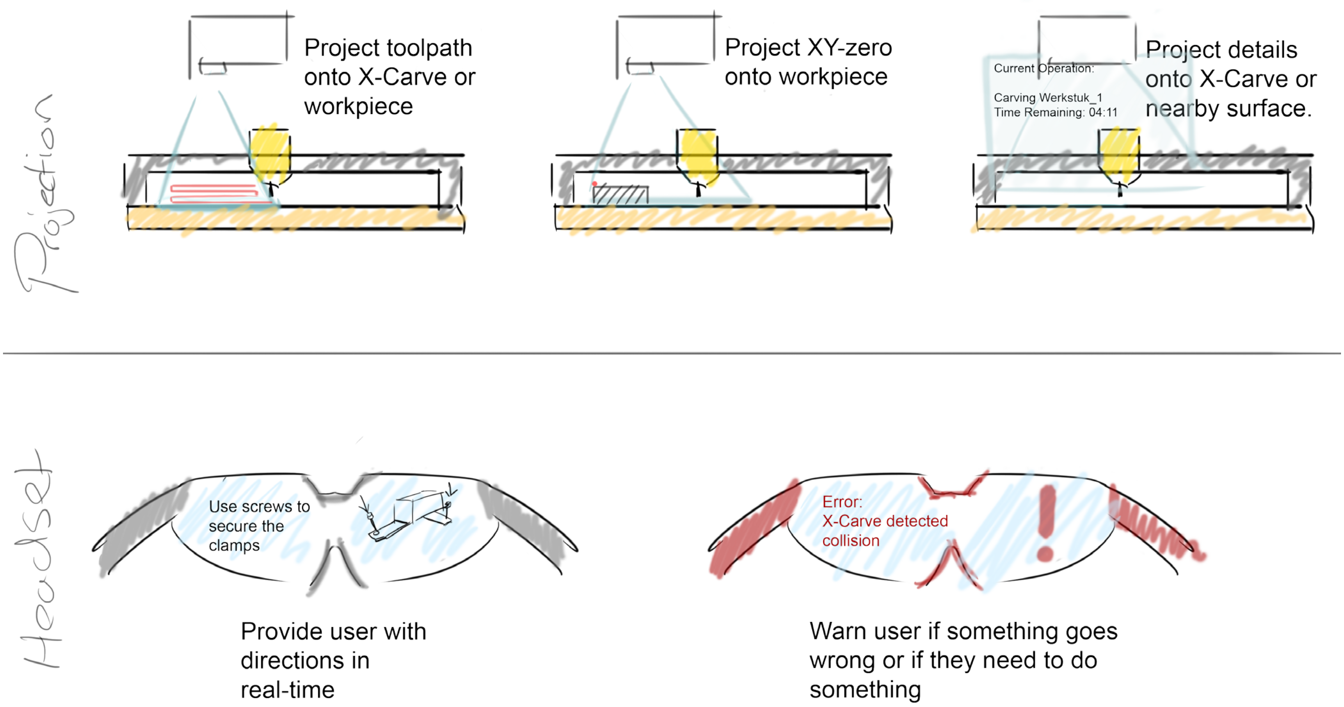

Figure 10 - AR possibilities

Mechanical Enhancement

Problem Analysis

To address the problem of the X-Carve lacking accuracy, it first needs to be determined where the origin of the problem lies.
First of all, let it be clear that for its cost, the X-Carve performs rather well. Similar machines offering higher accuracy are also much more expensive.

To begin with, the inaccuracy of the X-Carve is largely inherent to its design. First of all, the rubber belts are not an ideal method for translation when a high accuracy is required. The belts require a certain tension to operate properly, even with the teeth on the belt interlocking with the teeth on the stepper motor. If this tension is too low, the belt will slip, resulting in a loss of accuracy. If it is too high, the belt will be under excessive stress, meaning that it will wear out more quickly.
The belts of the X-Carve also continuously collect dust, which is produced while carving material, making the belts slightly more slippery and resulting in a loss of accuracy.

Another flaw in the X-Carves design is the usage of stepper motors which do not have any form of encoder. This means that the system is an open loop. In short, this means that the X-Carve has no idea when a stepper motor skips a tooth because of a slipping belt, leading to inaccuracies. This happens especially at high surface and milling speeds, when the belts are under a heavier load and more prone to slipping.

A final flaw in the X-Carves design is a lack of accuracy in the system itself. The portal which translates along the Y-axis, for example, is easily rotated at least 2 degrees by hand. Combine this with a slipping belt and it leads to inaccuracies when milling in the X-direction: Once a belt on one side of the portal slips the translation axes are no longer at a right angle to each other.
In this section a look will be taken at physical enhancements which might address the stated problems.

There are several ways to translate a CNC portal along its axes:

- Belts
- Toothed rail and cogs
- Track with wheels
- Lead screws
- Pistons

Each of these methods will be reviewed and the advantages and disadvantages will be discussed in this chapter.

Belts

The solution of belts is being used right now. Although they are prone to slipping when not tightened properly, they are a good choice cost and design wise. The belts used are simple, rubber, toothed belts, which are rather cheap to produce and replace in case they break.
This brings us to the second point in favour of belts: The belts are the weakest link in the X-Carve's geometry while also being one of the cheapest. This means that when the X-Carve encounters heavy resistance the belts will break, instead of a more expensive or hard to replace part.
Although toothed belts should not be able to slip, they will do so when not tightened properly.
A good way to ensure that the belts are kept tensioned might be through regular check-ups before using the X-Carve, or by providing the X-Carve with some sort of belt tensioner as can be found in most cars as well *(Figure 11)*.
Another way to prevent slipping is by using different belts. For example, belts with a tooth section which is circular as opposed to trapezoidal, provide smaller backlash and less chance of slipping.*(SDP)*[2]

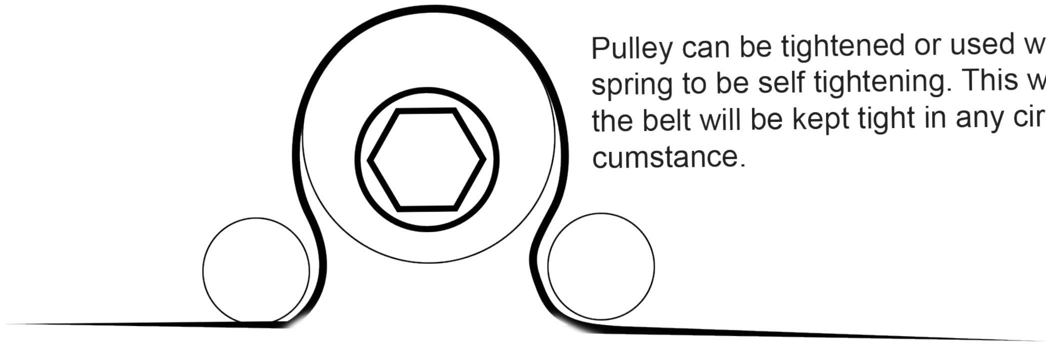

Figure 11 - Belt Tightener Pulley

Rack and pinion system

A solution which is less prone to slipping than the belts, is a rack and pinion system *(Figure 12)*, as it is much more of a closed shape system. It still provides for a limited amount of slip as a cog can still slip over the teeth it falls into. The problem, however, is that this does quickly wear out the pinion or rack (whichever is made of a softer material). A second downside is that the amount of slip, while being present, will be rather minimal, possibly leading to damage to other parts of the X-Carve when it encounters a collision.
Third, a rack and pinion are more expensive to replace than a simple rubber belt in case of wear. This wear also leads to errors more quickly, as a missing tooth in either the pinion or rack is skipped more easily. This is mainly because this particular system relies on its shape for translation, while a belt also offers a certain amount of friction, even if it is missing a tooth or two.

Figure 12 - Rack and Pinion

Track with wheels

A system which would rely purely on friction. Much like a train moving along a track, the wheels will push the cart forward. While this seems like a possibility, there are rather large downsides.
First of all, friction force is determined partly by the normal force and thus the mass of an object. While the friction force offered when the X-Carves spindle moves through thin air might be sufficient to keep the wheels from slipping, it would encounter much larger forces when milling material. Especially harder materials like hardwood or polyurethane. Probably making this technique rather unsatisfactory.
A plus, however is that the wheels, when they do slip, do not damage anything in particular, besides themselves, just like a belt drive would.

Lead Screws

A tried and true method to translate a machine along an axis, this principle is already used on the Z-axis of the X-Carve. Basically, a threaded rod *(Figure 13)* is screwed through a threaded hole. At which point rotation of the threaded rod in clockwise or counter-clockwise direction results in a translation along the axis of the rod.
This particular system is very accurate, and, depending on which thread is used on the screw, can take rather large loads without losing accuracy. *(Bhandari, 2007)*[3]
A downside to this system, however, is that it does not provide for any slipping, meaning that it will either destroy itself or another part of the X-Carve when a collision occurs.

Figure 13 - Example of a leadscrew

Pistons

Another way to translate the X-Carve along its axes would be to introduce a track with wheels, but have the translation be provided by a hydraulic *(Figure 14)* or air powered piston instead of an electric stepper motor.
Pistons can be computer controlled, and, depending on the piston and its controller, they can be controlled rather accurately. A downside is that pistons do not provide any form of slipping. They will just push through anything that is in the way, destroying the X-Carve or themselves. Pistons are also a rather expensive option in case they break or need servicing.

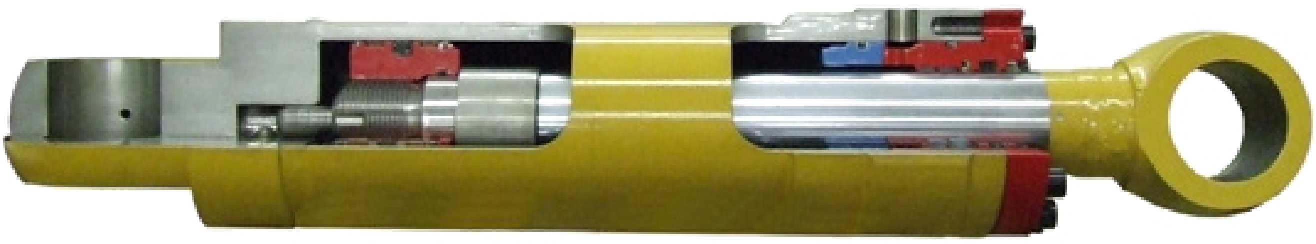

Figure 14 - A hydraulic piston

Motors

As stated, the motors used by the X-Carve are non-encoder stepper motors. The open loop this provides leaves a lot of room for inaccuracy as the X-Carve has no way of actually checking where it is. It just knows its theoretical position based on the amount of steps the motors have made.

A good way to have the accuracy of the X-Carve increase greatly, is to replace the current motors with ones that do possess an encoder. This would mean that the software currently used would need to be rewritten to provide for some kind of self-check. Something which should be possible as the X-Carve uses an Arduino as its main controlling platform.

Another way to provide the X-Carve with more accuracy is by providing it with a separate encoder. Usually an encoder works by counting pulses from a sensor. The simplest way to do this is to provide a long strip, divided into black and white sections with a distinct length. Each pulse then represents a certain distance travelled.
There are several ways of providing an encoder with this information. But, as the X-Carve needs to know its actual position and not the amount of rotations the motor or drive wheel has made, the only logical place to put this strip would be along the axes on the work surface. This strip could then be read by an optical sensor similar to the one used in an optical mouse, fed back to the Arduino and used to correct the X-Carve if necessary. *Figure 15* provides a small system diagram of how this might function externally, while *Figure 16 (p.20)* clarifies the system inside the motion controller.

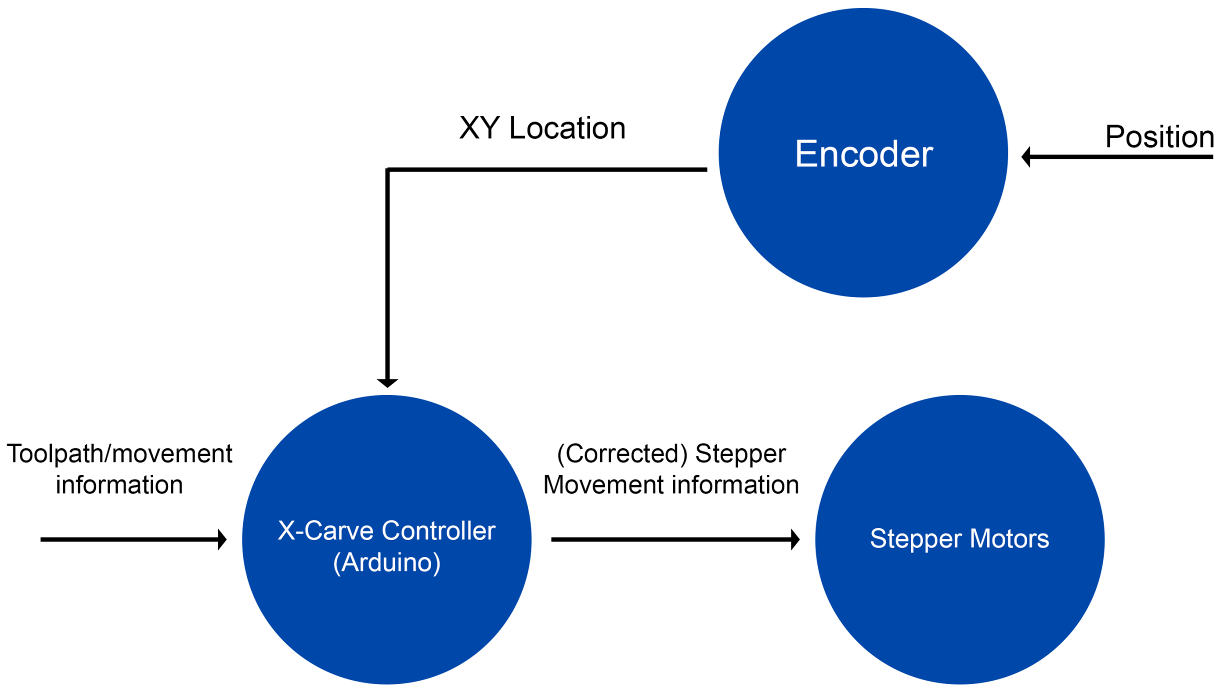

Figure 15 - External encoder system diagram

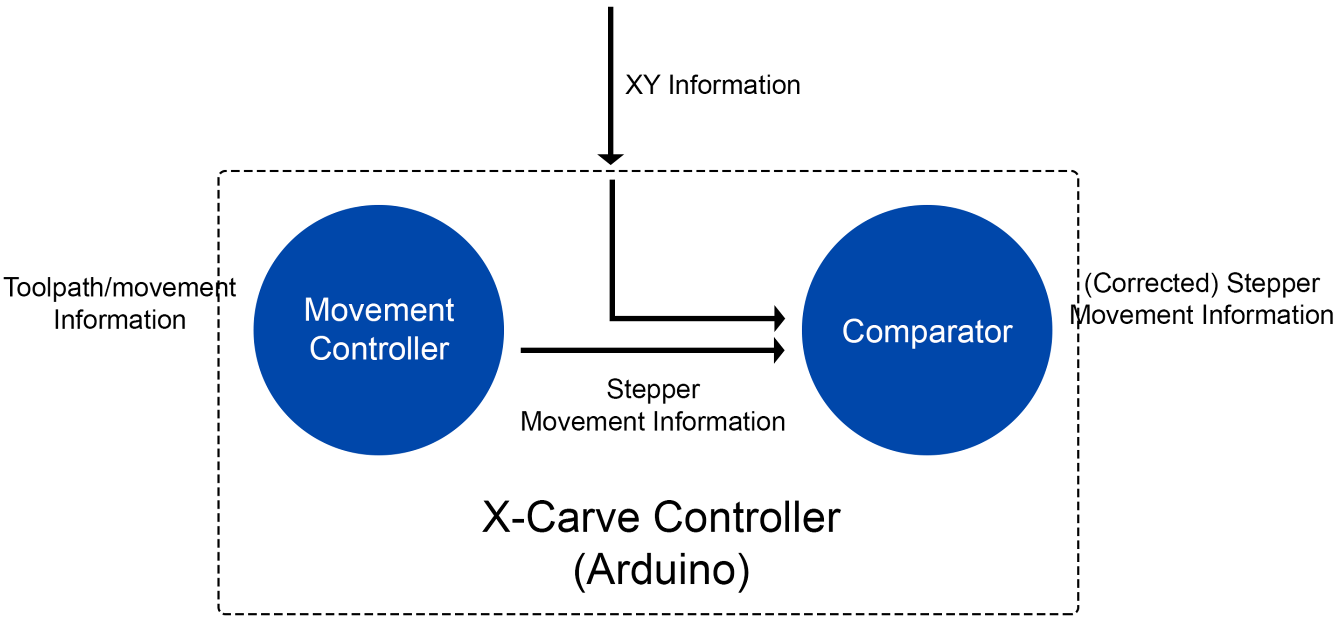

Figure 16 - Internal encoder system diagram

Dust

As stated in the problem analysis, another contributing factor leading to inaccuracies is dust. Besides that, dust gets into the computer controlling the X-Carve as well, eventually leading to larger issues.

A good way to prevent dust from getting anywhere would be to remove it as it is produced. There are several ways this could possibly be done. As can be seen in the sketches in *Figure 17.*

- Holes in the table through which dust is sucked away.
  A good way to provide dust removal while not hindering the mobility of the machine. Sadly, most of the dust is a very fine particulate matter which gets airborne almost immediately after it is produced at the spindle, so this method would not be very efficient at removing dust.
- Dust removal device at the position of the spindle.
  A good way to remove most of the dust as this is the main origin. A downside is that this method might hinder the freedom of movement of the machine.
- Cabinet with a dust removal system built around the X-Carve.
  The best way to keep the workshop clean. It might not be able to remove all the dust from the air before it settles down. Not entirely eliminating the problem of dust on the belts.

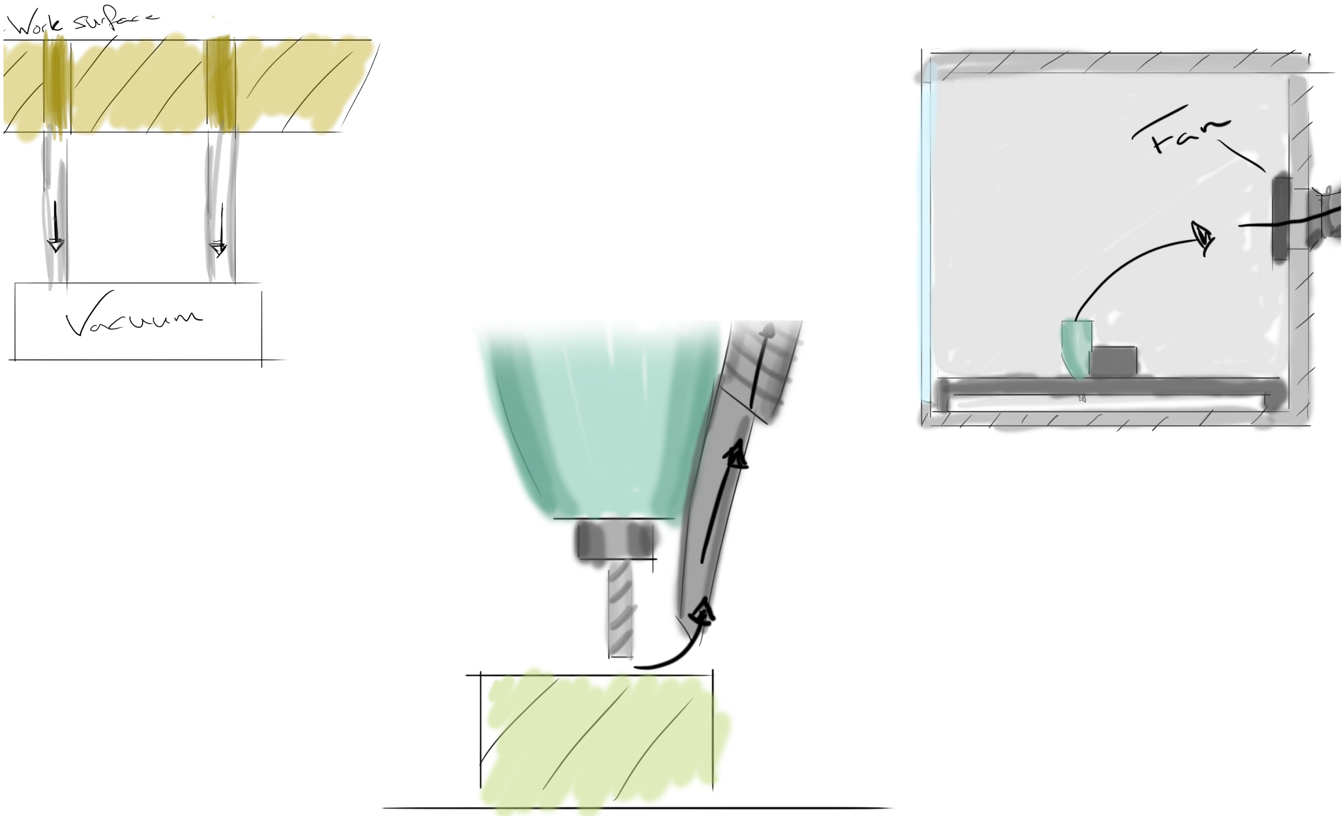

Figure 17 - Dust removal possibilities

Conclusion

There is a lot of room for improvement both in usage and function of the X-Carve.
Not all of these are as important, however. And a choice has to be made to be able to focus on a single aspect and continue the project.

From the research conducted and the information and ideas gathered, it seems clear that to comply with the set task of “Adapting the X-Carve to be used within education at the University of Twente”, there is a lot to be gained by providing a clear workflow for new and experienced users alike.

As can be seen there are also many ways to provide the X-Carve with the needed accuracy and improve it mechanically. Almost all of these solutions are quite expensive though, and each of them has its own set of unique requirements.
When all the methods are compared to the belts the X-Carve already has, the belts do not seem to be such a bad solution. In short, if the belts are kept tightened correctly, and are possibly swapped for ones less prone to slipping, the current system will most likely function fine, while keeping the low price and easy maintenance of the current system.

A good place to start then, would be to improve this workflow, before worrying about the mechanical drawbacks of the X-Carve, as it functions rather well as it is.
Further focus of the assignment will thus be on improving the workflow when carving a 3D object using the X-Carve. This might possibly be combined with some slight physical alterations if time allows.

Workflow Enhancement Comparison

In the previous chapter, several different ideas for enhancing the X-carves workflow were issued. This chapter focuses on comparing and then choosing one of these methods to be further refined into a final concept and product.

To recall, the stated methods were as follows:

- Comprehensive Software Suite
- Manual
- Live instruction feed
- Augmented Reality

Starting off with the comprehensive software suite, the positive and negative points of each idea will be analysed so a choice can be made according to the actual problem which shall be stated as follows:

"The (3D carving aspect of the) X-Carve is difficult to utilise and grasp for new users with no previous experience in CNC-machining and the workflow lacks streamlining and clarity."

The solution, naturally, should provide for solving (part of) this problem.

Comprehensive software suite

The first idea generated is the comprehensive software suite. One of the main strong points of this idea is that it provides a very streamlined workflow through a combination of programmes working through a common interface. This means that the user should very easily be able to import a model into the software shell to have it be converted into a G-Code file for the X-Carve to utilise.

Therein inherently lies the biggest problem with this idea, though. First and foremost, all the software used, be it SolidWorks, Fusion or ChiliPeppr, is regularly updated. This means that a small aspect of code or software might be changed, rendering the software suite obsolete until it is adapted to the new version. This is a very labour intensive process, as software is generally updated quite regularly. Combine this with the fact that SolidWorks and Fusion are not open-source, making it hard to actually integrate and communicate with them, and the idea begins to seem less and less likely.

Secondly, the software suite does in itself not teach the user anything about CNC-machining, as all the work is done for them, without any input being needed from the user. This is something that could be adapted through displaying more information or having the user still perform certain steps themselves. However, if this is not done just right, it will only provide more clutter to a single programme, as everything needs to be displayed in a single interface.

In short, while the software suite might supply the user with a streamlined and easy way to carve a 3D model, integrating it into the existing software already used would be rather difficult.
Combine this with the regular maintenance required and the (possible) lack of educational value and the idea seems slightly less feasible.

Manual

The second idea, a manual, dates back very far in history. We as humans have long tried to teach our knowledge to others who would like to possess it. Bluntly put, a study book can be judged as a manual as well. A manual is a way to share knowledge. In the form of a tutorial, it can be seen as a way to help someone achieve a certain goal.
The large advantage of a manual is that it offers no limitations to the user as their skill level progresses. A user might need the manual when they first start using the device, but eventually the manual becomes obsolete as all its knowledge has been transferred to the user.

This does not mean the manual will never be used again! The experienced user might still use the manual to look up something or another when they are in doubt or cannot quite remember how to perform a certain action anymore.

The disadvantage of using said system is that, instead of organising the workflow in a single programme, different programmes are still being used. This means that, instead of restructuring the workflow, the user just gets accustomed to it and learns to deal with it.
This disadvantage also carries an advantage with it, as having to understand the function of each separate programme within the workflow means that the user might learn something about CNC-machining and its requirements.

Live instruction feed /Augmented Reality

These ideas share a single heading as they are relatively similar to each other. They both provide an interactive display, either of what the user should do, or what the machine is currently doing.

The difficulty in the first, however, is that the user might want to use their own laptop to do some work on their model and code beforehand so they can just go into the workshop and carve their model. The Live instruction feed would then either only be useful for the steps performed when actually working with the X-Carve, or it would force the user to stay in the workshop the entire time with their laptop to work through the instructions provided.
Taking this to a more portable level would result in a combination of sorts. Providing the instructions in a location from which the user can easily access them, as well as providing them with, on, or next to the X-Carve.

The Augmented Reality idea suffers from the same drawback. While it might be great when working with the X-Carve when actually carving a model. It is much harder to integrate with the steps that have to be taken beforehand, which are just as important.
This option, then provides the users with instructions and an understanding of CNC-machining, but can be compared to the manual in that it does not really alter the general workflow.

Conclusion

While the software suite would seem like the best solution as it provides a very streamlined and clear workflow with some possibility of adding an educational component. It takes a last place when it is compared to the other two options, purely due to its feasibility and compatibility with the other software.

Both the other ideas provide a good base in educating the user and providing them with the correct instructions. However, due to its flexibility to experienced users, the manual comes before the AR proposition. But, this is not to say that the AR idea does not offer possibilities which can be put to good use still, or even be combined with the manual.

A combination of both (the manual and the interactivity offered by the AR) would be best. The manual could then be used like a manual, while it could also be displayed on or next to the X-Carve, possibly providing a form of interactivity.

Wishes and Demands

As the previous chapter concludes, a combination of the Live Instruction Feed/AR and a manual would be a rather good solution to the stated problem, this can then best be coined as an “Interactive Manual”.

There are several ways of generating such a manual, from a manual written in text with some simple web links or videos to a fully interactive video based manual detecting the user’s progress through the steps. There are several demands to be generated for an interactive manual, although hard to quantify, they can help guide the development.

Demands:

- The manual should offer a streamlined, linear process instruction for new users.
- The manual should offer enough flexibility in finding specific subjects to experienced users.
- The manual should be able to be consulted when working with the manual.
- The manual should be able to be consulted externally regardless of location.
- The manual should be able to be used cross-platform.
- The manual should be able to be displayed on, or next to, the X-Carve.
- The manual should be easily editable.
- The manual should run on older devices.

Wishes:

- The X-Carve or device used by the user should be able to communicate with the X-Carve.
- The manual should provide instructions or information directly on the X-Carve work-surface.

One of the most important aspects of the manual, as stated before, is the transformation it undergoes when the user becomes more experienced over time. An analysis of this can be found in *Appendix X3: REST.* This is one of the aspects which should definitely be kept in place.

The biggest question is: How does one provide for this while still keeping the linearity and steady progression through each step required for an inexperienced user.
The answer to this, luckily, is rather simple and has already been put forward by *Kuipers and Tieleman, 2015*[1] and has been mentioned earlier on. The manual should basically consist of two separate manuals from which the user can choose according to their level of expertise. One manual for experienced users and another for inexperienced users.

The first should offer some kind of navigation or table of contents so the experienced user can easily find what they are looking for. While the other should basically be a linear progression through each step, guiding the inexperienced user through the entire process from beginning to end.
A first idea of the structure of the manual can be seen in *Figure 18.*

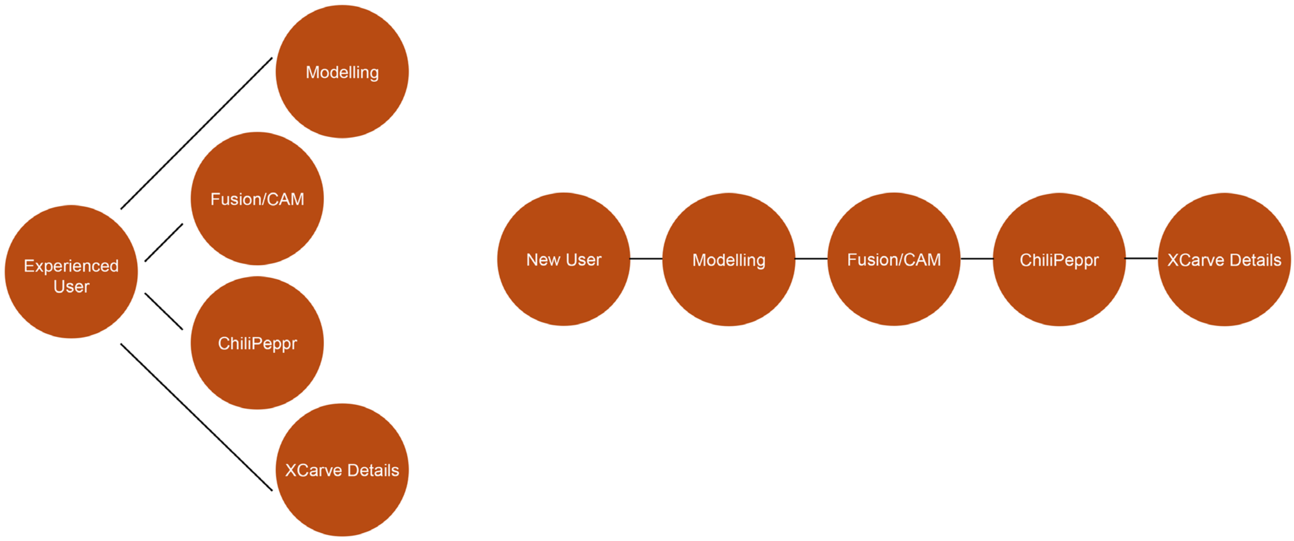

Figure 18 - Preliminary manual structure

Development

The proposed manual can be created in many different ways. An app would offer the advantages of being completely stand-alone without having to run a server or database of some kind.
However, most apps are not easily switched across platform. For example, an iPhone app would not run on Android and vice versa while a desktop app will be different to that and a tablet app again.

More possibilities for generating an interactive manual are displayed in the mindmap in *Figure 19*, which have been grouped into cross-platform and non cross-platform.
As can be seen, there are a lot more options for creating a cross-platform product than there are to create a single-platform product. Of course this is rather logical, as nowadays almost everyone seems to use a different device to view content. Concluding, the cross platform demand is a rather important one, so the Single-platform option automatically falls away.

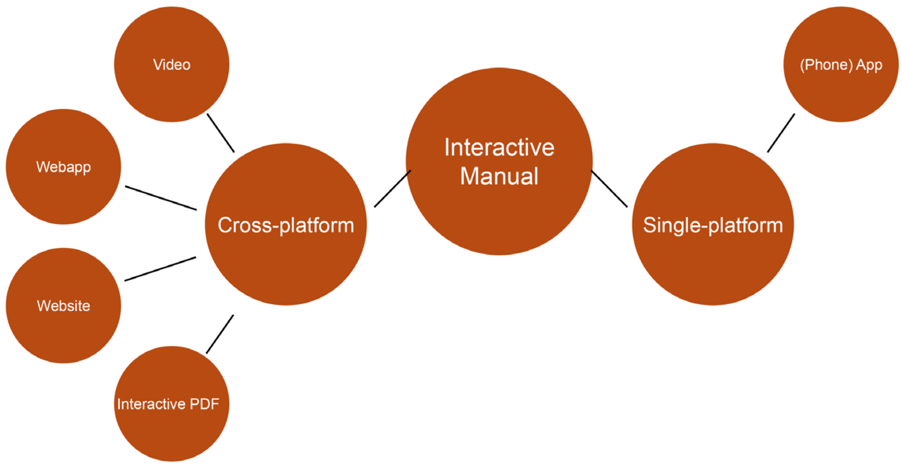

Figure 19 - Interactive manual mindmap

As the X-Carve should be able to possibly communicate with the manual in the future there will have to be some sort of connection between the X-Carve and the (device running) the manual. Secondly, the manual should be accessible by the user from any device regardless of location.

Combining these two leaves few options to choose from, besides the internet. Almost all devices are connected to the internet, and with the X-Carve connected to a computer with internet access, all communication could easily flow through this channel. As can be seen in *Figure 20.*

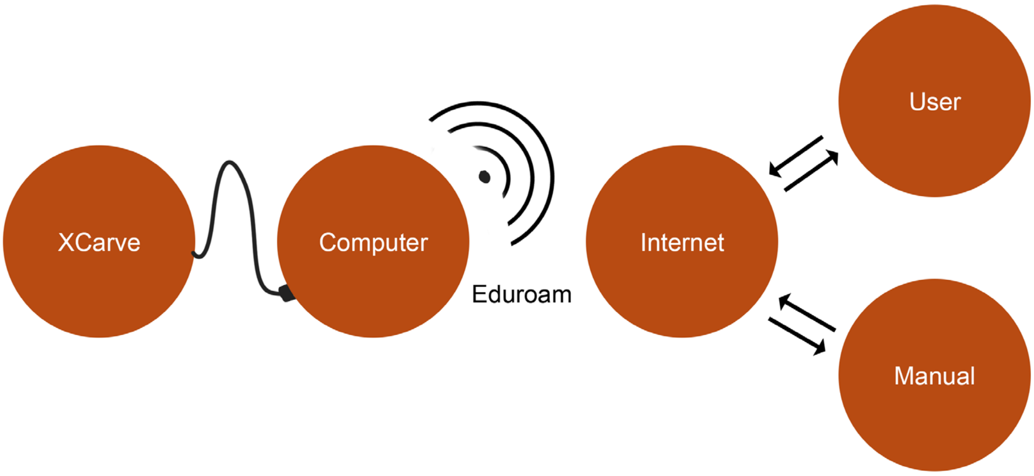

Figure 20 - X-Carve network

Combining all this leaves a rather easy decision in creating the X-Carve interactive manual: An interactive web page, or web-app.

This offers several advantages:

- True cross-platform compatibility when created correctly.
- Web-app runs on a server and as such, is able to communicate with different devices.
- Almost every electronic device with an internet connection has an internet browser, and theoretically, should be able to display the manual.
- Regardless of their location, the user can always access the manual by connecting to the webserver it runs on.

There are several ways to develop a web app, or interactive web based interface. The easiest and most maintenance friendly would be to use a WYSIWYG (What You See Is What You Get) editor.

The first software coming to mind was Intuiface *(Figure 21)*, a HMTL 5 based WYSIWYG web-app builder, primarily used to build interactive experiences. It has been used before to design and test User Interface designs, so it should be rather suitable.

The second coming to mind, still being rather user friendly, was a WYSIWYG HTML editor. Basically allowing the user to build a webpage using a visual interface instead of code. While slightly harder than Intuiface, it still offers a range of functionality and simple design choices.
There was only one true WYSIWYG HTML editor that functioned as required. Most of these editors are pure plug-ins to be run on a website to make editing easier or more accessible.
The software used was BlueGriffon (*Figure 22)*.

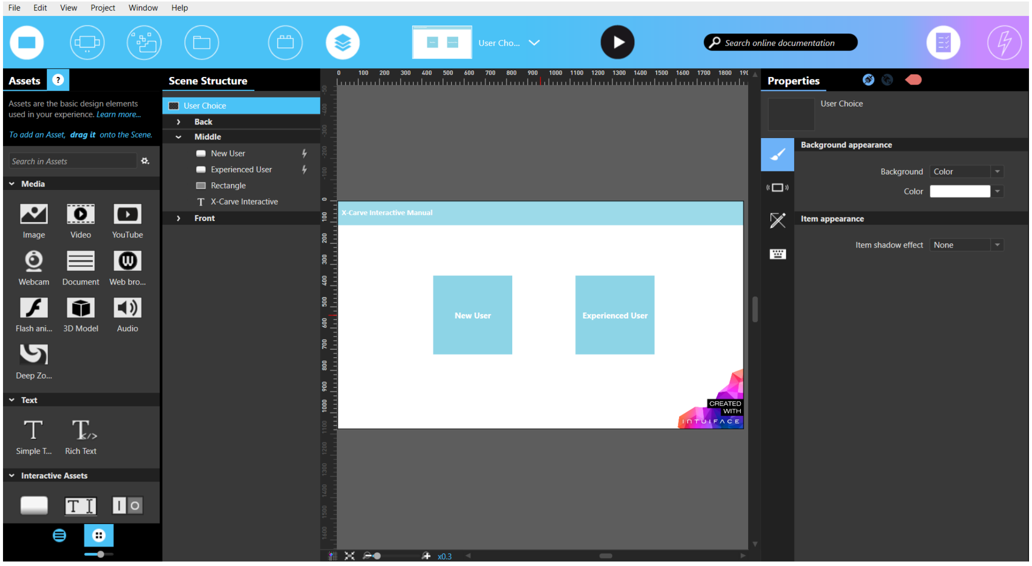

Figure 21 - The IntuiFace Editor

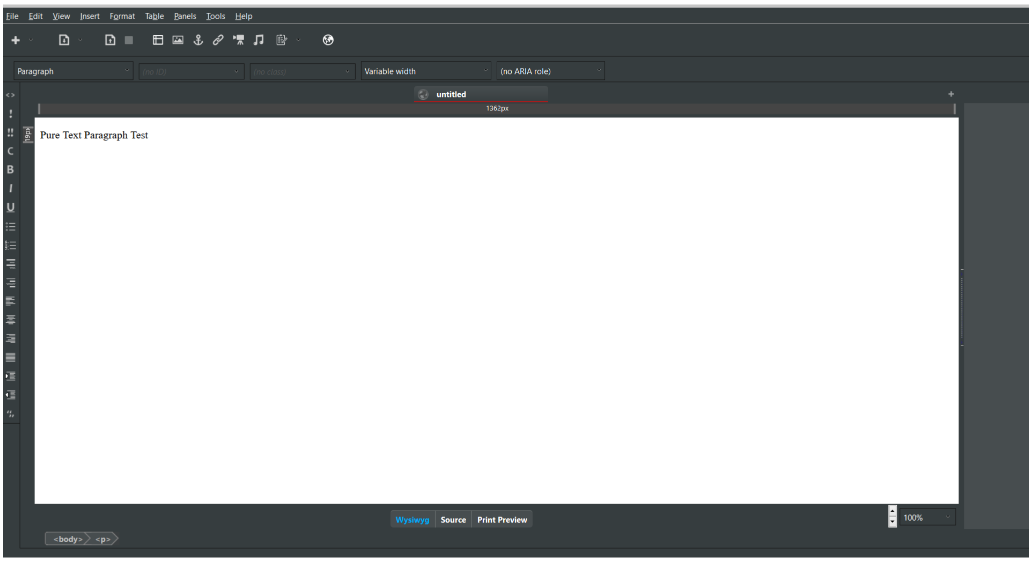

Figure 22 - The BlueGriffon Editor

IntuiFace provided a nice editor, interface and a whole host of possibilities for transitions and overlays, but had two rather serious drawbacks: It required a specialised “IntuiFace Player” to display the actual project and it put out code in its own format, so there was no freedom in adding personal preferences or functionality not offered inside the software.

BlueGriffon offered very basic functionality, not quite easily reaching the level of technical detail required to be able to integrate more advanced functions later on in the process or getting things to look exactly as required without editing the actual HTML files.
This left one final and very flexible possibility: Writing the entire manual in HTML/CSS/JavaScript by hand.

Despite having some experience with writing small websites during the Website design course offered to us in our second year, I was not entirely convinced that this would be easily doable. However, the flexibility offered by writing the manual from scratch and the ease of integrating new technologies or modules later on was something which prompted me to continue regardless.
The software that was used, finally, was Brackets.io. A multifunctional code editor suitable for writing HTML, CSS and JavaScript, among others.

Usage

A large part of the interaction with the manual will happen through usage. This is something which might happen when the user is working on a model on their own computer, but it might also happen when the user is working with the X-Carve and does not have their laptop or phone within easy reach.

This means that the manual should be just that; within easy reach.
The manual should thus always be accessible, regardless of what the X-Carve or the computer is doing, warranting something of an own platform to function on.

A good way to have the manual be easily accessible is to have a tablet always display the manual when the X-Carve is switched on or working. The user can then easily select what they want to know using the touch screen, and the tablet can be fully dedicated to displaying the manual and possibly other information related to the X-Carve. This removes the need for constantly switching between applications on a computer, streamlining the workflow a little more.

Recap

This section is meant to summarise the information from the previous pages, to get a clear idea of the form the manual will be taking.

- The manual will offer two sections, one for an experienced user and one for a new user.
- These sections will then be further divided into subsections to aid in navigation of the manual.
- The manual will be constructed as an interactive website, or web app, to aid in accessibility and flexibility
- The manual will be displayed on several platforms, the main platform being a tablet situated next to or on the X-Carve.

Interface

Before any content was added to the manual, attention was devoted to providing a well-structured, concise interface.
The interface went through several iterations which will be treated in chronological order in this chapter. First, the idea behind the interface will be explained, after which major changes will be reviewed and explained.

As the main platform for the manual will be a tablet, a touch screen friendly interface should be constructed. However, the user might still use the manual on a laptop, so it should also function with a normal mouse pointer.

Before starting to actually code the interface framework, several paper prototypes were made and discussed with Roy. As well as tested on several housemates.
The first result of this test was to keep it very simple to navigate. This was done because the manual will be used by the user when he or she is busy completing multiple (difficult) tasks at once and it would not serve to have the manual impact the user's working memory very heavily.
This means dividing the manual into clear sections and providing the user with a clear idea of which information each section contains.
It also means that the user should be able to determine which button leads to what section quickly, so navigation should be as straightforward as possible.

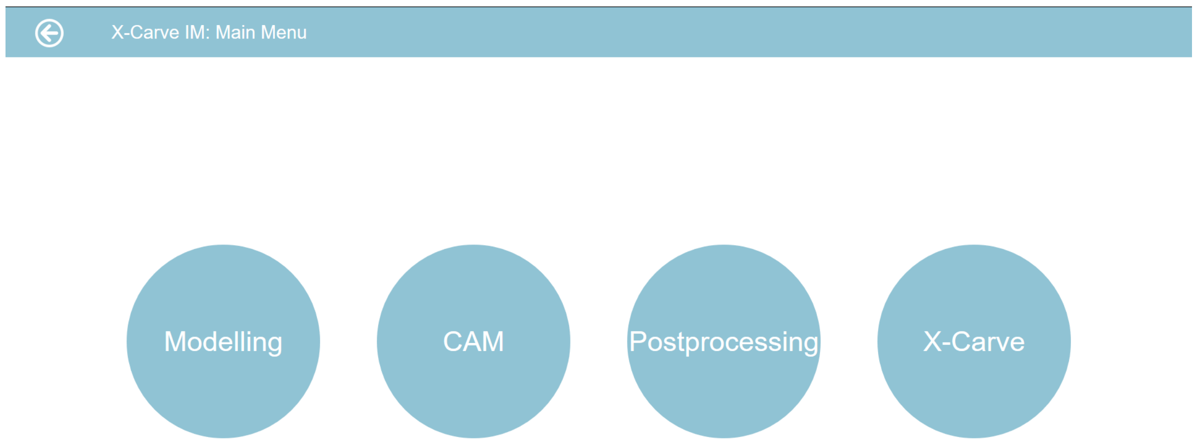

Figure 23 - The first manual UI

Of the paper prototypes used, the one with the large buttons in workflow order was the one which was appreciated most. This led to the first revision of the manual interface which can be seen in *Figure 23* and viewed using a web browser from the index.html file in the HTML_REV_0 folder.

As can be seen, the interface is rather simple. The opening screen offers two choices, one leading to a linear version of the manual, the other to a sub menu through which the user can easily browse the manual.
The manual is browsed through the large buttons making for easy and quick access with little clutter on the screen, displaying purely what is needed at that moment. Returning to a previous menu is done with the back arrow in the top bar, not unlike many apps we know in our daily lives.
This is done to make the user experience fit to the user's expectations gained from using most (touchscreen based) apps, so the user will intuitively know how to navigate through the manual.
The top bar also displays the section of the manual the user is at, making pathfinding through the manual a little easier.

The main "instruction screen", provides a form of slideshow with explanatory text to the left side, supported by images to the right side. Using the slideshow the user can navigate through the steps easily, only having to process a single step on screen at the time. Again, reducing clutter and taking up less of the user's working memory.
All in all, the interface was kept deliberately empty and simple to more easily enable the user to keep focused on the actual task at hand: Working with the X-Carve.

Changelog
In the Manual folder, several HTML revisions can be found, from revision 0 all the way to revision 4, the final revision.
This Changelog provides an overview of the changes made throughout the revisions, of which the most major changes will be explained.
Of course many changes in efficiency and small “under the hood” changes were made throughout the process, these are not treated as they are not as important to the process of the main interface.

HTML_REV_1

- Popup tooltips were added when hovering over the navigation buttons, to provide the user with a quick explanation of which section contains what, aiding in navigation.
  These tooltips were also optimised for touch screen use, displaying when the button is tapped once, and then linking to the next page when tapped again.
- Some minor changes were made to the manual framework, making certain it displayed a little better.

HTML_REV_2
Context awareness was added, meaning that the manual will detect the screen size of the device the user is using, and display the webpage correctly. This means it can be used on almost all devices now.

HTML_REV_3
The entire manual folder structure was reorganised, so future editors can more easily navigate and change content.

HTML_REV_4
This is a major overhaul of the manual navigation. One to go into more detail on.
When meeting with Roy and talking about the manual so far, one of the first things that became clear was that the manual did not scale correctly. It had been designed on a laptop and by that point (HTML_REV_1) not yet tested on any other devices. The thing was, certain objects would not scale properly, or even disappear completely when the manual was viewed on any other device.
This, then, became the main focus of improvement. After all, once the framework was set up in such a way that it displayed correctly regardless of the device, any aesthetical or functional alterations could easily be made.
When this was mostly achieved, focus shifted to an equally important aspect that had been pointed out: Navigation. During the first revisions, the navigation functioned, as stated, using a back arrow and a description in the top bar of where the user was at that moment.
However, during the entire process the user should be able to quickly glance where he or she is and consequently navigate to another part of the workflow. With the navigational structure used up to HTML_REV_3, this was a limited possibility.

As the manual already uses its buttons to provide an overview of the X-Carve workflow from left to right, these same buttons could very well be used to provide an overview in the top bar of where the user is in the manual.
The result can be found in HTML_REV_4 and can be seen in *Figure 24.*

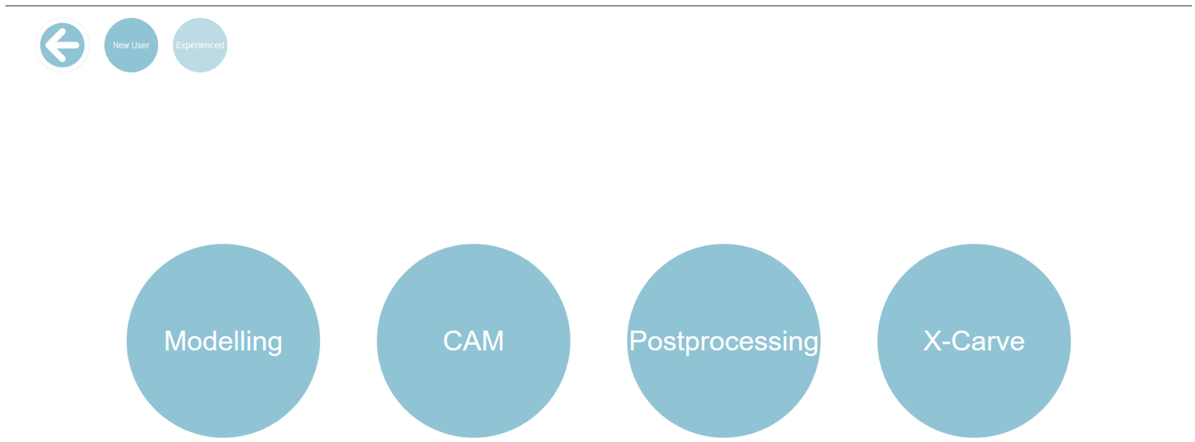

Figure 24 - HTML_REV_4

Basically, once the user has chosen a menu option, he or she is provided with the structure of the previous menu in the top bar. The item the user is at, is displayed in a lighter colour and the other items can be clicked to navigate through them using the top bar.

The return arrow is still present, so the user can navigate up a level again as well.
This way the manual structure is always present and easily visible. This improves the ease of navigation and the user's understanding of the process and where each step takes place.

As can be seen in *Figure 25 (p.32)*, there are many more and shorter pathways for the user to take in the new situation. Black arrows represent pure button interface navigation, blue arrows represent navigation possibilities via the top bar.

Another major change in Revision 4, completing the framework, is the dynamic resizing of the slideshow according to the screen size. Always displaying the slideshow in such a way that it does not fall off the edge of the screen.

With the framework in place, the next step was content generation, which will be treated in the next section.

To acces the manual, the index.html file in the HTML folder can be opened, or the server can be accessed by visiting http://www.8trackdesign.nl/Handleiding/ and logging in using the following credentials:
Username: BachelorThesis.8trackdesign
Password: XCarveIM

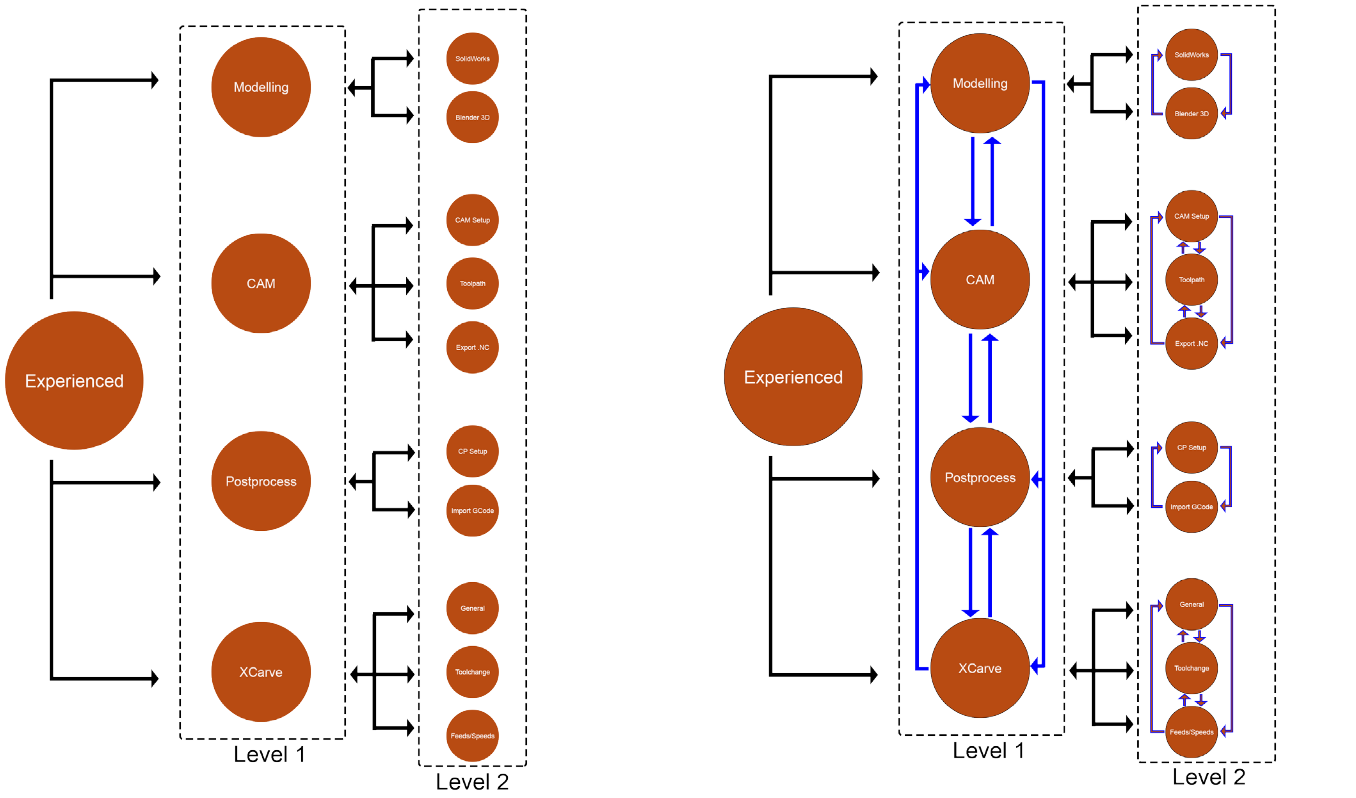

Figure 25 - Navigation pathways

PHP Database

One final change which was regarded as a possibility, was adding a WYSIWYG backend. In short, this would mean that an in-page editor such as TinyMCE would have to be implemented.
However, as there is no way to easily secure these interfaces, anyone would be able to edit the manual.
This, combined with limited possibilities in editing shapes and adding more buttons, led to another possible solution: A CMS (Content Managing System) backend using a PHP database. These are very difficult to integrate, however, and again provide only limited flexibility. This, combined with the assignment coming to an end, and limited knowledge of PHP and CMS meant that this option was not integrated in the end.

To still provide some form of editability the code was provided with inline instructions of the structure of the document, as well as a small text instructing the editor how certain elements can be added or edited. This, combined with a logical structure and naming of elements, should make most IDE students, who usually have at least a small amount of knowledge of HTML and CSS, able to edit the manual.

Content Generation

With the framework in place, the next step is to generate the content which will be going into the manual. This is something which is as important if not more important than the framework. Because, however great a framework might be, if the content which is put into it is not up to par, the manual will not function properly.

To explain usage of the X-Carve at least some form of explanatory text was needed. This meant writing a manual like one would normally write a manual, keeping in mind that it would be supported by images and other elements.
While writing the text, the workflow was walked through many times, documenting which step to take when and how to explain these steps. At the same time images were generated of certain steps.

This brought back the demand of the user having to be able to (easily) use the manual while working with the X-Carve or being otherwise occupied. A large swathe of text would not do, reading is a fairly intensive process for which a person needs a lot of working memory. Especially when the text tells the user to form a certain image in their head or imagine a certain action so they can complete it.

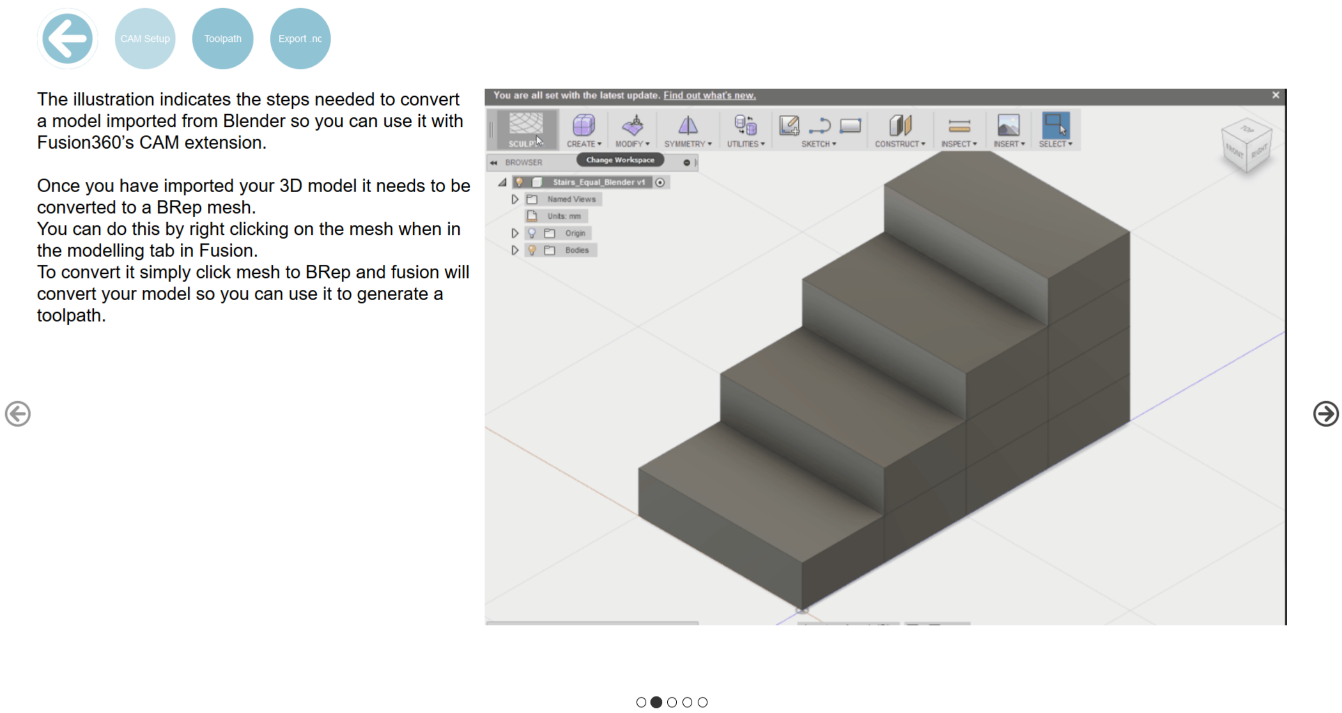

Figure 26 - Instructional Interface

A small section of text supported by clear images or infographics *(Figure 26)* would be comprehended much more easily and quickly, as our brain is used to quickly processing visual inputs without having to make the translation needed when reading a text. The text would then serve to further explain the image so the user knows what the images depict or instruct. This should reduce the workload for the user.
Another gain from this method of instruction is that the user who has used the X-Carve more often, might not need the text section at all anymore. Instead they look at the images and use them as a visual clue to remembering a certain step in the process, as they already know the outline of the process. This then further speeds up the process and with a little more experience might even lead to a fully independent capability of working with the X-Carve.

However, when working through the required steps and generating both text and images, it slowly became clear that some steps were too complex to simply explain using static images and text.
A much better way to display several steps in a sequence, for example saving a file, is to provide a video of said steps.
This way the user is shown exactly which steps to take in which order to complete the action.
In case of a very simple process the text purely becomes an explanation of what is happening, while in a more complex process the text supports the video by explaining the how and why of certain steps which the video cannot easily explain.

Again, to keep the impact on the user low and the steps simple and easy to follow, the videos should not be too long or complex, just like the text and imagery.
The written text can be found both in the manual, which can be displayed by opening the index.html file in the HTML folder, by visiting the manual's webserver, or in the Manual_Text.pdf file provided in the Manual folder.

The final form of the manual then, seen in *Figure 27,* becomes a combination of text, images and videos, wherever each is required and most appropriate. Supported by a flexible framework with a simple navigational structure, this makes the manual easy to pick up and easy to work with until the user can independently use the X-Carve

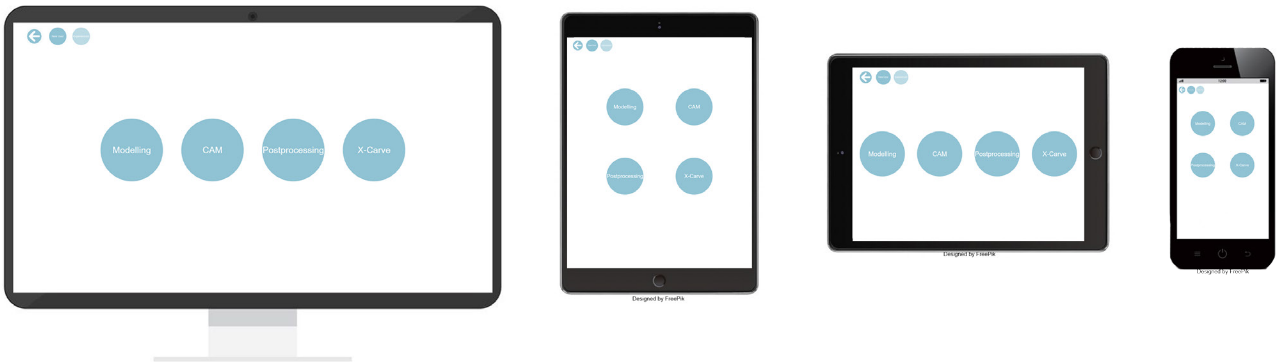

Figure 27 - X-Carve Interactive manual on different devices.

Usage Test

To evaluate the final manual, two separate usage tests were performed. The first usage test was performed to test the difference between the old and new navigational structure. This was done through interviewing the user about their experience with both interfaces.
This led to the following results:

Nino
The first interface was easy to navigate, I could easily get to each function and most buttons were clear. Some of the buttons could be titled differently to make it easier to understand what they are for. But then again, almost everyone who will use this should have some knowledge of the process, so it should be alright. It was not entirely clear to me that the buttons represented a workflow from left to right. Something to be added might be a timeline of sorts. I think arrows would complicate things too much. I like the slideshow idea, this really helps in making separate steps clear. Also for a new user.

Ella
Both interfaces were clear, I really liked the large buttons. When the manual is used on a laptop, some kind of image might be added to the tooltips to more quickly make it clear which button leads where. But I think this would be too much clutter on a tablet. I think the navigation through the top bar is nice, but in the main menu the back arrow might be replaced with a home button or something similar as it goes back to the beginning of the manual.

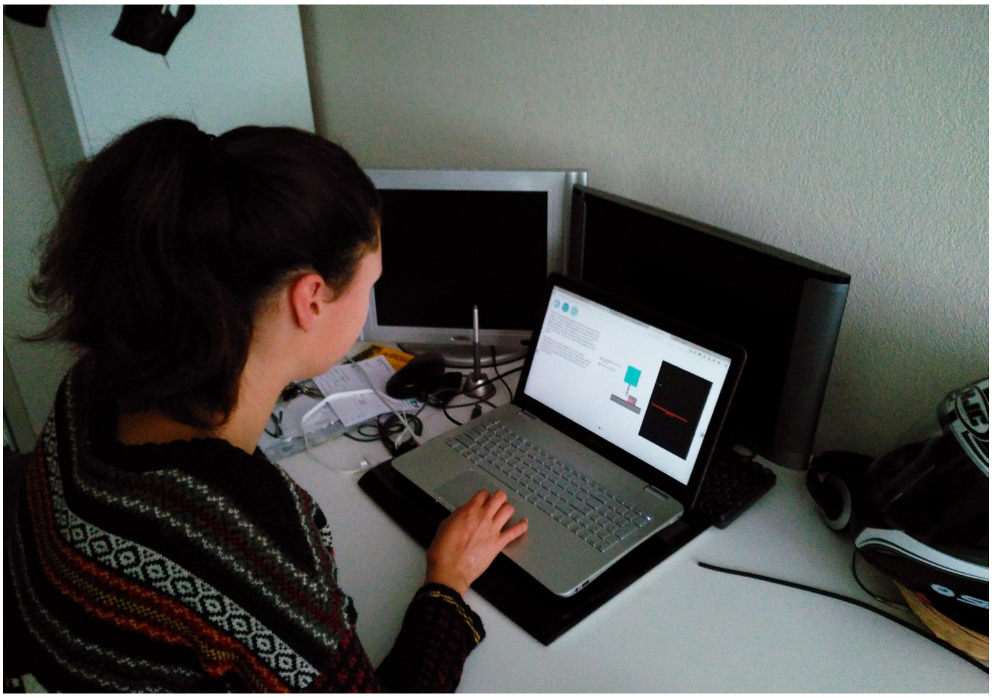

Figure 28 - Usage Test

The second test was done by having the user actually perform a task described in the manual. The tasks set ranged from simple to complex, to determine the performance of the manual in each situation. The users were observed and interviewed, which led to the following results:

Task	Observations	User Comments
Nino		
Export model from Blender 3D	Rather quick to navigate through the first steps, takes a little longer on the export, has to watch the GIF several times.	I found the usage of the GIF very nice. It is a very nice way to convey information in a short video. Normally you would have to pause a video and scroll through it all the time. This just repeats so I can easily follow each step.
Setup CAM in Fusion 360	Generating a setup is done quickly. A little more time is taken when determining the correct WCS orientation. Planes are easily added and copied from the manual.	This step was a little more difficult, as I had to think about the orientation of the work axes according to the X-Carve. Especially positioning them in the most efficient way is something to get used to. All other instructions were clear.
Generate toolpath in Fusion 360	All information is carefully read and Nino understands what specific parameters are used for. He tries to input them himself. After navigating through all the steps he finds out there is a tool library, which makes the whole process a lot easier and quicker.	This was a difficult step. Especially because I thought I had to input all the parameters myself. It might be better to tell the user about the tool library first, so they can more easily generate a toolpath, instead of going through all the steps first.
Ella		
Export model from Blender 3D	The steps are followed and a model is exported from Blender with no trouble at all.	I have some experience with 3D software like Maya, so exporting a file is something I do not find very difficult to do.
Setup CAM in Fusion 360	Ella has no experience with CAM of any kind, but her understanding of 3D space helps to navigate through the steps. Determining heights is easily copied from the manual.	Creating a new setup was easy. Determining the axes was a little harder, which is where the explanation of the X-Carve axes came in handy.
Generate toolpath in Fusion 360	As Ella has no experience with CAM, generating a toolpath is difficult. She seems to understand what the parameters are for, but actually setting them accordingly does not go too well. Eventually, using the tool library she manages to complete the step.	I think the tool library really helps in creating a toolpath, because I don't think I would have managed to do it when I had to read and set all of the parameters myself. And the tool library just does it for you!

Evaluation/Conclusion

In this section the manual will be evaluated according to the demands and wishes put forward, as well as the usage test.
Recalling the demands and wishes:

Demands:
The manual should offer a streamlined, linear process instruction for new users.

- The manual should offer enough flexibility in finding specific subjects to experienced users.
- The manual should be able to be consulted when working with the X-Carve.
- The manual should be able to be consulted externally regardless of location.
- The manual should be able to be used cross-platform.
- The manual should be able to be displayed on, or next to, the X-Carve.
- The manual should be easily editable.
- The manual should run on older devices.

Wishes:

- The X-Carve or device used by the user should be able to communicate with the manual.
- The manual should provide instructions or information directly on the X-Carve work-surface.

Going through the demands, almost all have been met in some way, there are several to be discussed in a little more detail:

The manual should offer a streamlined, linear process instruction for new users.
The manual should offer enough flexibility in finding specific subjects to experienced users.
These two demands, when looking at the manual and the usage test, have been met. However, these specific aspects of the manual might still be improved, as sometimes certain navigational aspects are unclear, especially the fact that the interface represents a workflow from left to right.

The manual should be easily editable
This demand has not really been met. Editing the manual through HTML is not the most user friendly way to do it, and is something which could definitely be improved.

The X-Carve or device used by the user should be able to communicate with the manual.
This wish has been met in the fact that all aspects of the system are connected to the internet, so theoretically, communication should be possible. The framework for this communication will still need to be provided though.
All in all, concluding from the demands and wishes and the usage test, the manual is a solid base. There is some room for improvement and definitely expansion, which will be discussed in the recommendations section.

Recommendations / Future

As it is, the manual can be used. It might benefit from some additions, however.
One of the main additions that could be made is the integration of a proper back-end with a login, so even an inexperienced editor can easily expand the manual, make changes when software is updated or correct any possible errors or mishaps.

Navigation and interface wise, some improvements could be made in clarity of the workflow offered. At this moment it is not entirely clear that the interface represents the workflow the user will be walking through. There are also some small aspects in the order information is presented, think of presenting the user with the tool library first instead of last, which could possibly be improved further.

The manual, as it is written in HTML, CSS and JavaScript, is flexible enough to be expanded with live update functions, telling the user what is happening while they are using the manual. It might even go so far as to include buttons in certain steps, like homing the X-Carve, to complete these steps from within the manual instead of from a different platform/computer.
Another advantage of this flexibility is that the manual could rather easily be adapted to be used for different devices than the X-Carve. At this moment there are plans for a smaller, simpler laser cutter in the workshop which can be used independently by students. The manual could easily be adapted for this purpose.

In the ideation chapter, several ideas for improving the X-Carves physical aspects were mentioned. As focus was put on the manual, the physical aspects became more of a side project, and due to limited time, were not fully implemented. However, some thought was given to a small project.

In cooperation with Simon Huijink, a small case to protect the X-Carves motion controller from dust was designed. This would, simply put, be a small box made from PET or a similar plastic, which would have one side with a small grille behind which a filter could be placed. In this way, the X-Carves motion controller can still cool itself, but not suck in as much dust as it did before. Something which would definitely improve hardware lifetime. The model for this case can be seen in *Figure 28.*

Another thing which was looked into was adding an emergency stop to the X-Carve, as it did not have one yet. However, after some research, it seems that when an emergency stop is installed, especially one which is red and yellow, it needs to be officially checked and approved. If this is not done and it fails to function in an emergency situation, it might lead to a whole host of problems.
This was a reason not to install the emergency stop yet, and care should be taken in complying with regulations when doing so later on.

All in all, not much progress was made in improving the X-Carve physically. This is something which will become a recommendation for future projects to focus on more. On a more positive note, Inventables have, as of the moment of writing this text, improved the X-Carve out of the box. *(Inventables, 2016)*[4]
The new features are mentioned in short below.

- The X-Carve now comes with the motion controller mounted on the waste board to the side.
- The X-Carve now has a case with filters built around the motion controller, including an emergency stop, proper cable connectors and a physical machine jog control.
- The X-Carve can be ordered with a Z-probe to reliably and more easily find the material surface.
- Inventables have a deal with Vectric, providing CAM software which they claim works well with the X-Carve.

As can be seen, some of the desired features, like dust protection and an emergency stop have already been integrated out of the box. However, the question of accuracy still remains as the X-Carve still has to work with stepper motors without any form of positional feedback.

Recommendations

One of the major aspects the X-Carve lacks in right now is its accuracy. As stated, it is alright for slower milling speeds and aesthetic purpose. However, it does get rather inaccurate when higher milling speeds are programmed. Something which should be a point of attention if further efforts are made into the X-Carve project.
A look might be taken at the motion controller container offered by Inventables, as it offers functionalities which are, honestly speaking, rather crucial. The choice could also be made to fabricate these functions, like a jog control and an emergency switch in-house.

Project Conclusion

Looking back on the past months, completing this project, things went differently than expected. The X-Carve turned out to be a possibly powerful piece of machinery, something which can be to good use at least within IDE. Some aspects of it were lacking and fixing all of these at once is an enormous task. However, by thoroughly analysing the problem at hand and coming up with a good solution for one of these aspects, the road can be paved for further improvement and eventually the X-Carve can be put to use just as it was intended: Free to use for all students to create almost anything they put their mind to.

A bachelor assignment is a big project. Basically, it's the first steps in the great big outside world.
Doing my bachelor assignment at the University itself offered drawbacks, as it does not provide any of the actual workplace experience an external bachelor assignment might.
It does however, provide a lot of freedom. This freedom is something which is good and bad at the same time.
On one hand, it allows for a lot of freedom within the project, as the project description is so global.
On the other hand, this freedom also means that there are no obligations, except to yourself.
This is hard sometimes, as it means that all responsibility for finishing something on time or sticking to schedule is on you.

Looking back, there are not many things I would do differently. Maybe a little less research could have been done on the X-Carve and its possibilities. But I also think that the research which has been done has provided a good foundation from which future projects could be continued.
All in all, my bachelor assignment, much like other assignments, was an experience from which I learned a lot about the design process and a more analytical approach to it.
It was different, however, in the fact that I also learned more about myself and work ethics in the process. Being solely responsible for such a large project has taught me that there are advantages and disadvantages to working alone. Something which I will take with me and add to my designer knowledge gathered over the past three years.

Image References

Figure 01 - X-Carve
http://indywoodworks.com/wp-content/uploads/2016/02/XCarve_Large_angle__0011-1.jpg

Figure 03 - Haptic pen
http://www.dentsable.com/documents/images/LargePHANTOMOmniImage.jpg

Figure 04 - Laser Engraver
https://en.wikipedia.org/wiki/Laser_engraving#/media/File:Laser_Engraver.jpg
Public Domain license

Figure 12 - Rack and pinion
http://g02.a.alicdn.com/kf/HTB11hjKIFXXXXbgapXXq6xXFXXXz/rack-and-pinion-gear-rack-differential-gear-design-plastic-font-b-metal-b-font-font-b.jpg

Figure 13 - LeadScrew
https://en.wikipedia.org/wiki/Leadscrew#/media/File:Acme_thread.jpg
By Yannick Trottier
Creative Commons license

Figure 14 - Hydraulic piston
https://upload.wikimedia.org/wikipedia/en/4/47/Cutawayweldedcylinder544x123.jpg
Public Domain license

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[1] Kuipers and Tieleman, 2015
Kuipers M. and Tieleman V. (2015). *Virtual Reality Minor.*

[2]SDP, n.d.
SDP Industries (n.d.) *Handbook of timing belts and pulleys.*
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Last checked: 16-09-2016

[3]Bhandari, 2007
Bhandari V.B. (2007) *Design of Machine Elements*

[4]Inventables, 2016
Inventables. (2016) X-Carve Website.
From: https://www.inventables.com/technologies/x-carve
Last checked: 16-09-2016

Workshop Research

As I had no previous experience with CNC-carving, at least not on a detailed level, I spent a morning in the workshop as a “completely new user”. The experience gained from this is that the Easel software is very easy to use and rather foolproof in its setup and operation, holding your hand every step of the way. It would be lacking for a more experienced user, however.
This is where the more complex CAD/CAM setup from Fusion 360 comes in. In my experience, modelling in Fusion is rather complex and cluttered, so modelling was done in Solidworks and Blender 3D, creating several shapes to test the X-carve.

After completing the models, it becomes clear how much of a hassle the current workflow is. Fusion 360 accepts .STL model files, but it does not want to do a CAM setup for these file types, which means that an IGES model is needed to properly complete this operation. Something which will already be much more difficult coming from a freeform modeller like ZBrush or Blender 3D as both do not support IGES export. MeshCAM, a pure CAM generation software, does support .STL files.

After successfully creating a new setup for the imported model in Fusion360, the axes, origin and stock size need to be defined, something which takes some getting used to but is rather straightforward after some fiddling around.
But then the biggest challenge is presented. It all starts with choosing the correct milling or carving method from the long dropdown menus. Fusion360 provides a basic explanation on the different methods, but these are very brief and sometimes rather complicated to understand. Luckily, the Adaptive Clearing method does quite a lot of thinking for you, determining the best toolpath for the provided shape.

After choosing one of the milling methods, one is presented with an endless list of options. Parameters and spindle speeds, feeds and RPM’s. Something which cost quite a while to figure out. Even with an understanding of CNC machining.
In short, it took about 8 tries to get the machine to do what I wanted, where I wanted it. It started off carving on the wrong axis, which was fixed rather easily by flipping axes. Then the negative and positive Y were the wrong way around, which was slightly harder to fix as it required re-determining the Work Coordinate System.
After that one of the workpieces was destroyed by the machine halfway through as there was still a G28 command left in the .nc code somewhere, telling the machine to return to zero without raising the Z-axis first.

Another issue found was that at high movement speeds (>250 mm/min) the machine would rapidly lose its positioning. Leading to the X-carve milling thin air or coming rather close to hitting the fixture as it got its bearing wrong or offset.

As can be concluded, generating a simple .nc code using Fusion360 is a slow and painstaking process, which is badly documented. Especially if the user does not have a large amount of experience with the programme or CNC-milling in general.

Another insight gained from the time spent in the workshop, is that zeroing in the machine is a rather easy but inaccurate process and something which needs to be repeated in Chillipeppr every time the GRBL cache is cleared. This means that when changing bits and loading another G-Code file the user has to re-zero the machine, never getting it quite as accurate as possible.

Another point deducting on the accuracy of the machine are, as mentioned before, the rubber belts. When I tried the X-carve, the belt on the X-axis had to be tightened as it was slipping when trying to move the machine along the X-axis. The belts are, however, a great and cost effective way to allow the machine to translate. They are the first thing to break when the machine hits a solid object, saving the rest of the machine, and they are relatively cheap to replace in such a case.

A form of checklist or something similar as to what Easel does before being able to run the generated G-code would be feasible as it prevents the user from making big mistakes which might damage the machine. This might also be an integrated guide of sorts so the user knows what to and when to do it.

App. X2: Workflow Research

Research; CAM Workflow

For this research a simple stepped model created in Solidworks and the same model created in surface modeller Blender 3D will be converted to a toolpath readable by the X-Carve using the following software:

- Autodesk Fusion 360
- MeshCAM
- Siemens NX

For each programme it is assumed that the user has little to no knowledge of the processes involved in CAM, so a clear and concise backend and interface are an important factor.
The goal of this research is to provide a recommendation as to which programme can most easily be used in combination with the X-Carve and its use in rapid prototyping and creating complex models.

The first step in this research is to make certain that all outside influences are removed. Therefore a fixed model is used for each workflow. As stated earlier, this model will be provided through two different pieces of software. A surface modeller, Blender 3D in this case. And a feature based modelling programme, Solidworks 2015. This means that the model does not change as the switch between different programmes is made. The same applies to the file type. For the Blender 3D model an .STL file will be generated to be opened and processed by the software used. For Solidworks an .IGS file will be generated. This is one of the best possible ways to keep all parametric information stored in a (mostly) transferable 3D file.

The model will consist of something resembling a small stairs, about 100x50x50mm (LxWxH). Both the Blender 3D and Solidworks model are shown below in *Fig. 1* and *Fig.2.*

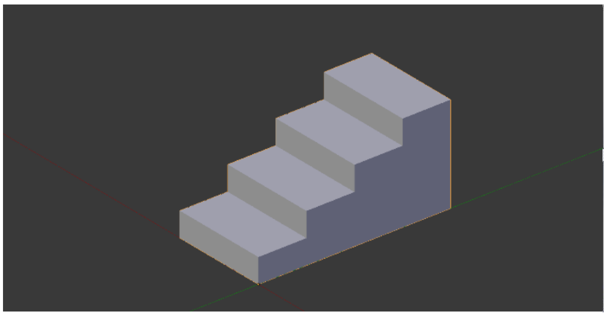


Figure 1 - Blender 3D model

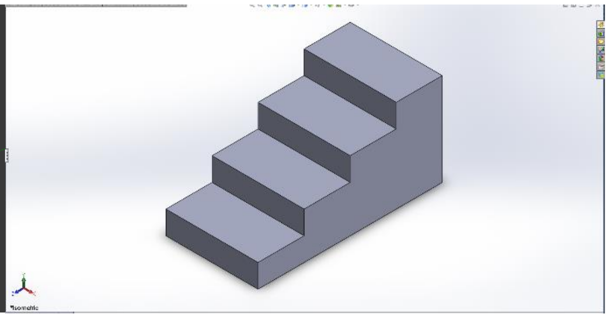


Figure 2 - Solidworks 2015 model

Execution
The following steps will be taken and assessed when researching the workflow in each programme:

- **Importing the 3D file**
  - *For .STL, converting the 3D file to a workable format inside the software used might be necessary.*
- **Determining a stock size**
- **Choosing a tool including feeds and speeds**
  - *Possibly loading a tool library*
- **Generating G-code**
- **Exporting G-code**

Autodesk Fusion 360

Autodesk Fusion 360 is a CAD/CAM software package. Much like Solidworks it uses parametric modelling to generate 3D shapes which can then be translated into G-Code using the integrated CAM-module. Which is in the interest of this research.
First of all, importing the two different 3D formats was tested. This brought an issue under attention rather quickly.

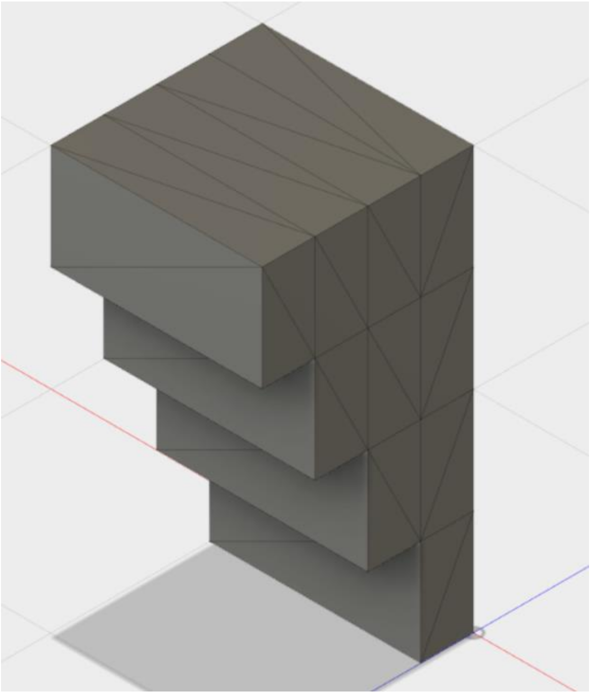


Figure 3 - .STL imported into Fusion 360

The first format to be imported was a .STL file generated using Blender 3D. Typical for this kind of 3D format is that it is triangulated on export, much like a lot of other 3D formats out there. Importing the model itself into Fusion 360 works fine as can be seen in *Figure 3*. While importing itself is something to get used to (one needs to upload the specific file into the cloud first) the model is displayed exactly as it is exported from the modelling package apart from some axial flipping, which is easily corrected in the exporting dialog within Blender itself.

However, the model is imported as a MeshBody, which means that it cannot be selected and used within the CAM module of Fusion 360. To do this it needs to be converted to a parametric model first. Fusion 360 offers an option for this. This is where the problem lies though, as it does not want to convert a triangulated mesh due to its inherent complexity. So, importing a .STL file is possible. It is not possible, however, to convert said model within Fusion360 and generate a toolpath for it. But, when exporting the model to an .OBJ file this works absolutely fine and the model converts nicely to a BRep mesh. A thing to keep in mind is that 1 unit in blender is seen as 1mm in Fusion, so the scaling factor should be set accordingly when exporting.

Importing an .IGS, as expected, works flawlessly.
Diving into the CAM menu, a new setup can be created easily. As shown in *Figure 4*, the axes can be set according to the way X-Carve treats axes to prevent any mishaps while carving. This means the Z-axis should be pointing up and from the bottom left corner of the work surface the X-axis should be positive to the right and Y to the back of the machine.

Setting a stock origin is also rather easy, after which the next step is selecting the right milling method and setting the correct speeds and feeds.

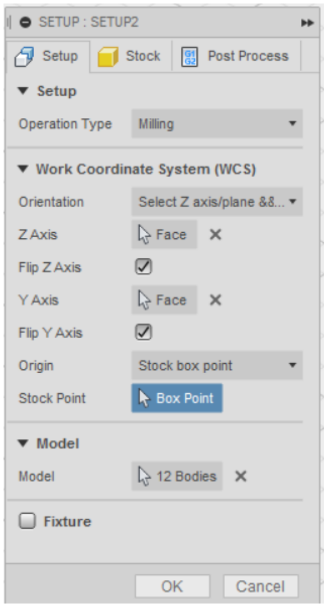


Figure 4 - WCS Setup

Selecting a milling method is rather easy as Fusion displays a comprehensive description of what each method does when the user hovers over it. Selecting one of the methods, the user is presented with a rather daunting list of options to choose from (*Figure 5)*. However, with a bit of work a tool library could be constructed supporting the bits used with the X-Carve and enabling the user to simply select a material and a milling bit. This way the user does not have to work through the entire list of speeds and feeds to mill a simple model and get the settings dialled in correctly.

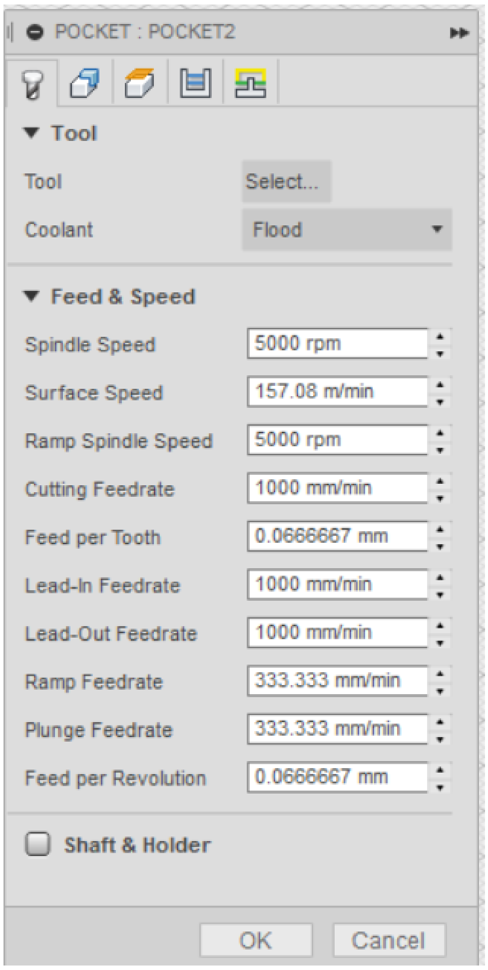


Figure 5 - Feed and speed options

After all the settings have been correctly chosen for all of the tabs, a toolpath is generated and displayed nicely within the model window. Several options allow for the stock to be displayed and the simulation of the milling process is rendered very quickly and displayed in a very comprehensive manner. As can be seen in *Figure 6.* Exporting the toolpath to G-Code is a matter of simply clicking the Post-Process button, choosing the GRBL postprocessor, so the G-code can be read by the X-Carve, and exporting the file to the location of the user's choice.

All in all, Fusion 360 offers a very comprehensive workflow and a good overview of which function does what exactly. It would, however benefit greatly from an X-Carve tool library, making ease of use a lot larger.

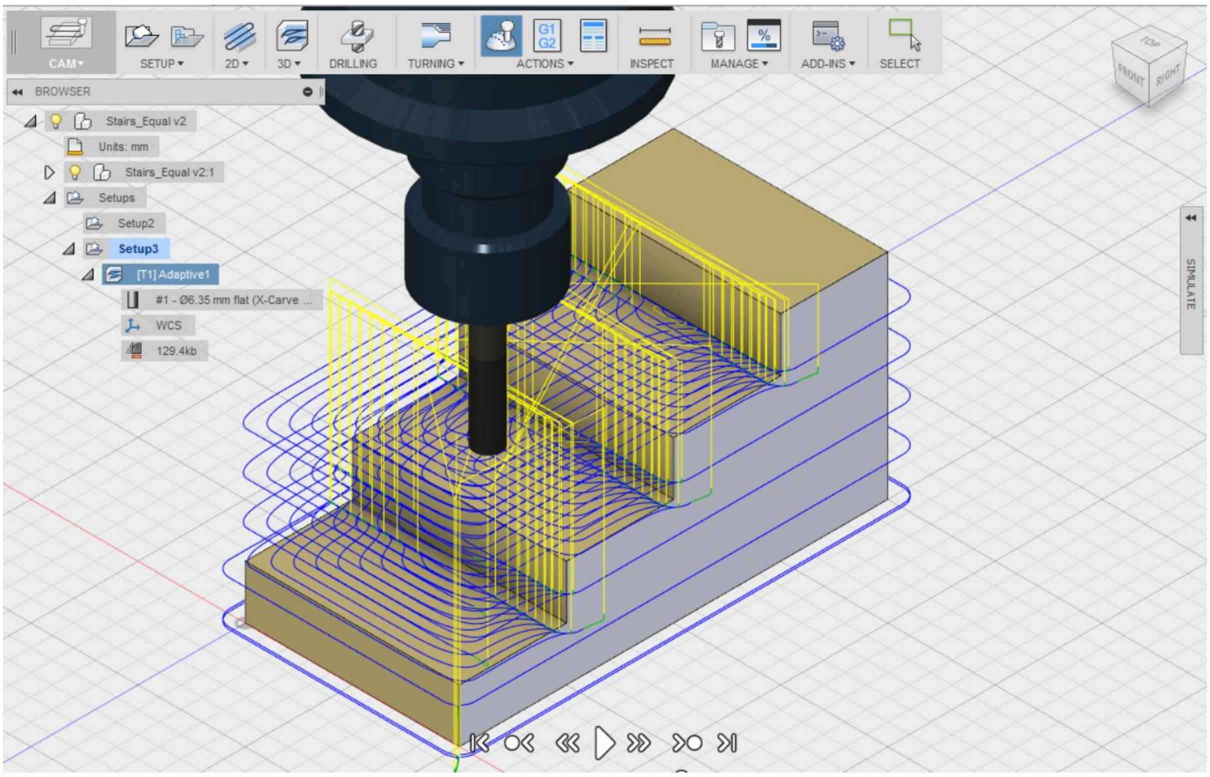


Figure 6 - Simulated toolpath

GRZ Software MeshCAM

MeshCAM is a piece of software developed by a machinist who wanted to make CNC-carving accessible to a larger audience. As such, it is a rather simple piece of software which does nothing more than import a model and, using various settings, generate a toolpath.

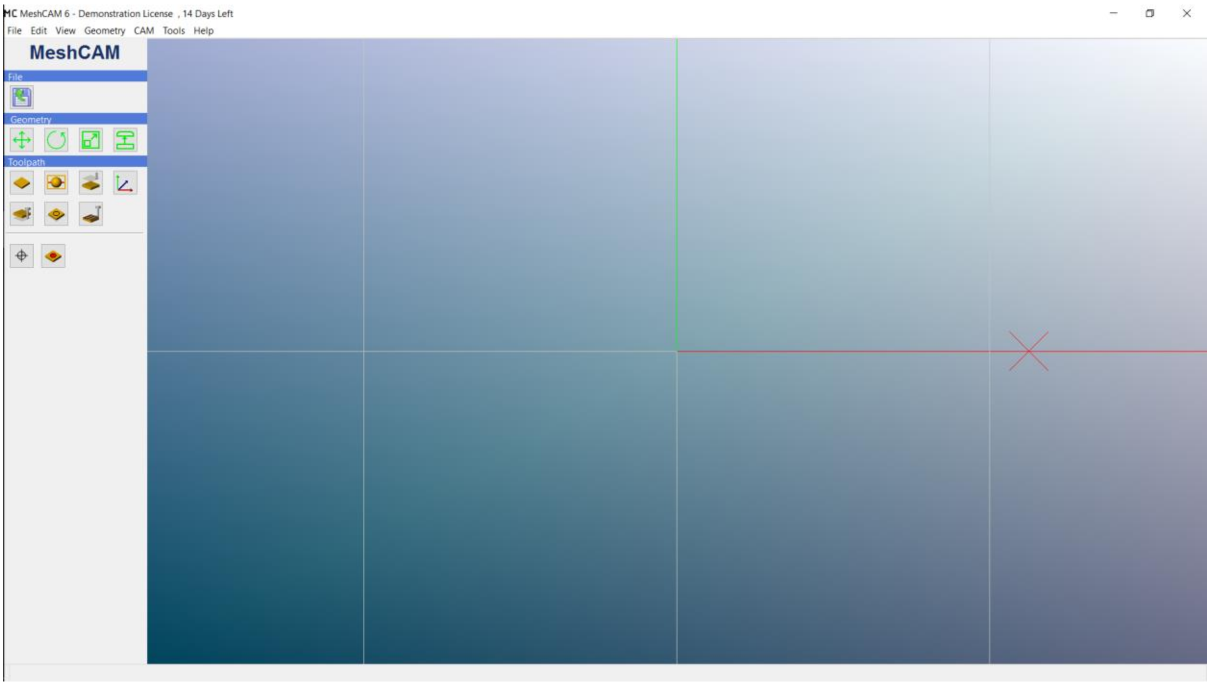


Figure 7 - MeshCAM interface

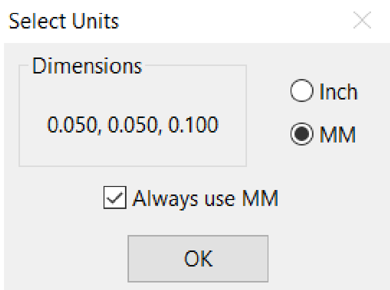
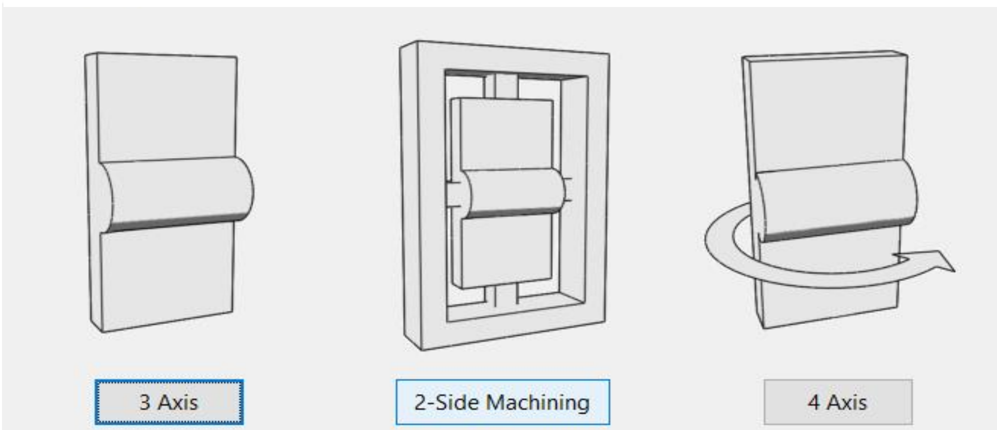


Figure 8 - Import scale dialog

Upon first glance the interface is rather clean and simplistic (Figure 7), with a number of buttons which are clearly sorted by function. The menu at the top provides the same functionality as the buttons to the left, but in a less graphic manner.
The 3D window is simple but effective, showing the model in a simple flat shading when imported. The mouse is used to orbit, pan and zoom.

Importing a 3D-model, either an .STL or an .IGS, is rather simple. During the import process the user is provided with several dialogs. Confirming the scale of the model where the user can choose to display mm or inches *(Figure 8)* and determining which type of milling operation will be used. More accurately, determining the amount of axes the machine which is to be used has *(Figure 9)*.

Figure 9 - Import milling method dialog



After importing, the model is displayed. In the case of the .STL file exported from Blender 3D, it was oriented the wrong way. However, MeshCAM offers a range of buttons for rotation, translation and scaling of the geometry *(Figure 10)*. All of this is done through numerical input or check boxes with a small illustration. Making correctly orienting and scaling the model a matter of seconds.

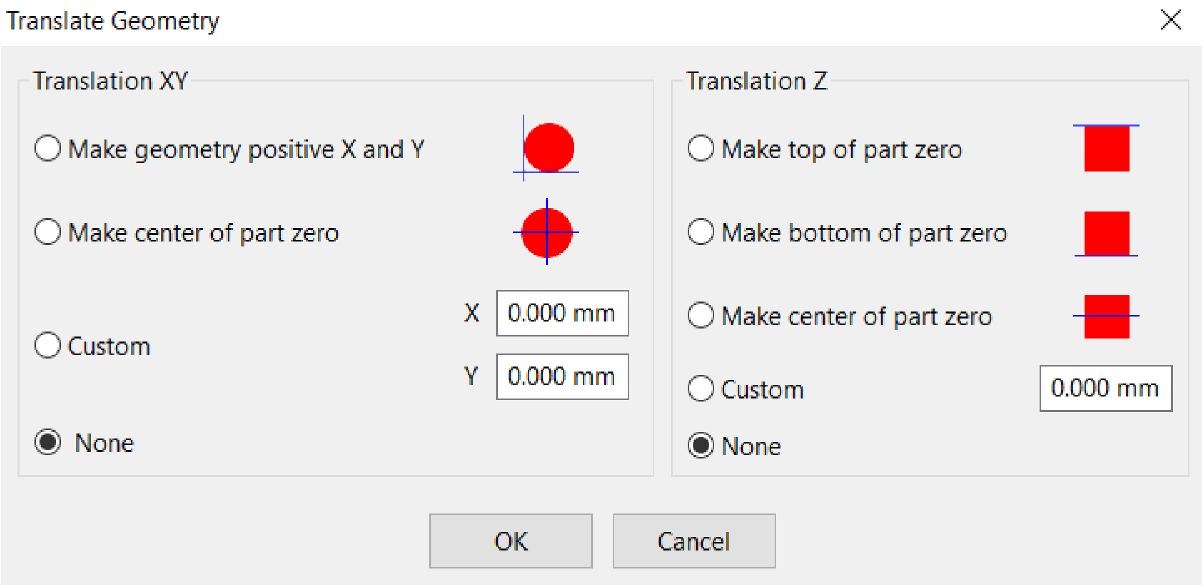


Figure 10 - Translate geometry dialog

After manipulating the mesh such that it is oriented correctly, a toolpath needs to be generated. MeshCAM offers two ways to do this. Either by setting all the parameters manually in the toolpath menu *(Figure 11)*. Or by using the built in toolpath wizard which determines the shape of the model and the best possible milling operation to be used on it, much like the adaptive clearing method Fusion has *(Figure 12)*.

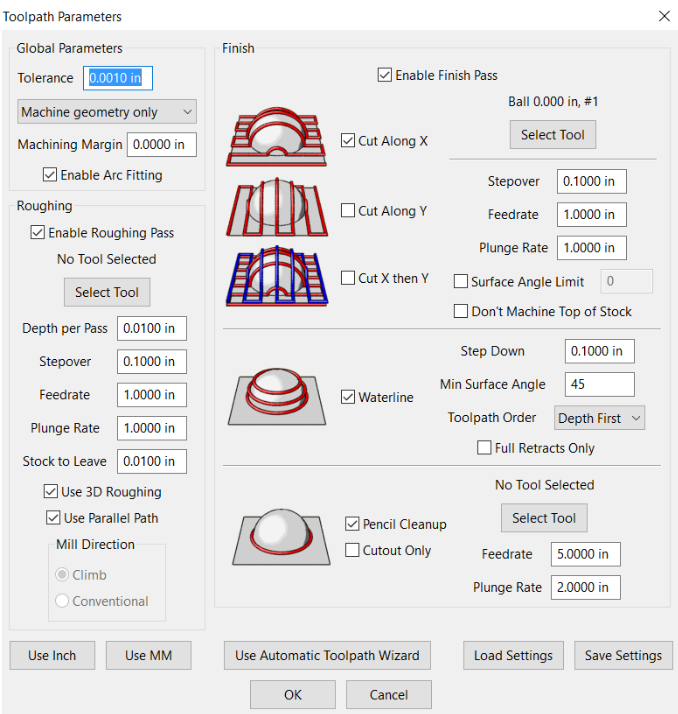


Figure 11 - Toolpath parameters

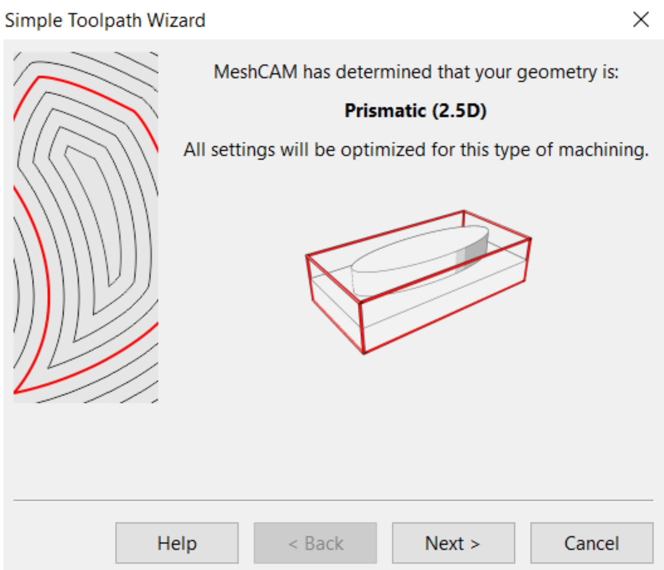


Figure 12 - Toolpath wizard

MeshCAM also supports a tool library which enables the user to quickly select the correct tool and possibly even the material as well. However, this tool library does need to be generated by a third party or the user themselves.

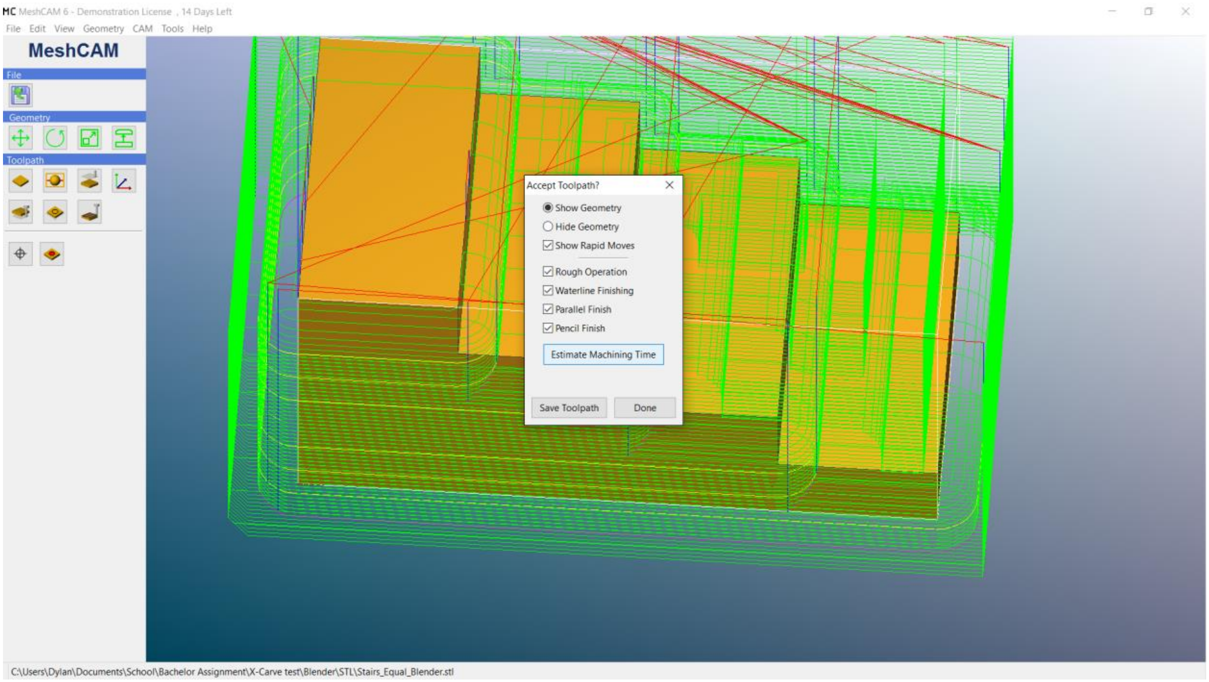


Figure 13 - Generated toolpath

After inputting all the settings or using the toolpath wizard. MeshCAM can generate a toolpath *(Figure 13)*, which gives the option for several roughing and finishing strategies and the possibility to display cutting time for the given operation.

Concluding, MeshCAM is a very simple piece of software which is easy to dive into and is very streamlined and quick to generate a working toolpath for almost any kind of 3D format.
There is a downside however, in that the software has a lot of different settings and parameters, which can be daunting to an inexperienced user. This could, however be rather easily be fixed by providing a correct and working tool library so the user can easily select the correct tool and use the toolpath wizard to generate the final toolpath and roughing strategy. Another downside is that MeshCAM is a paid software while Fusion360 is free for students.

Siemens NX
Siemens NX is a rather complex piece of software. It offers an immense spectrum of functionality. However, this means that it is inherently very complex. Even for me as an advanced SolidWorks user. As the software and its workflow will have to be grasped by even the most inexperienced user, this rules it out to be as the idea is to make the X-Carve and its software easier to use, not harder.

Conclusion
From the research conducted, it can be concluded that both Fusion360 and MeshCAM provide a good amount of features and possibilities, which can both be accessed and used rather easily. The choice eventually goes to Fusion, for the fact that it offers more features to the advanced user and it offers some explanation of what it is doing. It also provides a very nice and clear simulation of the generated toolpath and is completely free.
The Combination SolidWorks/Blender → Fusion360 → ChiliPeppr will be the one used in the rest of the process.

Reflection on Society and Technology

Reflection on adaptation of the X-Carve to the IDE educational track.

Introduction

For my bachelor assigment I was tasked with enabling and improving use of the X-Carve CNC mill within the educational track of IDE, among others.

To achieve this, I started writing a guide on using the X-Carve, which eventually turned into an interactive guide, enabling the user to more quickly and easily learn to use the X-Carve.

To get a clearer understanding of the X-Carve and the proposed manual, a small introduction is needed.

The X-Carve is an open source, 3-axial Computer Numerical Control (CNC) carving device. Generally used to carve 3D-shapes from a larger piece of solid material. As this machine is rather complex in its use, especially to new users, a form of manual or step-by-step guide is needed to speed up and streamline use of the machine.

A guide or manual, in a sense, can be seen as technology. Therefore its influence and, more importantly, its interaction with the user, can be analysed through the mediation theory proposed by *(Dorrestijn, 2012)*[1].

The question asked concerning the X-Carve and the manual designed then becomes: *"What forms of mediation does the designed manual embody and in which way does this embodiment change throughout the usage of the manual?"*

The proposed manual can be seen as a tool which the user can employ to more easily make use of the X-Carve. It is not a tool in its physical form. More accurately, it is something which is present throughout the use of the X-Carve and as such, embodies several forms of mediation. Which forms of mediation are embodied changes throughout the process of using, and working with, the X-Carve. As the user becomes more experienced in using the X-Carve, his or her relation with the manual will change, from a more pronounced and active one, to one which takes place in the background. Almost fading with time and experience.

As such, two different theories of mediation as proposed by *(Dorrestijn, 2012)*[1] can be applied: *Before the eye* and *behind the back.* Although these two theories could be seen as separate, both are present at all times in a form of synergy. Almost from the very start of the interaction the user has with the manual.

Both theories will be treated separately first, describing their embodiment through the manual. After which the synergetic relation of both, which will be treated as well, should already become much clearer.

Analysis

First, the seemingly most logical embodiment will be analysed: *Before the eye.*

In *Theories and Figures of Technical Mediation* Dorrestijn describes the "*Before the eye"* theory as follows: ***"Before the eye denotes mediation effects that work by addressing human decision making."*** *(Dorrestijn, 2012 p.06)*[1]

The manual in a sense embodies this theory as it, in a way, addresses the decision making of the user and forms and streamlines said process. While the manual tells the reader what action to perform at which time, there is a certain freedom built-in through the very nature of the interaction between the user and the manual. First of all, the user chooses to consult the manual. Either to learn to use the X-Carve, or to improve his or her knowledge of certain aspects he or she already has an understanding of. Secondly, the user is completely free in his or her decision to actually complete the actions described in the manual. These actions could be seen more as a recommendation, telling

the user which way is the best, although it might not necessarily be the best way.
Looking at these influences, the manual seems to occupy a function somewhere between *coercion* and *persuasion* depending on the way it is used.
A less experienced user, be it a new user, or someone who has already learned to use the X-Carve according to said manual, will find that the manual will function more or less according to the *coercion* principle. Also denoted as guidance, this principle suggests possible use of the product to the user. This would usually be applied to a physical product, but can be applied to the manual just as easily. The manual coerces the user into using the X-Carve and its peripherals in a certain way, without trying to change existing behaviour, as this is not yet present in a non-experienced user.

However, a user who is already used to working with the X-Carve might experience the manual to have more of a persuasive influence. This user has already possibly developed his or her own way of using the X-Carve and in such a case the manual might well offer a different, possibly better way to perform certain actions. This indicates that the influence of the manual changes to a more persuasive one, as it is, in a certain way, changing the behaviour of the user towards the intended product.

The more experienced user described above brings us to the second theory embodied by the manual: The *behind the back* theory, which Dorrestijn notes ***"… as it were behind the back. In the last case, technologies may constitute an environment that directs human history like a river bedding determines the river flow, …"*** *(Dorrestijn, 2012 p.05)*[1]
Combine this theory with a similar human-technology relationship mentioned by Verbeek; the background relationship, which functions as ***"…technologies play a role at the background of our experience, creating a context for our perceptions."***, *(Verbeek, 2005 p.01)*[2] and we can describe the change that happens in the embodiment the manual represents as the user becomes more experienced with the X-Carve.

As the user becomes more experienced he or she will start using the manual less and less. Before it was something which was consciously used and present at most times during the usage of the machine. However, as the experience of the user increases, he or she will start to memorize certain steps and procedures taught through the manual. The manual then, starts to change in influence from an active foreground role to a more secluded background role. It still influences the decisions the user makes, as the knowledge provided is stored in the users brain. But it does not do so in as much a tangible way.
This way, during the usage process of the manual and, of course, the X-Carve, the theories embodied by the manual change. Showing a very nice example of how technology interacts with the user and vice versa, changing the method of interaction in the process.

Evaluation

The evaluation will be used to evaluate the research question stated earlier: *"What forms of mediation does the designed manual embody and in which way does this embodiment change throughout the usage of the manual?"*

We can conclude that the manual embodies several forms of mediation, depending on the user's experience. Starting with the non-experienced user, the mediation experienced can be classified as before the eye, specifically being a form of *coercion.* A user who already has experience using the X-Carve before using the manual experiences the same mediation but in a more persuasive form.

Throughout the use of the manual, the user gains experience with the X-Carve and learns new techniques and methodologies. Leading to the manual being used less and less and the mediation changing to a more behind the back or background form. The knowledge is already present in the user's mind and does not need to come from a manual anymore. At any time during this conversion process from before the eye to behind the back, both influences are present in different amounts, changing with experience.

This does not mean that the before the eye relation disappears altogether. It might, eventually. But that would mean that the user does not need to use the manual anymore as all knowledge in the manual has been stored in his or her brain. Making the manual, and thus its technological relation with the user obsolete.

Conclusion

From the analysis and evaluation, certain conclusions can be drawn.

The first being that, even though a (digital) manual is not a tangible product, it is still a technology. As such, it is able to interact with the user, and change the principle and relationship of this interaction throughout the process.

The second being that a product or technology can embody several forms of mediation, even at the same time, all be it in different amounts. In turn, the interaction between product and user changes these, sometimes changing the form of mediation altogether (think of the coercion/persuasion example given earlier).

Outlook

In the analysis the X-Carve and the manual were seen as a separate entity. The manual being the product which was analysed, more or less making the X-Carve a negligible influence for simplicity's sake. However, as the manual is more or less a portal to using the X-Carve, there is a certain interaction between the two and the manual becomes more of a means of interacting with the X-Carve. Telling the user how to use the machine, almost like an affordance might. A good next step might be to take this relationship into account and rephrase the research question in light of the previous comment.

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Adaptation of the X-Curve to SPL calibration