Abstract

Creating and learning together will be the future. DIY/DIT: do it yourself, do it together. Technology is no longer only the pure mass production in specialized companies, but also the independent production of unique pieces.

However, if you have little or no experience with fabrication of some kind, or when you are in a new environment with different machinery and technology, fabricating independently is mostly not that approachable yet. The challenge was to study and enhance fabrication environments to make them more approachable, user-friendly and easier accessible. By developing a digital assistant, there is no need for a supervisor or a helping hand from an experienced user anymore.

After a broad study of the Makerspace and its visitors through interviews and field studies, some prototypes and tools were created with a user centred design approach. With active involvement of some end users and a clear understanding of the requirements for the users and tasks, iterations of design solutions have been made. A digital assistant is created by combining an object scanner with a camera and augmented reality for editing the digital model. With ease of use in mind, this model creating application and process is developed with the focus on some specific situations, technologies and machinery.

The digital assistant that helps creating models ready for fabrication, made independent working at the Makerspace better possible and is applicable in other fabrication environments and different technology facets.

Dutch Summary

Interactief voorwerpen meten en modelleren voor digitale fabricatie

Introductie en Motivatie

Technologie is niet enkel meer de pure massaproductie in gespecialiseerde firma's, maar daarnaast ook het zelfstandig fabriceren van unieke stukken. Dit kan men doen in fabricatielaboratoria. Het is een grote uitdaging om zelfstandig werken in deze omgeving toegankelijk te maken, vooral voor bezoekers zonder technische voorkennis. Om dit toch te realiseren, wordt in deze thesis een digitale assistent voorgesteld.

Gerelateerd Werk

De eerste stap in dit onderzoek was het verkennen van reeds eerder ontwikkelde toepassingen om fabricatieprocessen eenvoudiger te maken. Daarom werd gestart met een literatuurstudie en analyse van bestaande videodemonstraties.

De *Smart Makerspace* [1] is een platform om te werken waar gereedschap begeleiding, domeinkennis, veiligheidswaarschuwingen, gebruik van elektrische apparaten, advies, slimme tools, component herkenning en aanduiding, taakinstructies en taakoverzicht worden gegeven. Aangepaste elektrische apparaten worden toegevoegd zodat het systeem de huidige toestand en locatie kent. Alle informatie en feedback worden gekoppeld aan taken en instructies op een manier die de *Smart Makerspace* door uw doe-het-zelf project zal leiden.

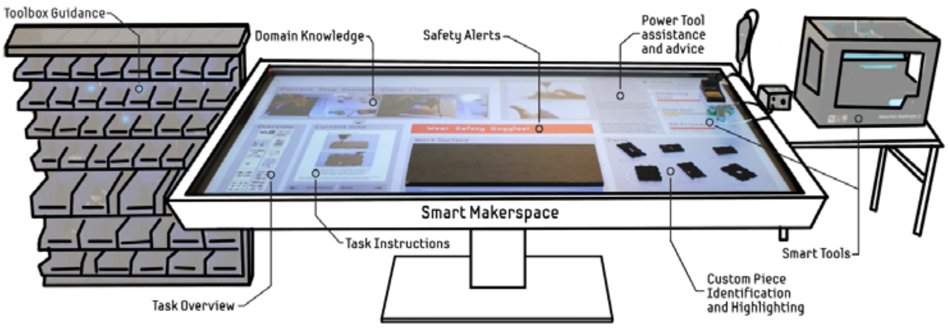

Figure 1. De Smart Makerspace, gefocust rond een slimme werkbank en gereedschap [1]. *(Bron: "Smart Makerspace"* [1]*, 2015)*

Het blijkt dat verhoogde verbinding tussen onderdelen en gereedschappen leidt tot goede feedback van het systeem die kan worden gebruikt om ondernemende en instructieve omgevingen te creëren. Verder onderzoek is gedaan naar het verbeteren van gereedschappen en prototypes, naar het gebruik van traditionele technieken op een innovatieve manier en naar fabricatie als een extensie op bestaande producten.

Mogelijkheid tot het oefenen van een bepaalde fabricagetechniek is er niet altijd, bijvoorbeeld wanneer er maar één werkstuk geproduceerd moet worden. Daarom zijn er reeds verschillende elektrische gereedschappen gecreëerd zodat ze feedback geven en voortgang bijhouden. Zo kunnen real-time tutorials gegeven worden waarbij instructies aan de gebruiker worden gegeven wanneer ze nodig zijn. De feedback en instructies kunnen geprojecteerd worden waar ze van toepassing zijn, dit wordt dan "augmented gereedschap" genoemd. Gecombineerd met het bijhouden van de voortgang van het hele project, kan zulk augmented gereedschap een grote hulp zijn. Zelfs voor ervaren gebruikers blijft project afhankelijke informatie handig en tijdbesparend.

Om zelfstandig fabriceren meer toegankelijk te maken, is het ook een goede aanpak om gebruik te maken van traditionele technieken die al gekend zijn, maar toegepast op een innovatieve manier. Een voorbeeld van een welgekende traditionele techniek is printen op papier met een gewone printer. Uit bestudeerde werken blijkt dat men nu ook elektronische circuits op deze manier kan uitprinten, zonder dat daarvoor uitgebreide kennis over printplaatontwerp nodig is. Een extra voordeel van deze techniek is dat de uitgeprinte elektronische circuits ook buigbaar zijn. Dit maakt ze heel geschikt om toe te voegen aan prototypes gemaakt van constructiematerialen. Een andere techniek is laser cutten. De laser cutter wordt veel gebruikt om 2D objecten uit te snijden, maar men zoekt meer en meer naar innovatieve manieren om met deze snelle en precieze manier ook 3D objecten te creëren.

In een derde luik werd fabricatie als uitbreiding op bestaande producten bestudeerd, zowel binnen als buiten fabricage-omgevingen. Uit studie blijkt dat fabricatie evolueert van industrie naar doe-het-zelf fabricage, toegankelijk voor iedereen [2]. Veel mechanische problemen werden vroeger opgelost door mecaniciens. Maar tegenwoordig worden, door de opkomst van 3D printers, laser cutters en computergestuurde machines, veel problemen door onervaren personen zelf opgelost door het fabriceren van mechanische onderdelen. Dit is niet voor iedereen een gemakkelijke stap, zeker indien men geen informatica-achtergrond heeft. Daarom worden omgevingen ontwikkeld waar de combinatie van fysieke objecten en digitale toevoegingen zoals projecties het handig maken om te fabriceren, zelfs zonder voorkennis van de technologie die achterliggend gebruikt wordt. Deze omgevingen maken gebruik van 'augmented reality' en worden ook wel 'mixed-reality' omgevingen genoemd.

Digitale Assistent Vereisten

Het doel van deze thesis is een grondige gebruikersstudie uit te voeren en de noden te bepalen van de mensen die zelfstandig willen werken in fabricatielaboratoria. De volgende stap is de ontwikkeling van een systeem om mensen met weinig of geen technische achtergrondkennis hierin te ondersteunen.

Om de noden van gebruikers te bepalen, werd er eerst een grondige studie uitgevoerd in de Makerspace, een ‘maaklabo’ in de PXL/UHasselt waar fabricagetools aanwezig zijn voor het creëren van prototypes. Om waardevolle antwoorden te verzamelen, werd vooraf een vragenlijst opgesteld. De focus van de studie was gericht op volwassen studenten en professionele gebruikers voor zakelijke doeleinden. Een veldstudie werd uitgevoerd door de gebruikers te observeren, gevolgd door persoonlijke interviews met een vragenlijst. De vragen zijn opgedeeld in drie categorieën: achtergrond, fabricage en evaluatie. Dit was nodig omdat de makers zelden in één sessie klaar waren met heel het fabricageproces. Op deze manier konden de interviews in sessies afgenomen worden.

Veel van de geïnterviewde personen in de Makerspace volgen technisch hoger onderwijs of ingenieursstudies, maar een groot gedeelte van deze studenten hebben geen technische middelbare opleiding gehad. Daardoor is de Makerspace ook voor hen vaak een eerste kennismaking met techniek. Wanneer de bezoekers wel al ervaring hebben met fabriceren, is deze vaak beperkt tot enkele keren iets gelijkaardigs fabriceren. Het is laagdrempeliger om iets te fabriceren waar men al enige ervaring mee heeft, dan een onbekende technologie te gebruiken. De interviews maakten duidelijk dat een veel gebruikt apparaat de laser cutter was, zowel voor nieuwe bezoekers als voor de meer ervarene.

Er wordt veel gekozen voor zelf fabriceren omdat men unieke stukken wilt maken die men niet standaard ergens kan bestellen. Belangrijke redenen om zelf te fabriceren zijn ook dat er op deze manier veel onmiddellijke feedback is, en dat het proces veel sneller is dan een uitbesteding. De meest gecreëerde items maken onderdeel uit van iteraties van prototypes. In de Makerspace hebben veel gebruikers, of groepjes van gebruikers, een verschillende manier van aanpak en verschillend stappenplan, terwijl ze wel gelijkaardige processen beogen. Meestal worden stappen vergeten, waardoor men in de assemblage nog extra hulpmiddelen moet fabriceren ter ondersteuning. De meest verwachte moeilijkheden hebben te maken met de eigenschappen van de gemaakte technische tekening. Daaraan gekoppeld zijn er velen die niet goed weten of het idee wat ze in gedachten hadden en waarvan ze een tekening gemaakt hebben, ook zal overeenkomen met het gefabriceerde eindproduct. Efficiënt tijdsgebruik tijdens het fabricageproces bleek ook een bekommernis van veel bezoekers.

Na het fabriceren bleken de verwachtingen over de moeilijkheden met de tekeningen overeen te komen met de effectieve problemen waarmee men te maken had. Daarnaast bleek ook het meten een struikelblok en dat had niemand van de geïnterviewde personen op voorhand verwacht. Meten bleek moeilijker en meer tijdrovend dan gedacht, en er werden ook regelmatig meetfouten gemaakt waardoor er extra iteraties nodig waren om werkstukken te verbeteren of opnieuw te maken. Aan de geïnterviewde personen werd gevraagd of ze een andere aanpak zouden gebruiken, met de opgedane kennis in het achterhoofd, wanneer ze een nieuw gelijkaardig product zouden moeten ontwerpen. Ze bleken een andere aanpak te wensen indien een meer tijdbesparende technologie ook mogelijk was, bijvoorbeeld waar mogelijk door gebruik van de laser cutter in plaats van de 3D printer. Ook zou men veel meer gaan tekenen met de assemblage in het achterhoofd. Meten, en vooral correct meten, is daarvoor uiterst belangrijk.

De veldstudie en interviews in de Makerspace toonden aan dat er nood is aan ondersteuning in het gebruik van gereedschap en machines om zelfstandig werken gemakkelijker en toegankelijker te maken. Hulp bij het meten en afstemmen van het idee op het eindproduct zijn essentieel. Om een oplossing hiervoor aan te bieden wordt een systeem voorgesteld waarmee men kan meten en onmiddellijk feedback verkrijgen. Later zal ook modelbewerking in het proces komen om zo de verschillen tussen idee en eindproduct te minimaliseren.

Objecten Meten en Modelleren

Om objecten te meten in het systeem, is er een camera nodig om deze beelden vast te leggen. Een projector boven de werktafel kan onmiddellijke feedback projecteren bovenop het fysieke object. Dit geeft een 'augmented reality' omgeving waar men zich beter kan voorstellen hoe een mogelijk eindproduct er zal uit zien.

Een eerste vereenvoudigd systeem is het meten in 2D door gebruik te maken van een gewone scanner. Feedback, aanduidingen en mogelijke wijzigingen aan de gescande tekening worden digitaal weergegeven op een computerscherm. Het meetalgoritme gaat eerst de pixels aanduiden die tot de tekening of het object behoren en vervolgens doormiddel van de pixeldichtheid de werkelijke maten berekenen. Het resultaat met feedback wordt op het scherm weergegeven.

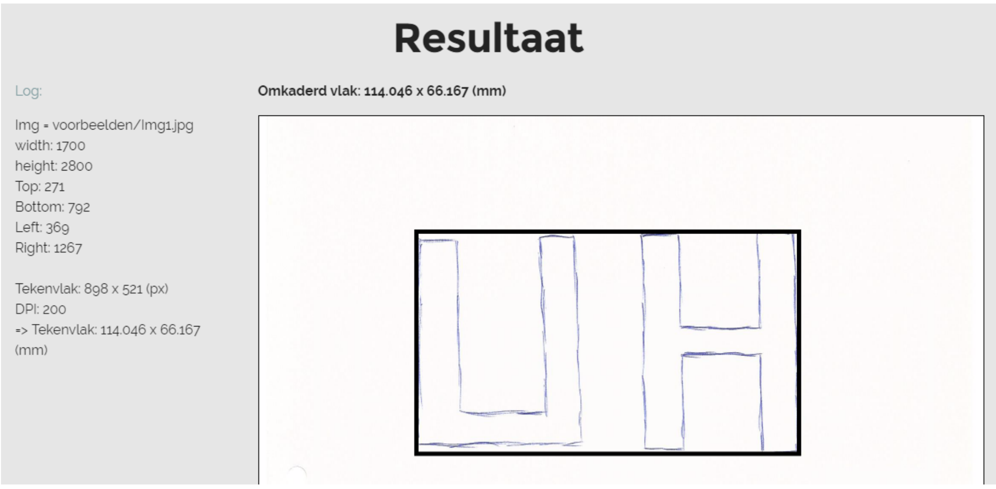

Figure 2. Resultaat met feedback op het scherm weergegeven.

In 3D-ruimte meten is voor veel meer situaties van toepassing, bijvoorbeeld wanneer de doelstelling is om een voorwerp te maken dat in een ander voorwerp past. Daarom is een opstelling gemaakt met een visiecamera om voorwerpen te kunnen meten, een computer met applicatie en een handige interface om het model te bewerken, en tenslotte een projector om live een voorvertoning bovenop het fysieke object te kunnen weergegeven in ‘augmented reality’.

Om de gebruiker een goed begrip te geven van wat het systeem doet, kan er uitgebreide feedback gegeven worden in het systeem zelf. Tijdens het meten gebeurt dit bijvoorbeeld door aanduiding van alle pixels die tot het gemeten object behoren. De basisinformatie zal altijd weergeven worden tijdens het meten. Na het meten worden de resultaten op het scherm weergegeven, en al dan niet kunnen hieraan automatische verdere acties gekoppeld worden. De toepassing in deze thesis maakt het mogelijk om met de meetresultaten een model te creëren en te bewerken in de ‘augmented reality’ omgeving.

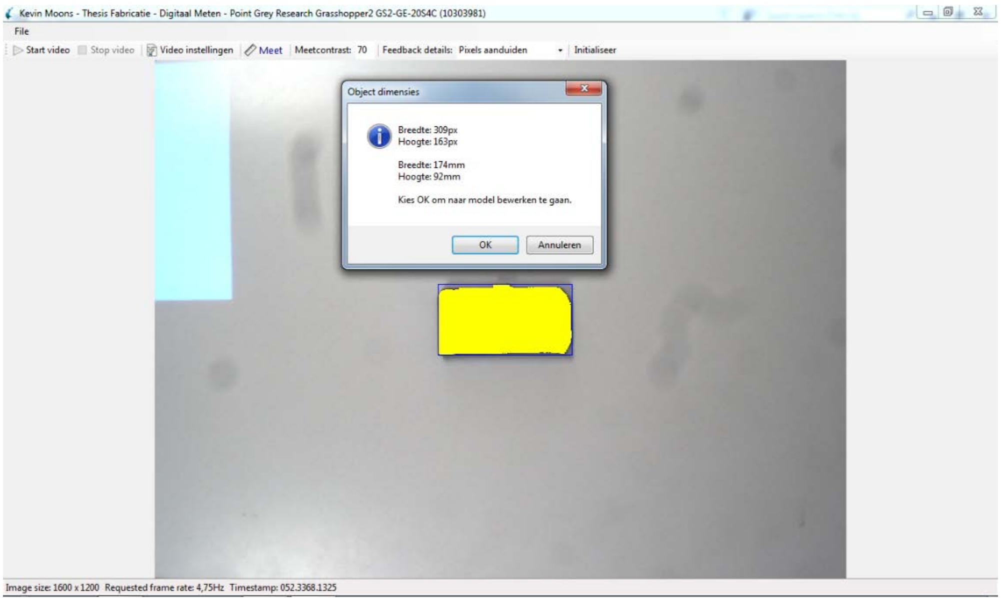

Figure 3. De interface van het meet gedeelte, met resultaten en feedback weergegeven.

In de applicatie kan men bijvoorbeeld een omkadering of behuizing maken voor het gemeten voorwerp. Bewerken van het aangemaakte model kan door gebruik te maken van een schuifregelaar of door numerieke input te geven om een bepaalde ruimte rondom het voorwerp te creëren. Deze ruimte zal op het scherm weergegeven worden, maar ook geprojecteerd bovenop het fysieke object. Zo kan de gebruiker een heel goed zicht krijgen hoe het eindproduct er uit zal zien, en uitproberen of de gecreëerde ruimte naar wens is.

Figure 4. Augmented reality projectie van de offset.

Wanneer de gebruiker tevreden is van de voorvertoning, kan het gemaakte model geëxporteerd worden naar PDF-formaat. Dit document met het object in vectoren kan geïmporteerd worden in Inkscape of andere modeleringssoftware. Inkscape wordt veel gebruikt door de makers in de Makerspace. Het geïmporteerde ontwerp is klaar om uitgevoerd en geprint te worden met behulp van bijvoorbeeld de laser cutter.

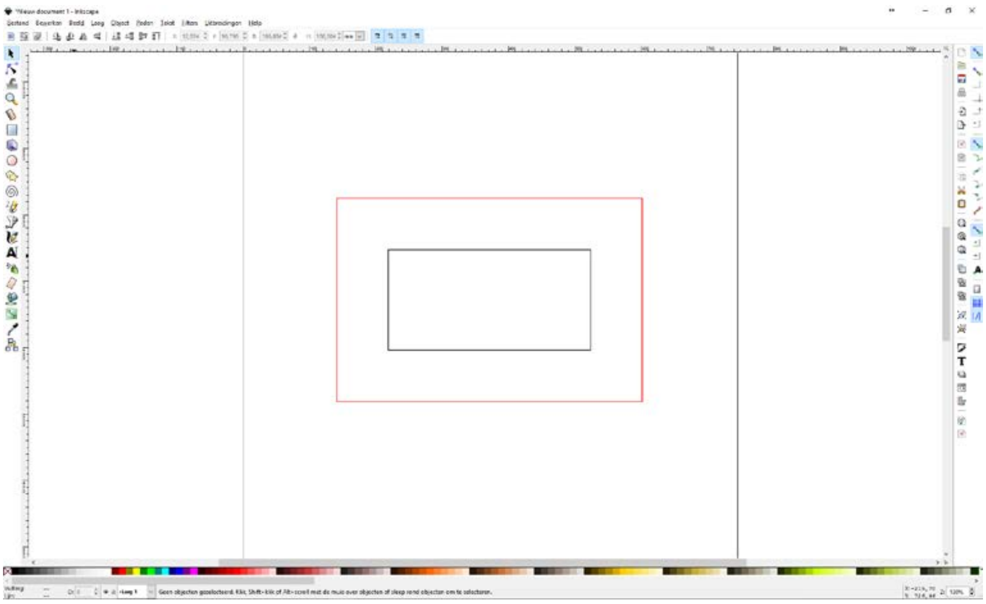

Figure 5. Resultaat: tekening van het model in Inkscape.

Evaluatie

Tijdens de ontwikkeling van de meet- en modelleerapplicatie zijn gebruikerstesten georganiseerd. Om te testen of het gecreëerde prototype voldoet aan de eisen, bestonden de proefpersonen uit voorgenomen eindgebruikers. Voor de onervaren gebruikers is het belangrijk dat het systeem zichzelf uitlegt en gemakkelijk is in gebruik. Ze weten ook niet uit zichzelf welke stappen achtereenvolgens uitgevoerd moeten worden, dus het systeem kan dit best ook weergeven. Voor de gebruikers met ervaring en technische kennis is het belangrijk dat er geen onnodige stappen zijn. Het systeem mag hen niet frustreren of gelimiteerd doen voelen. Het moet ook hen ondersteunen om te fabriceren. Daarom is feedback belangrijk, dit kan helpen om het vertrouwen in het systeem te versterken. Ten slotte voor de zakelijke gebruikers is het belangrijkste dat ze onmiddellijk feedback krijgen. Deze gebruikers willen experimenteren om hun idee te valideren en een product te creëren dat past in hun zaak. Daarom moet het systeem duidelijk gidsen en een intuïtieve interface hebben.

De gebruikerstesten in dit gebruikersgerichte systeemontwerp zijn uitgevoerd in een gecontroleerde omgeving waarbij de facilitator en de observator één en dezelfde persoon was. Daarom zijn de sessies opgenomen om later te kunnen hernemen en niets over het hoofd te zien. Een procedure is uitgewerkt en uitgeschreven zodat elke tester dezelfde volgt. Het laten invullen van een demografiedocument maakte het mogelijk om de ondervindingen van de testers te vergelijken met hun voorkennis. Omdat in het uiteindelijke systeem de initialisatie van het systeem automatisch dient te gebeuren, werd dit vooraf door de facilitator gedaan.

In de testen hebben de gebruikers iets gemaakt om hun bureau ordelijk te houden: een houder om voorwerpen in te leggen. Het object waarvoor de gebruiker een houder wilde maken werd gekozen en onder de camera geplaatst. Met behulp van het systeem werden vervolgens de afmetingen bepaald en werd er feedback aan de gebruiker gegeven. Wanneer het meten succesvol bleek, werd een model gecreëerd en kon men dit gaan bewerken in ‘augmented reality’. Tijdens het bewerken werden de aanpassingen zowel op het scherm getoond als op de werktafel geprojecteerd. Ten slotte, wanneer de gebruiker tevreden was van het resultaat, werd de tekening geëxporteerd naar PDF. Openen in een tekenpakket of uitprinten in 3D of laser cutten is mogelijk, maar behoorde niet meer tot de takenlijst van deze gebruikerstest.

Elf deelnemers hebben het systeem getest, en ze waren allemaal tevreden met de proces flow doorheen de applicatie. Ze vonden deze tevens duidelijk en intuïtief om te volgen. Door te testen zijn er enkele aspecten gevonden die sommige gebruikers misten. Een deel hiervan was reeds voorzien in een volgende iteratie van het prototype van het systeem. Een aantal andere aspecten bleken een zeer waardevolle toevoeging te zijn. Meten ging voor iedereen gemakkelijk, maar er zijn toch een aantal suggesties gekomen om het meten nog eenvoudiger te maken. Aanpassen van het model in ‘augmented reality’ was voor iedereen handig in gebruik, maar men wenste dit model uitgebreider te kunnen aanpassen in de applicatie. Ook extra feedback tijdens het aanpassen van het model werd gevraagd.

De deelnemers zouden de applicatie in de toekomst gebruiken voor soortgelijke fabricages, voornamelijk omdat het meten heel eenvoudig is en het aanmaken van het model zeer snel gaat in vergelijking met traditioneel meten en digitaal tekenen. Een vereiste is wel dat het systeem accuraat genoeg is, en voor sommigen is 3D-model representatie ook nodig. De onmiddellijke feedback die het systeem geeft en het feit dat er geen voorafgaande kennis nodig is, zijn ook sterke punten waarom de gebruikers het systeem opnieuw zouden gebruiken in de toekomst.

Om volledig zelfstandig werken met het systeem mogelijk te maken, is het nodig dat de stappen die de gebruiker nu op papier kreeg, mee in het systeem ingebouwd worden. Enkele gesuggereerde veranderingen aan het systeem door de test-gebruikers waren zeer taakgerelateerd, en worden daarom niet verder in beschouwing genomen. Andere kleine gebruiksvriendelijkheidaanpassingen in de user interface werden in een eerste ronde van testen ondervonden. Deze werden aangepast om een consistente interface te verkrijgen, en tijdens de andere testen bleken de hierdoor ontstane verwarringen niet meer terug te komen. De overige suggesties vielen in onderdelen van toekomstig werk in volgende iteraties.

Conclusie en Toekomstig Werk

In deze thesis is een systeem gepresenteerd dat zelfstandig werken beter toegankelijk maakt in fabricatielaboratoria, zonder de nood aan voorkennis of een technische achtergrond. Dit systeem helpt de gebruiker om fysieke voorwerpen te meten en een model hiervan te maken en te bewerken in ‘augmented reality’. Om volledig zelfstandig fabriceren te ondersteunen dienen er nog verdere stappen ondernomen te worden.

Het systeem dient uiteraard te evolueren van prototype naar volwaardig systeem waarbij de vereenvoudigingen helemaal uitgewerkt zijn. Andere algoritmen voor objectherkenning en modelbewerking dienen geïmplementeerd te worden. Vervolgens kan er verder gegaan worden door het systeem te integreren in een omgeving waar meerdere soortgelijke systemen staan. Zo wordt de gebruiker meer gestimuleerd om dingen te proberen en nieuwe technologieën en mogelijkheden te ontdekken.

Mobiele uitbreidingen zijn ook nuttig. Zo kan men bijvoorbeeld in een fabricatielabo rondgaan met een tabletapplicatie en is men niet meer gebonden aan een statisch systeem. In het huidige systeem is een visiecamera gebruikt om objecten te detecteren. Deze kan vervangen worden door een apparaat dat het hele object kan scannen en een gedetailleerd 3D-model kan teruggeven. De Kinect van Microsoft is hier een voorbeeld van. Dit apparaat maakt het ook mogelijk om de aanpassingen van het model volledig in ‘augmented reality’ mogelijk te maken, door projectie van de interface of door gebruik te maken van gebaren. Ten slotte kan men het systeem nog integreren samen met de gebruikte machine, bijvoorbeeld met een laser cutter. Zo kan men rechtstreeks de modellen gaan fabriceren wanneer de gebruiker tevreden is, zonder dat een extra tussenstap nodig is.

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1 Introduction and Motivation

"The future is creatable ... and in our hands!"

1.1 Digital assistance

The goal of this thesis is to make fabrication laboratories more accessible and usable with little or no assistance from a supervisor, even for makers with little or no experience in the field.

Digital assistance is possible in many ways. From guiding tutorials to tools that enhance independent working without the necessary experience.

To start with, days were spent at the Makerspace to get to know its facilities and machinery. Staff and visiting students were asked general questions to become familiar with followed procedures. At this point, also the observation of the users of the Makerspace has started. During the observations, much was learned about the struggles with drawings and machinery settings, the queues to do some actions, and the work that must be done manually afterwards. Many times, fixes and iterations of the prototypes were necessary. Many problems could be avoided by more guidance during the fabrication process. Of course, there cannot be a personal assistant available for everyone all the time. This is where digital assistance comes in.

Literature about personal fabrication, smart makerspaces, augmented fabrication, wearables in labs, mobile fabrication and other related topics were studied to become aware of research and solutions that are already created. More details about the literature will be given in the following chapter.

To create a prototype application of a digital assistant, it is necessary to know more about the specific needs of the users. That's why users were interviewed about their experience in the Makerspace, in a broad user field study. The first set of interviews revealed many details about the procedures that are followed on different machinery. It was very educational and it gave more insights on the struggles that users were having. But the answers on the questions of these interviews were focussed too much on technical procedures. To make a user centred design of a digital assistant application to create models ready for execution on production machinery, questions with answers that are measurable and comparable are needed. A presentation of the questions will be given with explanation and purpose of them. That section will be followed by interpreting the answers and making consequences and decisions on how to use these insights to create a working high-fidelity prototype.

Digital assistance is given through the model creating application that is developed in this thesis. With active involvement of some end users and a clear understanding of requirements for different users and tasks, iterations of design solutions have been made. A digital assistant is created by combining an object scanner with a camera and augmented reality for editing the digital model. With full user experience in mind, this model creating application and process is created with the focus on some specific situations, technologies and machinery.

The creation of the prototypes and the user tests performed are discussed in later sections of this thesis.

2 Related Work

To become aware of research and models that are already created in the world of fabrication, interesting literature with examples and video demonstrations were studied.

Smart Makerspace: An Immersive Instructional Space for Physical Tasks [1] and Wearables in the Wet Lab: A Laboratory System for Capturing and Guiding Experiments [3] were proposed as starting points in the literature study.

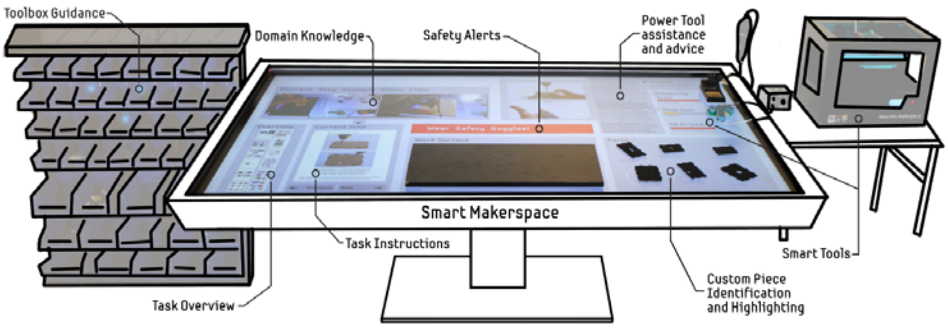

Figure 6. The Smart Makerspace. Focused around a smart workbench, toolbox and power-tools, the Smart Makerspace provides an immersive, integrated instructional experience for novice makers [1]. *(Source: "Smart Makerspace"* [1], *2015)*

The *Smart Makerspace* is "a context-rich, immersive instructional workspace for novice and intermediate makers" [1]. It's a platform to work on where toolbox guidance, domain knowledge, safety alerts, power tool assistance and advice, smart tools, custom piece identification and highlighting, task instructions and task overview is given. Augmented power-tools are added such that the system knows its current state and location. All the information and feedback is coupled with tasks and instructions in a way that the Smart Makerspace will guide you through your DIY project. The paper concludes that it provides "a rich instructional experience for physical tasks" [1]. It is shown that increased connectivity leads to great feedback from the system that can be used to create immersive instructional environments. To create connectivity in an interactive way, two kinds of devices are needed and need to be connect in the *Internet of Things* concept. One group are sensors and devices to let the system be aware of its environment e.g. knowing if tools are in use and where they are, determining materials and tools, ... The other group are devices that provide the user with feedback from the system. These devices are often also providing input for the system themselves, making them even more interesting to use. E.g. the Smart Makerspace's table/screen provides a lot of feedback and is also identifying custom pieces.

Interesting examples of devices providing feedback are wearables: a smaller shift of attention is needed to learn about given feedback. *Wearables in the Wet Lab* [3] is describing a situation and some super useful wearables to enhance the wet laboratory environment.

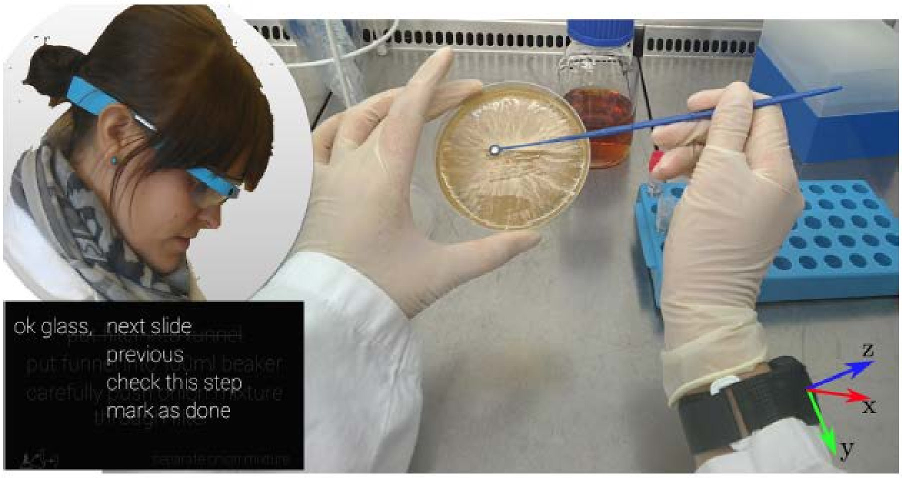

Figure 7. A hands-free wearable system combines Google's Glass (top-left) with a wrist-worn accelerometer logger (lower-right) to allow capturing and reviewing of experiments in a wet laboratory environment [3]*. (Source: "Wearables in the Wet Lab: A Laboratory System for Capturing and Guiding Experiments"* [3]*, 2015)*

Wearables in the Wet Lab presented a "hands-free wearable system to support experimenters in a wet laboratory environment" [3]. It is an inspiring paper and it shows that thinking out-of-the-box can lead to great combinations of wearables and other devices to enhance fabrication/laboratory environments.

With the knowledge from previous papers in mind, research about fabrication leads through many interesting projects and papers. This goes from enhancement of tools and prototypes to using traditional techniques in innovative ways and fabrication as an extension on existing products in and out of fabrication environments. These categories are the structure of the following literature study.

2.1 Tools to Enhance Interactive Fabrication

Fabrication can be a big challenge to people who have no experience in the field, or with a certain type of machinery or set of materials. It is not always possible to exercise on a fabrication technique when only one part has to be created. "Mapping techniques from software tutorials onto physical craft processes can assist novices in building multi-material assemblies [4]." If Smart Power Tools are created in a way that they provide feedback and progress tracking, real-time tutorials and instructions can be given to the user. *Drill Sergeant: Supporting Physical Construction Projects through an Ecosystem of Augmented Tools* [4] demonstrates how smart tools and techniques can be enabled by augmenting workshop tools. An example is distance measurement to determine depth of a drill. With a laser distance finder, proper holding of the drill can be guided.

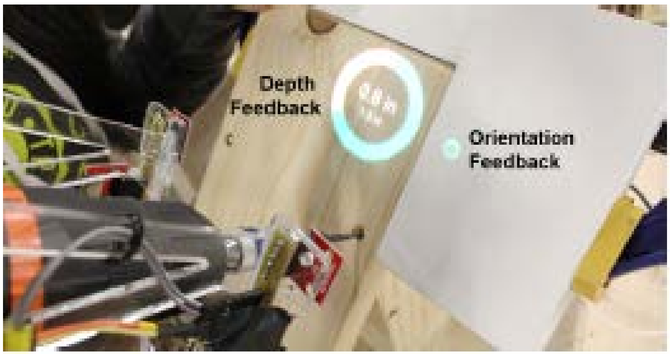

Figure 8. Users are given perpendicularity and depth feedback while drilling. (Source: "Drill Sergeant: Supporting Physical Construction Projects Through an Ecosystem of Augmented Tools" [4]*, 2016)*

Combined with progress tracking of the project to fabricate different parts, such augmented tools can be a big help. When more experience with certain tools and materials is gained, these augmented tools can be less necessary, but project-dependent information and progress tracking will always be helpful and time-saving. Another example is the projection of drawings on materials: drawing them onto construction materials can be time consuming. Drawing on a computer will also take time and will remove users from the workpiece. Projecting on working materials can be a solution. *Interactive Construction: Interactive Fabrication of Functional Mechanical Devices* [5] states that "recent interactive fabrication tools reintroduce this directness, but at the expense of precision" [5]. This makes interactive fabrication suitable for creating (rapid) prototypes. The paper introduces 'constructable': "users interact by drafting directly on the workpiece with hand-held lasers". A laser cutter then cuts the desired lines into the workpiece.

Figure 9. Constructable users interact by drafting directly on the workpiece with hand-held lasers. (Source: "Interactive Lasercutting" [5]*, 2012)*

When necessary quick adjustments can be made with this way of working. Of course, when material is cut away, it cannot easily be made as a whole again. In rapid prototyping this is not a problem; a more iterative design process is mostly used in personal fabrication. "Laser cutters are one of the preferred personal fabrication devices, since they are powerful and fast [5]."

So far, a taste of enhancement of fabrication tools is presented. A big challenge exists in creating artefacts that can be used to enhance such tools. Sensing technologies are advanced nowadays and they are widely applicable. *FlexiBend: Enabling Interactivity of Multi-Part, Deformable Fabrications Using Single Shape-Sensing Strip* [6] presents "a shape-sensing strip that enables interactivity of multi-part, deformable fabrications" [6].

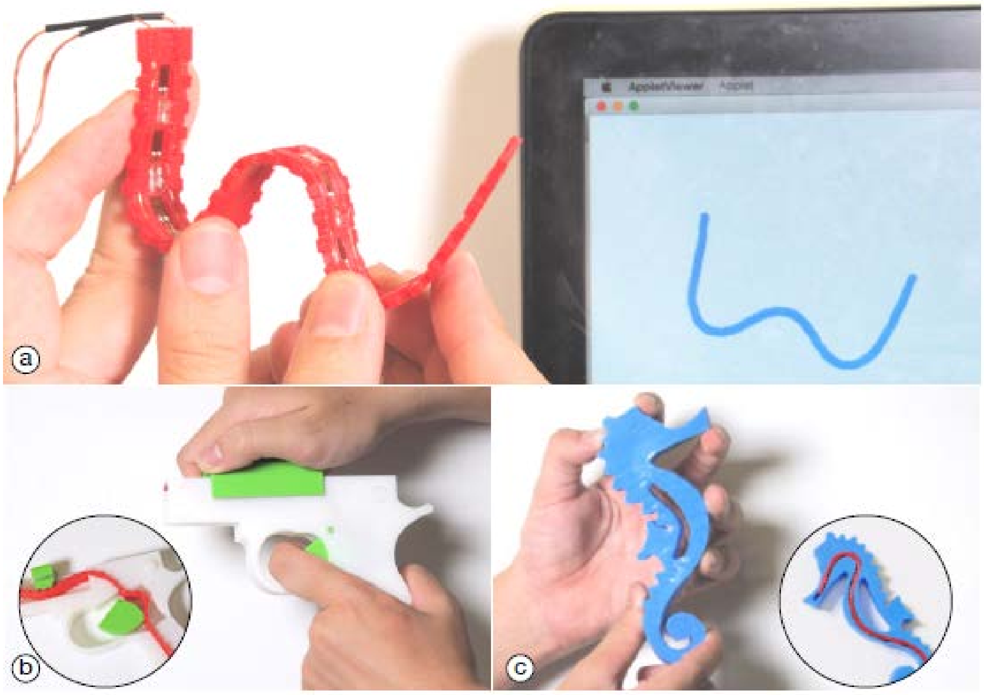

Figure 10. FlexiBend is an easily installable shape-sensing strip that enables interactivity of multi-part, deformable fabrications. (Source: "FlexiBend: Enabling Interactivity of Multi-Part, Deformable Fabrications Using Single Shape-Sensing Strip" [6]*, 2015)*

Such sensing techniques are enjoyable to make fun objects coupled with digital feedback. By adding such sensing techniques to fabrication tools, a whole new dimension of interaction and feedback in construction processes is formed. Not only 2D interaction like providing feedback on a pressed button but also 3D operations like twisting, bending and stretching can be sensed by FlexiBend. "Due to the ease of installation, makers also can reuse the FlexiBend in different physical models, which makes it a useful tool for iterative prototyping [6]." Sensing strips attached to handheld fabrication tools can provide feedback on how to put pressure in the right way on the tools.

2.2 Innovative use of Traditional Techniques

To make fabrication more accessible, a good approach is using traditional techniques in innovative ways. Traditional techniques are known by general users. If these techniques can be used to fabricate new products or prototypes, the building tools will be easy accessible.

Common in the quest to enhance fabrication are sensing techniques on devices and people. "The development of wearable, on-skin devices is still difficult and expensive [7]." To encourage building smart fabrication devices and environments, accessible on-skin devices are highly usable. *Digital Fabrication Technologies for On-Skin Electronics* [7] proposes "a new technology to print highly conductive traces and patterns onto flexible substrates such as paper and plastic films cheaply and quickly" [7]. Circuits can be printed with common inkjet printers and commercially available ink.

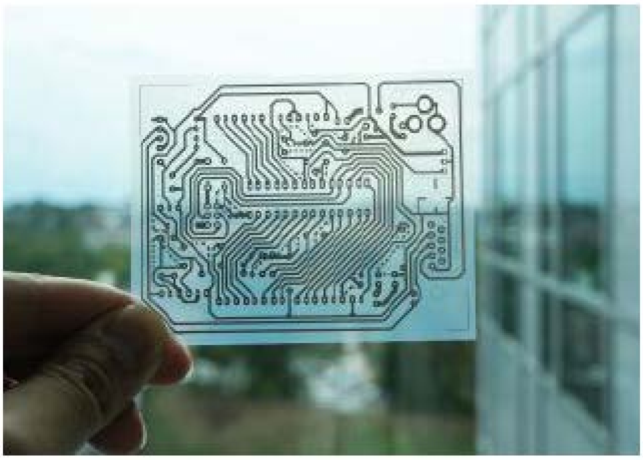

Figure 11. An Arduino circuit board printed by inkjet printing. (Source: "Digital fabrication technologies for on-skin electronics" [7]*, 2016)*

In line with On-Skin Electronics are electronics suitable for Shape-Changing Interfaces. For example, when fabricating rapid prototypes, the development of the electronics can be a real challenge: interfaces are changing quickly in iterations and electronics are mostly not that easy adaptable. *uniMorph – Fabricating Thin-Film Composites for Shape-Changing Interfaces* [8] provides inspiration to a solution in making electronics that can change shapes following the changes of the prototype's appearance. Different usage of energy, fabrication processes, sensing and electronics are presented in the paper. The technology is still in early stage, but when it gets easily implementable, it could greatly improve accessible fabrication of rapid prototypes with working electronics.

"Printem film, a novel method for the fabrication of Printed Circuit Boards for small batch/prototyping use" [9] is presented in *Printem: Instant Printed Circuit Boards with Standard Office Printers & Inks* [9]. Printing circuit boards is made possible with standard office inkjet or laser printers with the use of standard inks. Production of circuit boards with techniques described in Printem on Printem film is easy to use and inexpensive. The film is flexible because it must fit and pass-through the paper path of a printer. This property makes it usable in cases where foldable and bendable electronics are desired.

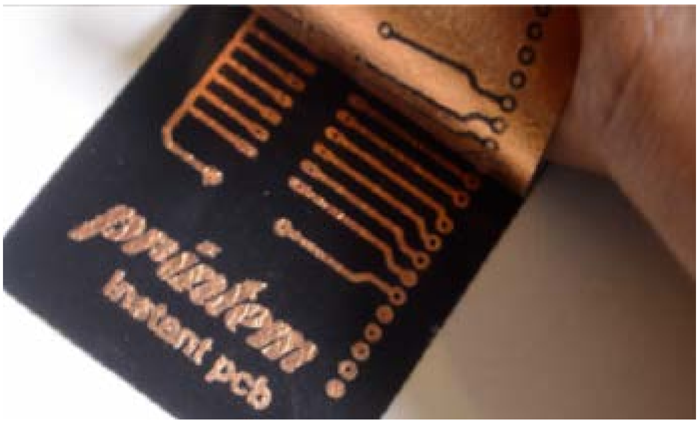

Figure 12. Printed and foldable PCB on Printem film. (Source: "Printem" [9]*, 2015)*

2.2.1 Laser cutting

Another traditional technique, with many ways of use open for exploration, is laser cutting. Lately the laser cutter is widely used in fabrication laboratories simply to cut out 2D objects from different plate materials. Since a laser cutter's overall performance is fast and precise, makers tend to use it where possible. An out of the box thinking team started *Laser Cooking: a Novel Culinary Technique for Dry Heating using a Laser Cutter and Vision Technology* [11]. A laser cutter is used as a dry-heating device. It's an example that shows how interdisciplinary approaches can lead to interesting and innovative ways to use known technologies and machinery.

Compared with 3D printers the big advantage of laser cutters is speed. While laser cutting is mostly used in 2D, it can be used in 3D too. *LaserOrigami: Laser-Cutting 3D Objects* [12] presents "a rapid prototyping system that produces 3D objects" [12], using a laser cutter. Three-dimensionality is gained by folding and stretching the material through heating up selected regions. With synthetic materials like plastics, it's known how much heat is necessary to bend a certain angle. It maintains the speed of a traditional laser cutting system and eliminates the need for manual assembly.

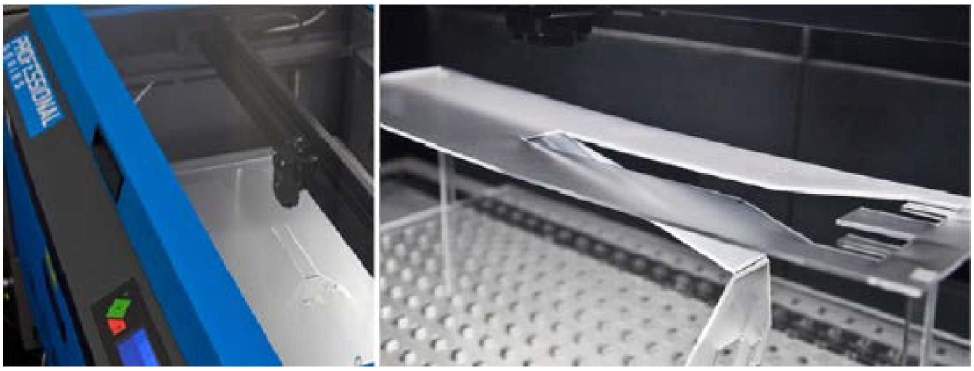

Figure 13. LaserOrigami fabricates 3D structure by bending, rather than using joints, thereby eliminating the need for manual assembly. (Source: "LaserOrigami: Laser-Cutting 3D Objects" [12]*, 2013)*

Another approach to use laser cutting in the creation of 3D objects is stacking them as layers and weld them together. The welding itself can also be done by the laser cutter. *LaserStacker: Fabricating 3D Objects by Laser Cutting and Welding* [13] explains: “The key idea is to use the laser cutter to not only cut but also to weld. Users place not one acrylic sheet, but a stack of acrylic sheets into their cutter. In a single process, LaserStacker cuts each individual layer to shape (through all layers above it), welds layers by melting material at their interface, and heals undesired cuts in higher layers. When users take out the object from the laser cutter, it is already assembled [13].”

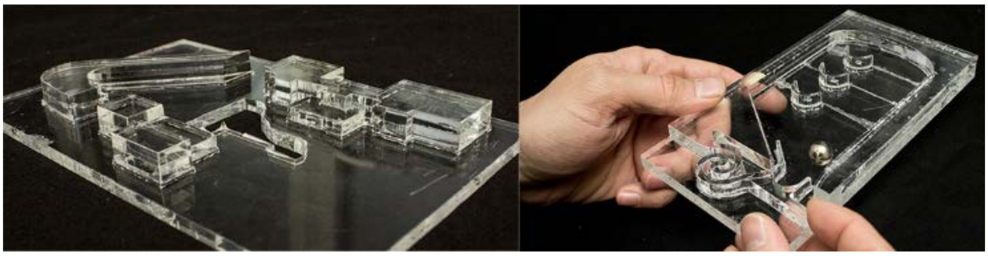

Figure 14. LaserStacker: Fabricating 3D Objects by Laser Cutting and Welding. (Source: “LaserStacker: Fabricating 3D Objects by Laser Cutting and Welding” [13]*, 2015)*

2.3 Fabrication to Repair and Extend products

Fabrication is evolving from industries to personal fabrication accessible for everyone [2]. Many mechanical problems used to be solved by a mechanical engineer. But nowadays, due to the popularity of 3D printers, laser cutters and computer-controlled machines, many problems are solved by inexperienced people themselves by manufacturing mechanical parts. In general, fabrication is frequently used to repair broken items or extend existing items. In *Towards Augmented Fabrication: Combining Fabricated and Existing Objects* [14] this is called “augmented fabrication”. This is not an easy process, because it is necessary to consider the existing item that needs to be repaired or extended.

The next big step in the future of fabrication is mobile fabrication, personal fabrication on the go, to meet the needs that are required in a certain space and time. *Mobile Fabrication* [15] presents a small and portable makers device that can be used on the go.

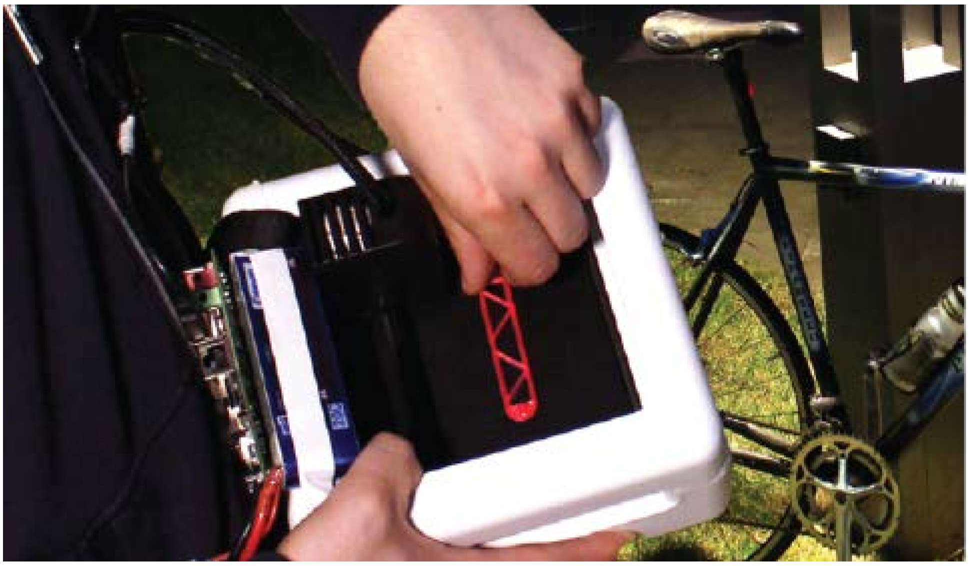

Figure 15. Personal fabrication on the go. (Source: "Mobile Fabrication" [15]*, 2016)*

Mobile fabrication is still at an early stage, but already multiple tools and approaches are presented: small 3D printers, material-printing pens, apps to help users fabricating…

The computer science step in personal fabrication is not evident for all users: most people do not have a background of computer science and have a hard time creating 3D models, CAD/CAM drawings, or use a computer at all. To tackle this problem the team behind *MixFab: A Mixed-Reality Environment for Personal Fabrication* [16] introduces an accessible way to do personal fabrication. In a mixed-reality environment users can "design objects in an immersive augmented reality environment, interact with virtual objects in a direct gestural manner and can introduce existing physical objects effortlessly into their designs" [16]. Real life objects can be placed into the mixed-reality environment and virtual reality objects can be combined with them. These virtual reality objects can be manipulated through gestures without the need of an engineering or computer science background. Once the user is convinced that the virtual object fits their needs, it will be printed out and become real and tangible.

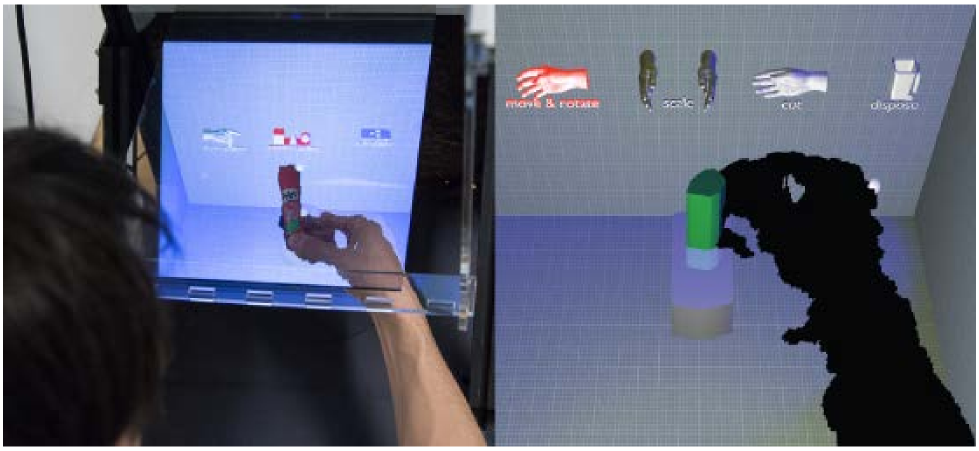

Figure 16. MixFab: mixed-reality environment for personal fabrication. (Source: “MixFab: A Mixed-Reality Environment for Personal Fabrication” [16]*, 2014)*

When printing out objects in personal fabrication, the process is currently mostly one-way: once fabricated, it cannot be changed anymore. “Any change requires printing a new version from scratch. The problem is that this approach ignores the nature of design iteration, i.e. that in subsequent iterations large parts of an object stays the same and only small parts change [17].” Again and again, fabricating from scratch consumes much time and leads to a big waste. *Patching Physical Objects* [17] demonstrates how 3D printed objects can be adapted after production. The printer uses materials that can be milled away and afterwards a new part can be printed on top. The software calculates and determines what has been changed since the previous design and tells the machinery to mill all unwanted parts away. A surface is created where is printed on again. This is not only useful in iterative design but also when an object breaks: it can easily be fixed again.

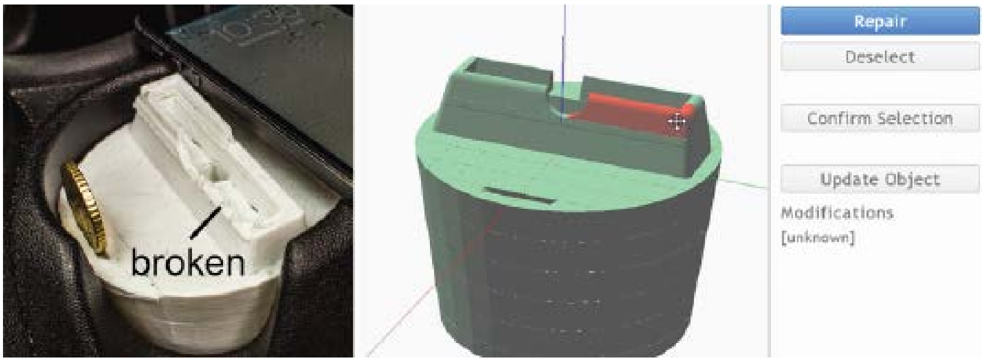

Figure 17. Broken or changed objects can be patched. (Source: “Patching Physical Objects” [17]*, 2015)*

The big challenge towards personal fabrication will always be engaging users in their daily life. *Engaging Amateurs in the Design, Fabrication, and Assembly of Electronic Devices* [18] explores personal fabrication “as a means of engaging new audiences in the creation of electronic devices” [18]. This study focusses on electronic creations but is applicable to other fields of personal fabrication. The main challenge towards personal fabrication is lowering the barrier of skills and domain knowledge necessary to be a maker. The relationship between real objects and computer models, but also the inverse relationship from computer models to real objects is not easy to understand for novice users.

In the following sections of this thesis the needs of novice users in personal fabrication is studied and a solution to close the gap between real objects and computer models is proposed.

3 Digital Assistant Requirements

The goal of this thesis was to do a thorough user study and determine the needs of people who want to work independently at fabrication laboratories like the Makerspace. With these results, a system is designed and developed to guide makers without the need for much technical knowledge.

3.1 User Study – Questionnaire

To determine the needs of the makers, a thorough user study was necessary. An introduction to the Makerspace made clear that a predefined set of questions was highly necessary to receive valuable answers, because otherwise the visitors tend to talk more about product specific technical problems.

To make fabrication laboratories more accessible and ready for independent working, the focus of the user study is aimed at adult students and professional users from small companies. A mix of unexperienced and medium experienced students and prototype developers from companies form our target respondents.

The user study has been done by observation and conducting personal interviews with a questionnaire. The questions are ordered and divided in three categories: background, fabrication and evaluation. The questionnaire was tested with some regular Makerspace visitors and fine-tuned to receive extensive answers.

3.1.1 Background of the makers

Makerspace users have a wide variety of educational and technical experience. Background questions were asked to gain more insights about their skill sets and fabrication goals. In order to create guidance tools to enhance independent working, it is necessary to know what help is needed, at which level of experience, with certain materials and machinery.

3.1.2 Before fabricating

Important to know is why users choose to fabricate themselves instead of outsourcing. After all, making independent working easier has the aim to encourage personal fabricating to a wide variety of people.

Preparation of the fabricating process is questioned to determine how users tend to start off. After the fabrication, the expected work flow can be compared to the actual followed process.

Expectations about working independently at the Makerspace and expected difficulties whilst working are also listed to compare them later with actual troubles. Misalignment of expectations and effective experience in the fabricating process were shown in the pre-study and thus further investigated.

3.1.3 Evaluation of process and product

After fabricating and finishing the workpieces, the final questions are posed to compare actual findings of the users with the expected ones.

Literature study showed that personal fabricating and prototyping in fabricating laboratories is a highly iterative process. There are questions about eventual next iterations to determine whether better and/or different approaches are possible and applicable in the process.

Final questions are about suggestions and open feedback from Makerspace users on how the fabrication laboratory would be more accessible and how working independently could be made easier.

3.2 User Study - Interviews

After following some users fabricating in the pre-study, a field study with questionnaire was held. Most Makerspace users were happy to participate when they were told that the goal of this thesis is to make fabrication laboratories easier to use without the need for intensive guidance and/or extensive technical experience. Some users were limited in time and chose to not participate at that time, but agreed to come back later when the fabrication process was finished.

To have a good idea about the needs at the Makerspace, the goal was to interview between twenty and thirty users. This goal has been achieved but was more time consuming than initially expected. The main reason it took longer than expected was because at the start of the new semester mostly inexperienced people visited the Makerspace. They needed to explore the fabrication lab to form an idea what is possible to create. Partial interviews about fabrication intentions and goals were conducted. In the second half of the semester, these interviews were concluded and interviews with more experienced users were held. The students with previous experience at the Makerspace explained that they already know what's possible there, and therefore didn't need to visit it again before starting their projects. They came mostly prepared with digital engineering drawings and a good idea of what they want. However, the actual processes they followed to fabricate were often different from the planned ones.

A nice mix of interviews from unexperienced, medium and highly experienced users together with some business users from small companies, is collected and synthesized in following section about the results. Most interviews were held with all the members of one project team together in one interview. The participants preferred to participate in this way because mostly the experience level and answers are very similar. Interesting results led to the start of a tool that makes the gap between problem and fabrication smaller with the use of computer science.

3.3 User Study – Interview Results

3.3.1 Background of the makers

During the field study period at the Makerspace, most visitors are enrolled in technical or engineering courses. There are approximately as much master students as bachelor students fabricating. Some working people, that came to make their prototypes, were also studied. Many fabrication projects by students are in group. Therefore, the interviews were also conducted in groups, so they could do this in a time-efficient way.

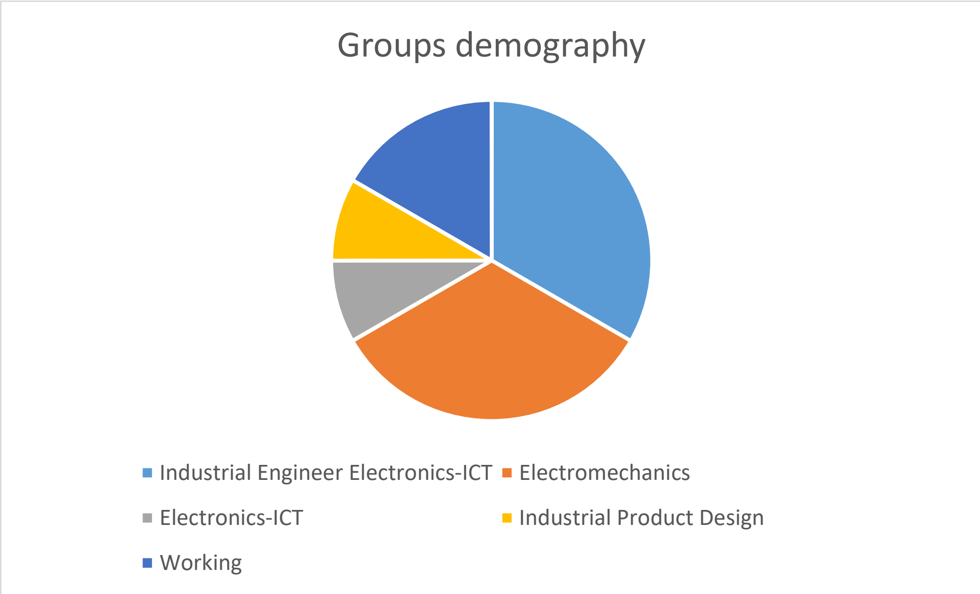

Figure 18. Groups demography Makerspace visitors.

A correlation between previous education and first experience has been explained by the students. Students with technical education in the past, find it more natural to visit workrooms or fabrication laboratories. About 60% of the visitors have a technical background.

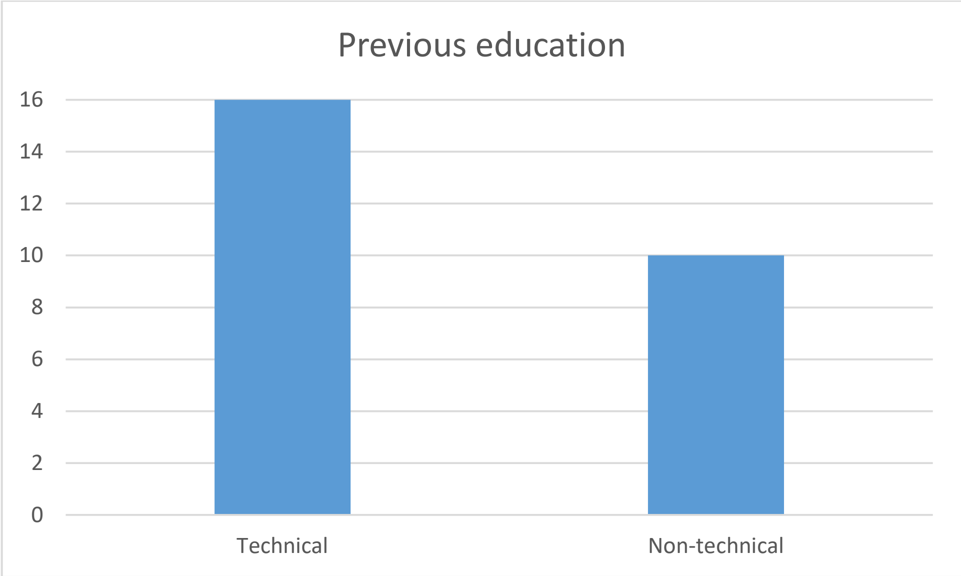

Figure 19. Previous education.

Often the respondents have previous fabrication experience, but this is mostly limited to once or a few times fabricating something similar. There is a lower threshold to manufacture new things when they have. Previous experience is often limited to one piece of machinery, eventually with some handcrafting tools to finish the products. In the Makerspace, many have experience with the laser cutter.

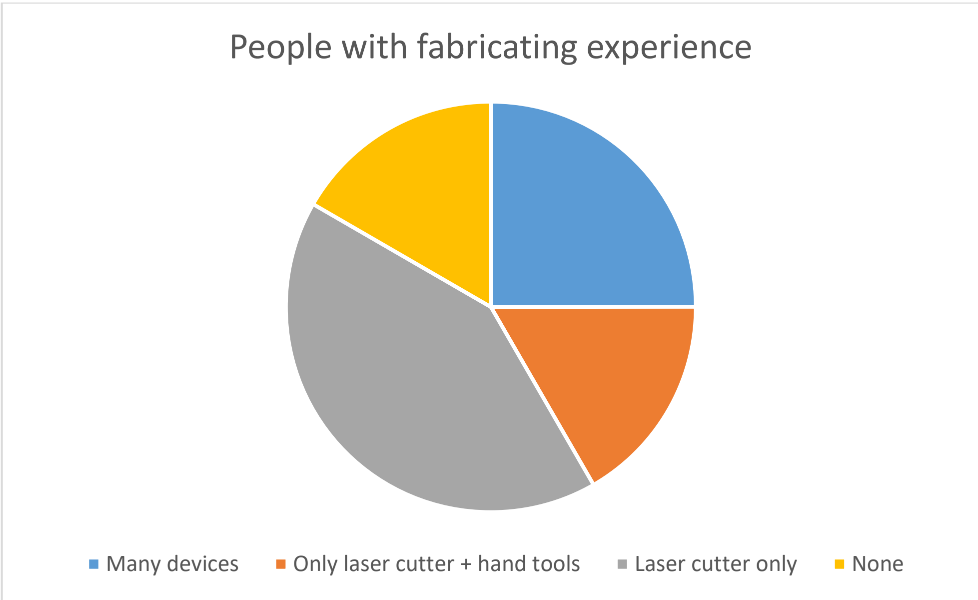

Figure 20. Previous fabrication experience at the Makerspace.

School assignments are the most reasons to fabricate. Saleable prototypes, whether school assignment or new product prototype development as business are the second most. Some are experimenting with a new product design or it's just their hobby.

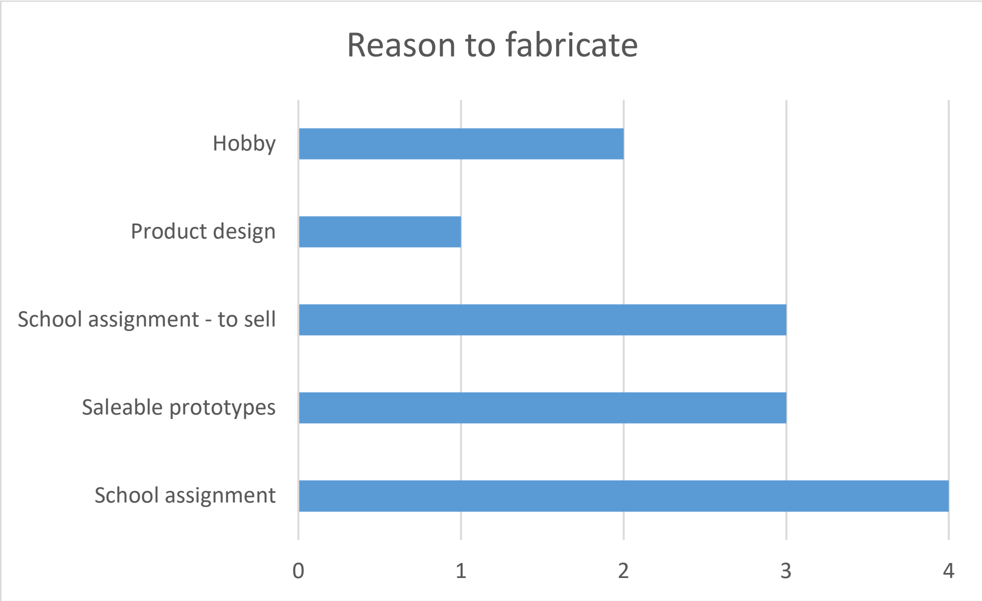

Figure 21. Reason to fabricate.

As stated earlier, most come to fabricate in groups. Teams vary between one and five people. Interesting observation were some groups where only one person did the fabrication, whilst others were doing other project work.

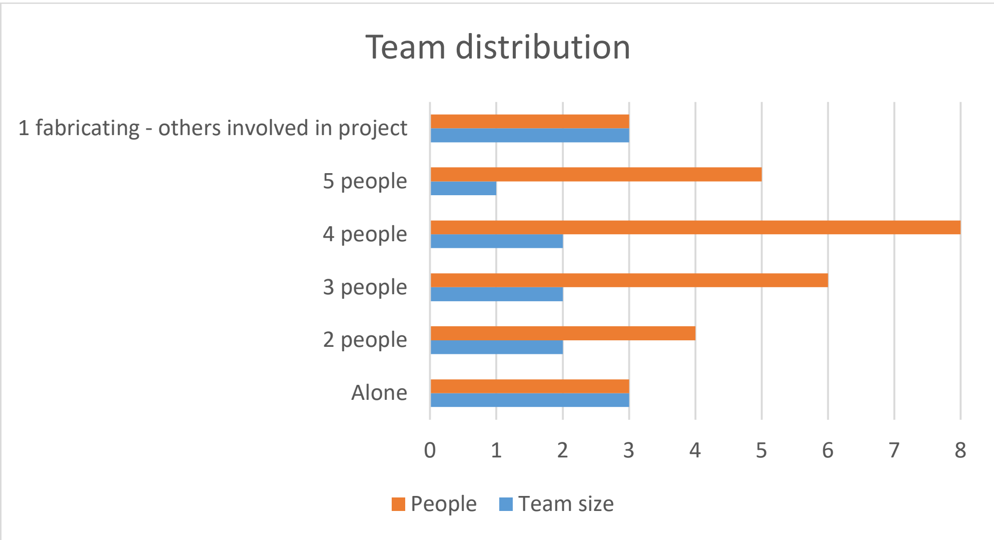

Figure 22. Team distribution at the Makerspace.

3.3.2 Before fabricating

Specific parts or products that not yet exists are often created. Experimenting, discovering and learning new technologies is also done in fabricating laboratories. Business users also explained that in the figuring-out phase it is crucial to see and get immediate feedback about their creations. The process is also less expensive and less time-consuming.

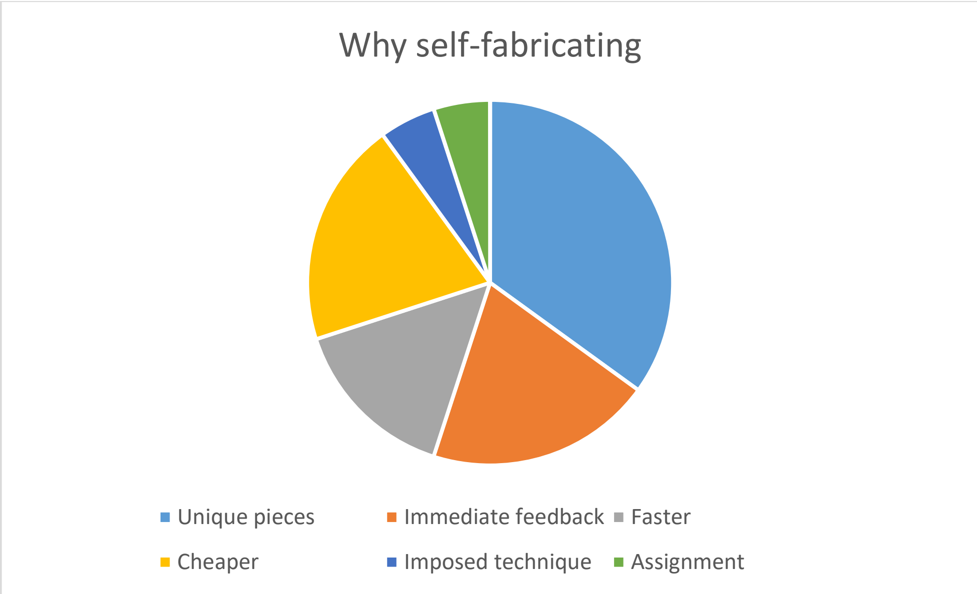

Figure 23. Why self-fabricating is chosen.

Most created items are iterations of prototypes. Another purpose is to fabricate pieces that fit into a bigger project as a whole. These pieces are often created to help in the assembly phase. In contrast with experience with machinery, there is not much or no experience at all with fabricating similar products. This is logical because most Makerspace users are fabricating unique pieces. To find similarities between different products, a high level of experience is necessary.

Many groups have a different action plan to fabricate with similar processes. Even in a specific group that is creating one item, team members are not fully aligned about the action plan to fabricate. Initially not all steps are taken in consideration. Most groups start with a digital drawing without measuring or pre-study. That's why during assembly many adjustments are made by users of the Makerspace in general.

In some cases, there is information searched, but often limited. Many don't know about the information that is displayed on the Makerspace's website. But who did some research, preferred the website of the Makerspace because specific information about the available machinery and materials is available there. Business users tend to contact the Makerspace assistant to get the necessary information.

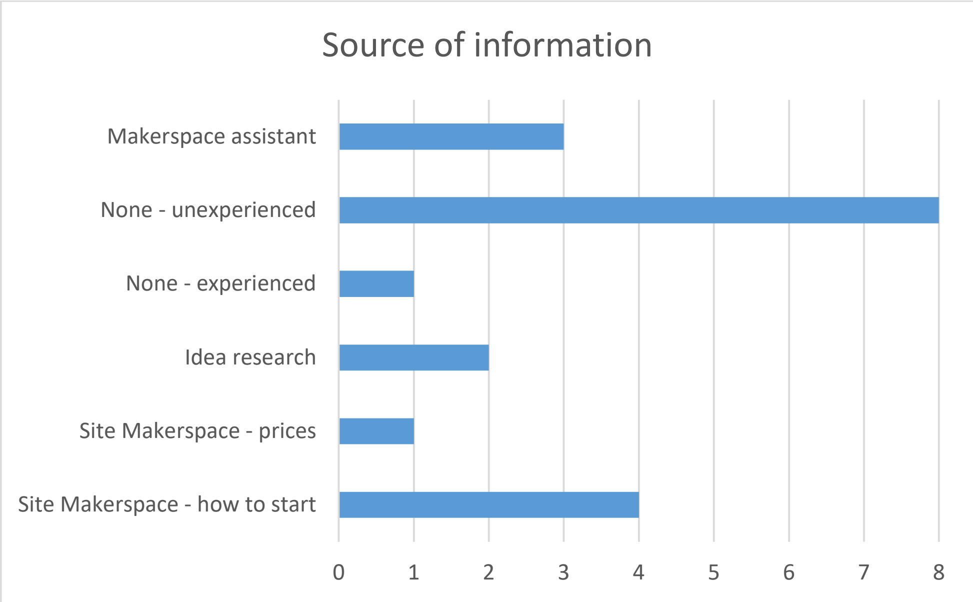

Figure 24. Sources of researched information.

Especially students without technical experience tend to have questions about what to expect in a fabrication lab and how to start. But once inside the Makerspace, there is a low threshold and most of them find it a pleasant experience. Some indicate that much initiative is needed without really knowing what to do first. Independent working without assistance can eventually be possible, but only with enough experience at certain machinery with specific materials. Many indicate that an assistant will always be necessary to help solve problems, introduce new machinery and to prevent accidents.

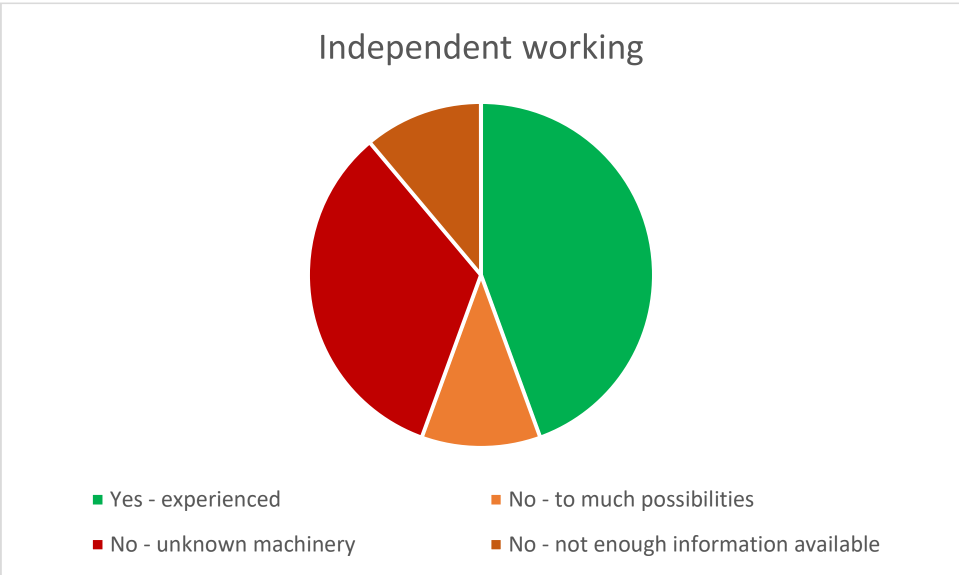

Figure 25. Independent working.

Before fabricating, most of the expected difficulties are about the properties of the drawing. This can be explained because most users have just created their drawing when walking into the Makerspace. Second most expected difficulties are about the alignment between idea and end-product, together with efficient use of time while fabricating in the Makerspace.

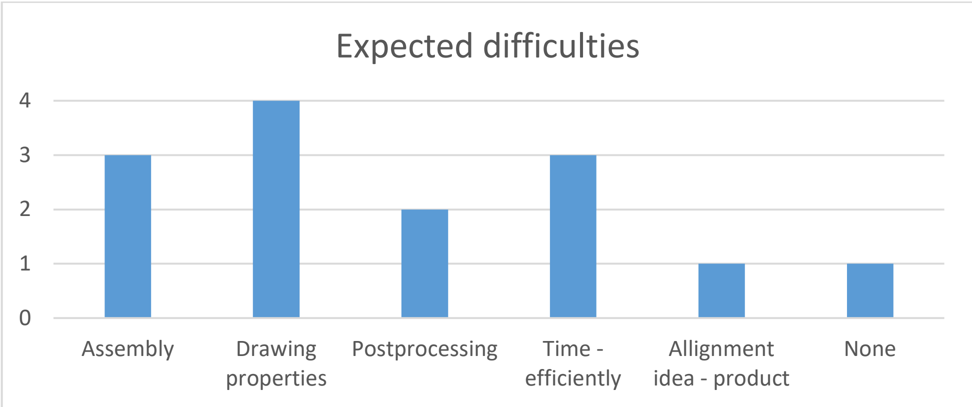

Figure 26. Expected difficulties before fabricating.

3.3.3 Evaluation of process and product

After fabricating, expectations about difficulties with the drawings proved to be true. Notable were the unexpected difficulties with measuring during the fabricating process. Nobody expected these difficulties but they often occur.

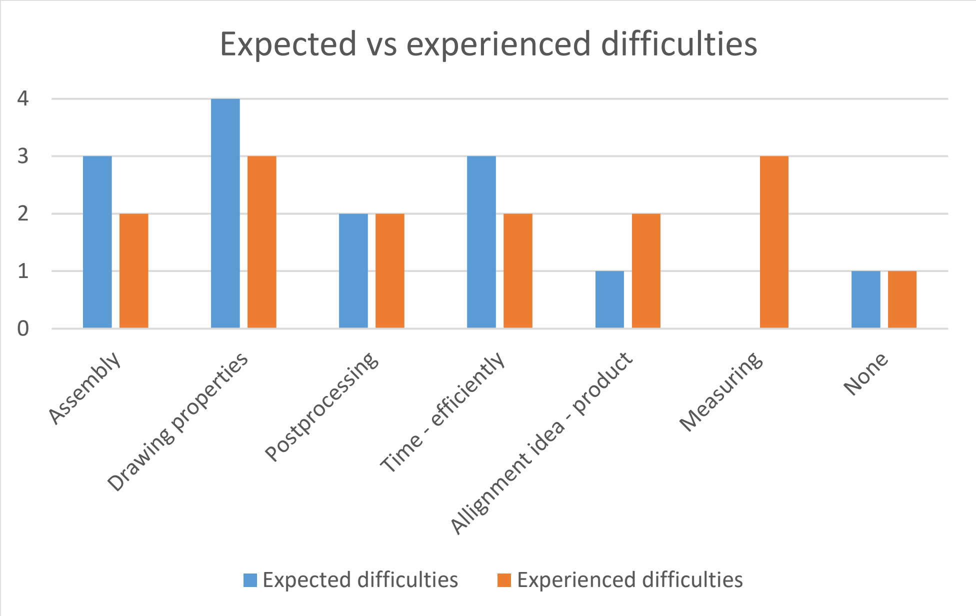

Figure 27. Expected vs experienced difficulties.

Mostly the finished product is as desired, because when necessary quick adjustments can be made ad-hoc. Also, many iterations are possible in a time-efficient way in a fabrication laboratory. This makes the overall user satisfied with their end-products. Only when users are running out of time, they indicate not to be fully satisfied, but tend to plan another iteration when possible to be fully satisfied with the finished product. Users only think about outsourcing the fabrication process of their products when large numbers are demanded. Most of them only need one piece, or a few at most. Also, fabricating is easy and controllable at the Makerspace. This control is lost when outsourcing.

In general, time is considered as efficiently used and many things are learned in a short time span. Waiting while the machinery is producing the user's pieces is considered and users tend to tackle this waiting with partially assembling the end-product. On the other hand, waiting for machinery while other's pieces are produced is not considered. Because of the first-come first-serve policy, it's unknown when using certain machinery can be done without waiting.

When asked if starting again, with gained experience in mind, would result in another approach, makers tend to make a shift to less time-consuming machinery. For example, using the 3D printer would be switched to the laser cutter where possible, because laser cutting is much faster. Another remark made by Makerspace users was drawing with assembly in mind. During the assembly phase, many fixes are needed. With a new start, drawing would be done differently. To do this, measuring is more important and necessary. When starting over, most users would not use another device because the fabricating process is mostly evolved towards the most appropriate machinery. Also, it would take more effort and time as overhead to produce the same. But on the other hand, most would like to experiment with other machinery.

Users were asked for suggestions to enhance the Makerspace and make it more approachable for independent working. Extended manuals at machinery were highly demanded, especially from groups with some technical background. Evolved from the extended manuals, the idea of action plans and scenarios at the device were proposed. In this way, more experience is gained while fabricating for real. Tutorials and workshops are also proposed with the purpose of getting more experience. With more experience, working independently is automatically easier.

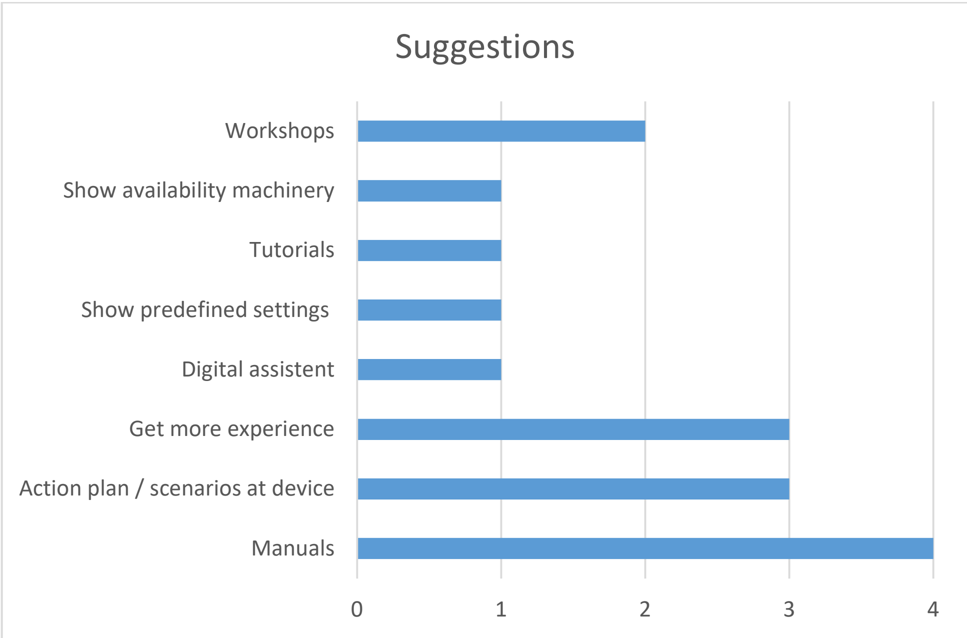

Figure 28. Suggestions towards independent working.

Overall, users are enthusiastic after working in fabrication laboratories like the Makerspace, but enhancements on many levels are possible. For example when people want to try other machines than were they are familiar with, tutorials are appropriate to learn. This can best happen with surplus material so there is no extra waste and it costs less. Tool awareness and guides are other examples.

3.4 User Study – Consequence

Field study and interviews at the Makerspace showed that there is a need for support to use the tools, to make independent fabricating more easy and approachable. A set of tools to enhance fabrication laboratories was proposed in the literature study. These are a good start in assisting the user without the need for human intervention. More specific, with the conducted interviews at the Makerspace in mind, many users did not expect to have difficulties with digital drawing and measuring what needs to be drawn. But in contrast to initial plans, adjustments are mostly necessary throughout iterations of development. Making these adjustments is not simply on intuition but needs to fit with other fabricated parts. That's where measuring comes in again, but that's not always easy. For example, measuring a curved object to create parts that fit on the curve, is hard by hand.

Unexperienced users tend to enter with an idea and sometimes together with a digital drawing. However, the idea and especially the drawing are not aligned with the end-product that is fabricated. Drawn objects do not always have the correct dimensions. Drawings can have much details, that are not visible anymore on the fabricated product because they are too small. The consequences can even be worse, some parts have minimal necessary dimensions to be technical possible to create. For example, there must be a certain space between two laser-beam paths that is thick enough to not be burned. When too small, nothing will be left. Another example is when crafted items are an extension to existing objects, they need to have the correct size to be useful and fit the design.

To cater to a solution to these problems, a measurement tool with direct feedback is proposed. Hand-drawn figures can be captured and the system can respond immediately by scaling the digital drawings. This scaled result is directly visible as a projection together with the hand-drawn figures or the item with which the fabricated product must go together. Such a tool makes measuring easier and brings closure in the alignment between idea and product. This should result in easier fabrication with fewer iterations and lesser materials to waste.

4 Object Measurement and Modelling

4.1 Emplacement

To measure objects and hand-drawings, a camera is needed to capture the images. These images are sent to a computer that responds immediately by eventually scaling and showing digital drawings. Through a projector, located above the platform where will be measured, the digital output can be directly shown and combined with the input. The camera, projector and computer are combined on a framework that can be placed on a table. This gives the augmented result that closes the gap between drawings and products.

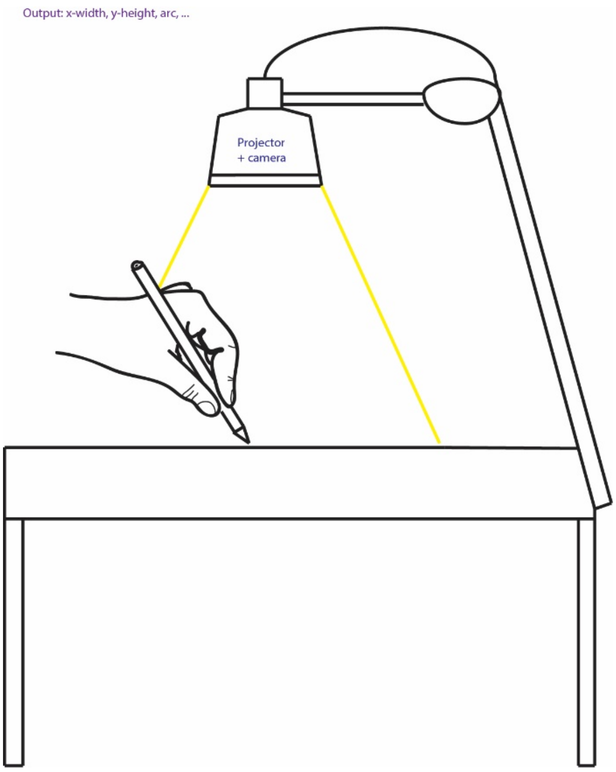

Figure 29. Prototype sketch of the framework to capture input and directly project output.

Applied to laser cutting, in a later stage the proposed system can be mounted above the laser cutter itself. Then measuring can be directly done and the projected result can be shown on top of the materials in the laser cutter. In this way the user can draw, and when satisfied with the result, the laser will cut as drawn. Figure 25 shows a system that has a camera mounted above a laser cutter to measure input. In the proposed system, a projector should be added to directly project output.

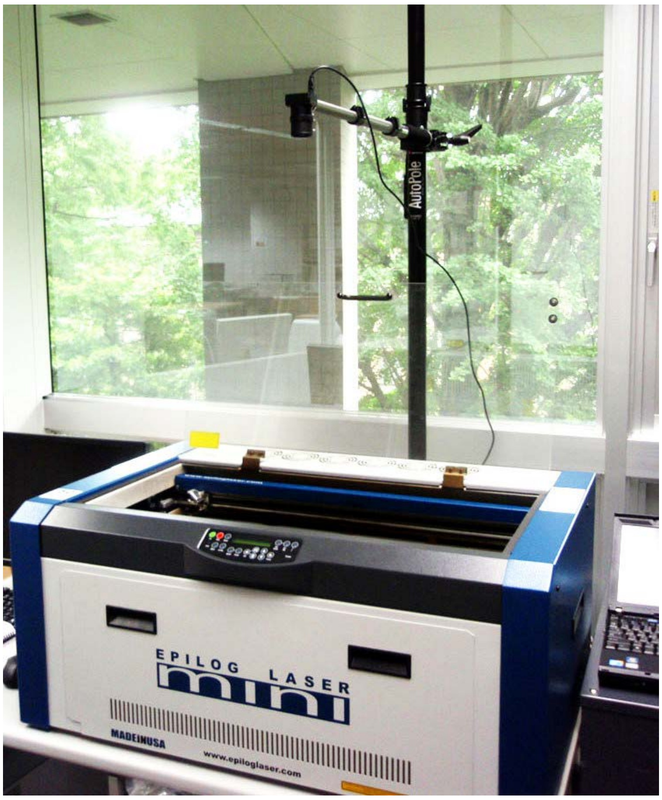

Figure 30. A camera system placed above a laser cutter [11]*. (Source: "Laser Cooking: a Novel Culinary Technique for Dry Heating using a Laser Cutter and Vision Technology"* [11]*, 2012)*

4.2 Measuring 2D

To encounter the measuring problems, a camera system is proposed to help with measuring and provide immediate feedback. This should result in better drawings, less iterations needed to obtain the final result and lesser struggles in the assembly.

To simplify the problem, in the first step reduction from 3D to 2D is made. The objective is to measure an imaginary rectangle that fits around a drawing. With the dimensions of this rectangle, users can check if the drawing for example fits on a T-shirt or on a piece of fibreboard for laser cutting. The other way around can also be very helpful: a sketch at actual size can be made, and measured by the system. Then the output can be used to make a digital drawing with the right sizes in the first time. In this step feedback is displayed on the computer screen of the system. In a later step, feedback can be projected on top of the sketch and the dimensions of the sketch can be passed to the digital drawing which would be even scaled immediately.

4.2.1 Idea of measuring

The basic idea of measuring in 2D is to measure pixel distance between the highest and lowest part, and between the most left and right pixel. If pixel density is known, real distance can be calculated.

4.2.2 Web application

Initial tests to measure drawn objects were conducted with Matlab. Matlab is a technical software environment frequently used for mathematic applications. It has functions, that are easy to apply, to perform complex operations. But it's hard to see what's going on at low level. That's why there is switched to a web application programmed with PHP. With PHP, it's possible to calculate at the level of pixels. Because it's made as a web application, it is easy to turn into a web service. This makes it easy to use in an internet of things setup to enhance fabricating laboratories. Also, the web application is responsive and scalable, thus usable on all kind of screens.

Figure 31. Web application 2D measuring.

4.2.3 Camera usage

To make 2D images, an office scanner is used. Pixel density of the scans is 200 dpi (dots per inch). This means that measured pixels divided by 200 dpi gives dimensions in inch. PHP can determine pixel density of most images, included scanned ones. But tests have showed that not all images on the internet have the meta-data included to determine the amount of dpi. To be safe, a manual field is included so dpi can be entered manually when necessary.

4.2.4 Algorithm

To be safe, first the uploaded image will be checked if it has a suitable format. The dimensions of the image are determined in pixels. These dimensions are the boundaries when looping through the individual pixels of the image. Also, a colour threshold value is set.

Within the boundaries of the image, there will be looped through the pixels, and if a pixel passes the threshold, it will be a candidate of a limit. The candidates will be evaluated with the most top-, bottom-, left- and right pixel. If it turns out to be a new maximum or minimum value, new limits are set. The dimensions of the drawn image are formed with these limits.

With determined or input dpi the dimensions in millimetres are calculated. Sizes in pixels are divided with the dpi and gives sizes in inches. These are converted to millimetres by multiplying with 25.4.

4.2.5 Result

The result is showed on-screen together with visual feedback. A rectangle is drawn around the area where the sketch is made. This visual feedback proved to be very helpful. When there is an impurity on the sheet, the system can see this as actual drawing. In that case actions can be taken like cleaning the spot or adapt the system's settings to only measure what's intended.

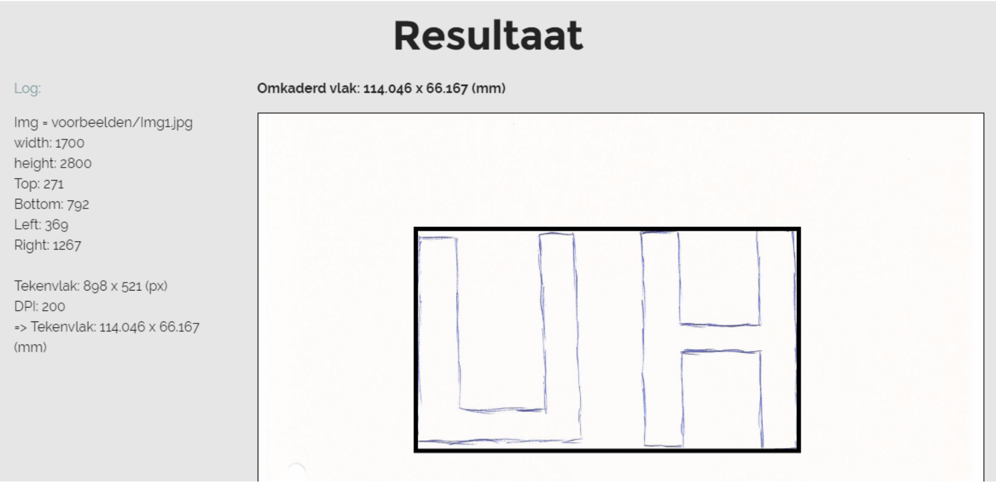

Figure 32. Result with visual feedback after measuring with the system.

4.3 Measuring 3D

Measuring in a 3D space can be very helpful. For example, when the objective is to create an object that fits another. Therefore, a setup in 3D is made with a camera to capture the object, a computer with a user interface to manipulate the model, and a projector to show a live preview in augmented reality on top of the object.

4.3.1 Camera usage

FLIR, formerly Point Grey Research, is a global leader in the design and manufacture of innovative, high-performance digital cameras for industrial, medical and life science, traffic, biometric, GIS, and people counting applications [19].

In this thesis, a Grasshopper2 GS2-GE-20S4C is used to capture images in a 3D space. This camera has a resolution of 1624x1224 and a GigE interface. The provided SDK supports programming with C++, C# and VB.net.

Figure 33. FLIR - Grasshopper2 Vision Camera. (Source: www.ptgrey.com [20]*, 2017)*

Another camera that is investigated is the Kinect. It is part of a line of motion sensing input devices by Microsoft. It is mostly used in gaming applications and enables users to control and interact without the need for a game controller. The Kinect provides ways to create a natural user interface using gestures and spoken commands. With the Kinect Fusion library, 3D object scanning and model creation is possible. The user can paint a scene with the Kinect camera and simultaneously see and interact with a detailed 3D model of the scene [21].

Figure 34. Kinect and Fusion example. (Source: www.123Kinect.com [22]*, 2017)*

In this thesis, the FLIR camera is used because it is the next logic step after 2D implementation. A next iteration of implementation would come with the Kinect camera.

4.3.2 User interface

A user interface has been built to make measuring possible in an easy way.

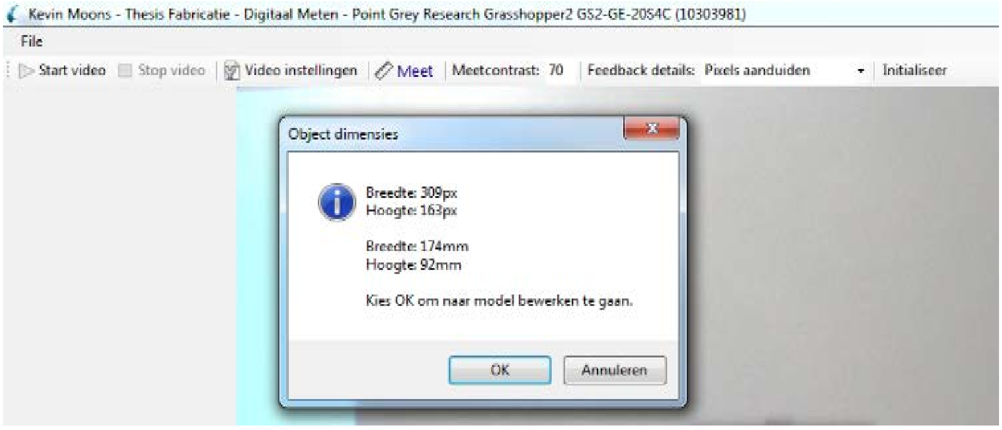

Figure 35. Easy to use and intuitive User Interface.

To start measuring, calibrating the program is necessary. To achieve this, an initialising hardware object is placed under the camera. The object has a square shape with known dimensions. The system measures the dimensions of this object and calibrates by calculating the average measured dimensions in combination with the known dimensions of the object. After the calibration, other objects or drawings can be measured in mm's. The "pixelToMmFactor" (pixel-to-mm-ratio) calculated in the initialisation step will later be used to export the right dimensions to the modelling software.

User support is given by an axis cross drawn on the live preview of the system. The best results are achieved when the object is placed at the centre focus point of the camera.

There are buttons provided to control the live capturing. When the user is satisfied with the view of the live camera, he can capture the image.

To give the user a good understanding of what is happening, the measured object can be highlighted in the application. This function is optional because it slows down the system and it is not always necessary to see this. A basic indication of the measured pixels is always given on the preview, by indicating the perimeter of the of the object. In the prototype, a pixel belongs to the object if its value is above the detection threshold. If the object is not properly marked, e.g. because of changing environmental light, the user can change the sensitiveness of the system. To avoid these issues, a booth could be created with appropriate lighting or by using another algorithm to detect the physical object.

After measuring, the results will be shown on screen and other actions could be coupled automatically. The application of this thesis will use the measurement results to provide an augmented reality environment, where the user can specify further actions to change the created model. At the end, a technical drawing that can be imported in modelling software, is created.

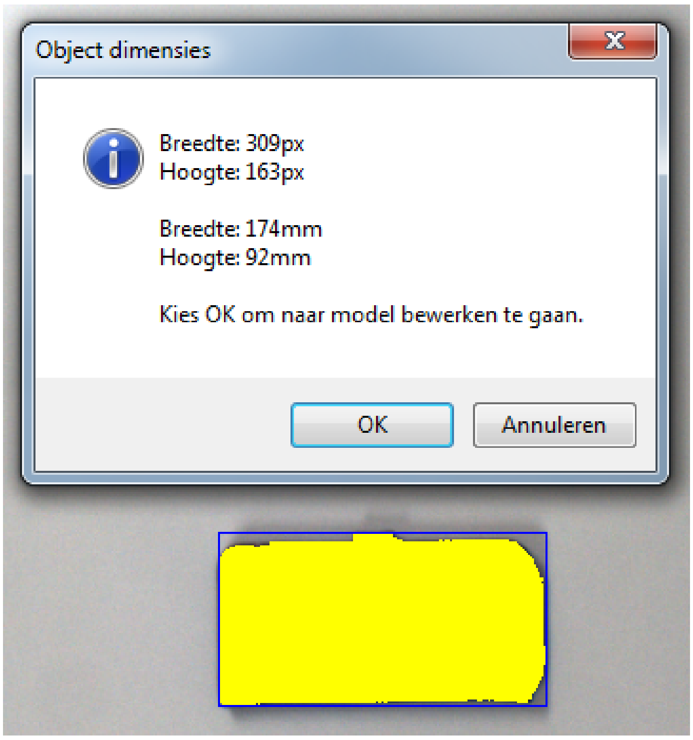

Figure 36. Pixel selecting and area lines + measurement results.

4.3.3 Algorithm

To initialise and calibrate, absolute dimensions in mms of the calibrating object are stored in the system. In the calibrating step these dimensions are compared with the pixel dimensions, and then the pixel-to-mm-ratio is calculated.

Algorithm 1 Calibrate

procedure CALIBRATE($pxWidth, pxHeight, mmSize$) ▷ Calibration object dimensions
  $avgObjectSizePx \leftarrow (pxWidth + pxHeight)/2$
  $pixelToMmFactor \leftarrow mmSize/avgObjectSizePx$
  return $pixelToMmFactor$ ▷ Scaling factor from pixels to mms

To help the user to place objects at the right location, the coordinate axes is drawn on-screen. These axes and other indications given by the system, are drawn on a transparent overlay over the live preview of the camera.

When the user chooses to measure, first the contrast of measurement is detected and an overlay to draw on is created. Then the user can choose to visually show what pixels are considered. If necessary, the user can change the used contrast to react on changing environmental light. This can be done without creating new snapshots from the camera because an image is already grabbed and stored for future usage.

Next, before actual measuring, the pixels above the threshold are detected and stored. With these pixels, dimensions are measured in the same way as provided in the 2D algorithm. The function “GetPixel()” provided by C# is pretty slow, therefore a quicker loop through the pixels has been devised. RGB values are then separately stored in arrays. When the pixel value is bigger than the specified threshold, pixels are considered as part of the object, and coloured if the user wants to. To provide feedback in an understandable way, the visual feedback is scaled to fit on screen with the same ratio as the video. From the stored pixels, the top-, bottom-, right-, and left-most pixels are determined. With measured pixel dimensions and stored calibration data, the dimensions in mms are calculated. Finally, the dimensions are shown on screen and further actions can be taken by the user.

Algorithm 2 Measure

```
procedure MEASURE(contrast)                                  ▷ Measurement contrast
    myBitmapData ← newBitmap(cameraProcessedImage.bitmap)
    myBitmapData.LockBits(dimension, ImageLockMode, PixelFormat)
    myGraphics ← pictureBox.Creategraphics()
    intPtr ← myBitmapData.Scan0          ▷ Get the address of the first line
    bytes ← myBitmapData.Stride * videoHeight      ▷ Declare an array to
hold the bytes of the bitmap
    rgbValues ← newbyte[bytes]
    r ← newbyte[bytes/3]
    g ← newbyte[bytes/3]
    b ← newbyte[bytes/3]
    Marshal.Copy(intPtr, rgbValues, 0, bytes)▷ Copy the RGB values into
the array
    CalculateScreenScaleFactors()
    while Loop through all rows do
        while Loop through all columns do
            b[count] ← rgbValues[(row * stride) + (column * 3)]
            g[count] ← rgbValues[(row * stride) + (column * 3) + 1]
            r[count] ← rgbValues[(row * stride) + (column * 3) + 2]
            if pixelValue is bigger than contrast
            DrawFeedback(extensive)
            objBottom ← row.BottomMostPixel
            objTop ← row.TopMostPixel
            objRight ← column.RightMostPixel
            objLeft ← column.LeftMostPixel
            endif
            count + +
    DrawContours(objBottom, objTop, objRight, objLeft)
    mmWidth ← (objRight − objLeft) * pixelToMmFactor
    mmHeight ← (objBottom − objTop) * pixelToMmFactor
    model ← measuredObject(objBottom, objTop, objRight, objLeft)
    return model
```

4.3.4 Result

This first part of the application allows the user to initialize the system and measure objects with the camera. In the next section these measurements will be used to create models ready for fabrication.

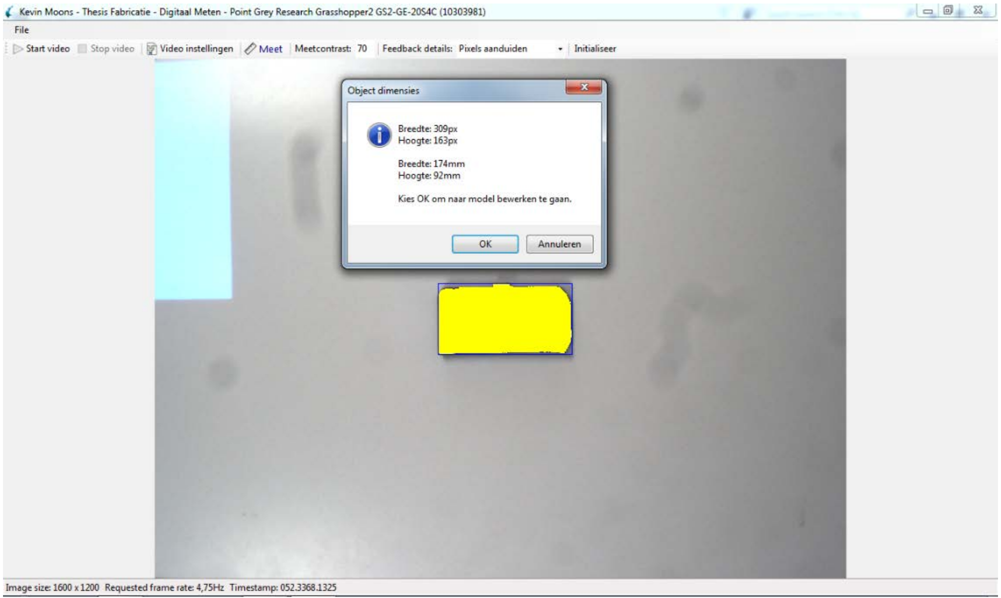

Figure 37. Part 1 of the interface: initialise and measure.

4.4 Model Creation

After measuring, an application is provided where the user can use the measured dimensions to create a technical model for fabrication. In this case, the user will create a housing to put some objects in, e.g. a wallet emplacement should be fabricated.

4.4.1 Application

An abstract representation of the physical object is shown on-screen. The user can specify an offset size of open space that's needed, by inputting the number or make use of the slider control. In the canvas on the screen, an offset is drawn around the physical object.

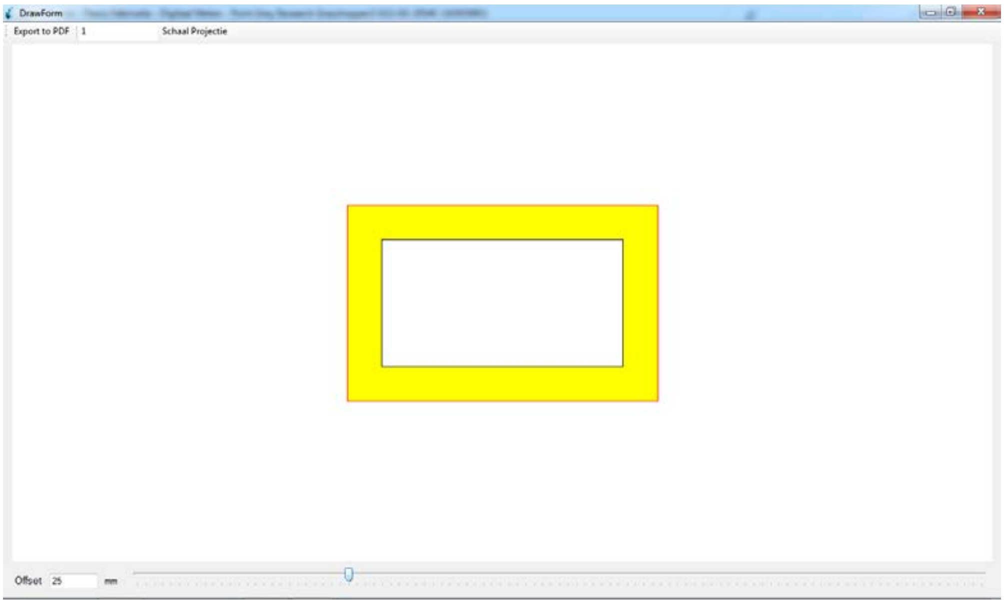

Figure 38. Abstract physical object with offset on canvas.

With a projector, the canvas is projected right on top of the physical workspace of the user. Thus, the user can change the offset in the system and see the changes in augmented reality, projected on the physical object. In this way, it is possible to check, for example, if enough offset is used so the object remains removable from its housing!

Figure 39. Augmented reality projection of the specified offset.

Figure 40. Projector creating Augmented Reality with Physical Object.

When the user is satisfied with the preview, it is possible to export the model to PDF format. This document can be imported in Inkscape. Inkscape is a professional vector graphics editor [23]. Most of the Makerspace users use this editor to draw technical documents for use with the laser cutter or 3D printer. The imported design is ready for execution and printing, with the correct dimensions and without difficult manual measurement procedures.

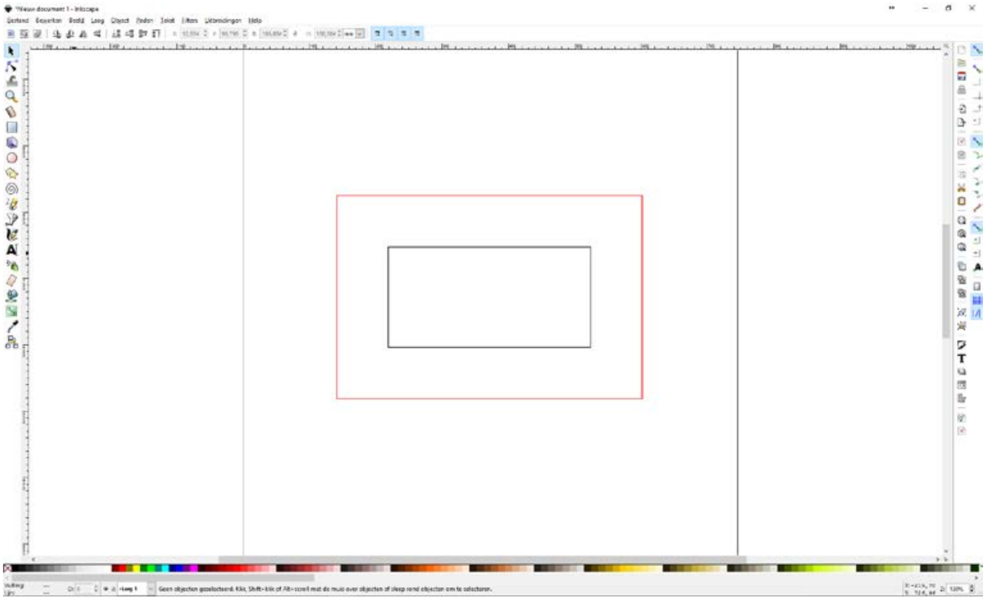

Figure 41. Resulting drawing in Inkscape.

4.4.2 Algorithm Offset Calculation

In the simple rectangle representation of the physical object, it is easy to calculate the offset by adding space around each side. When non-regular shapes are used, this becomes harder and other algorithms are used. A polygon offset algorithm can be used. Such an algorithm will go over each pixel with a circle brush, with the size of the offset. The brush colours all pixels underneath it. After going over every pixel, a new and bigger area will be coloured. The contours of this object form the newly created polygon-offset.

4.4.3 PDF Creation

To export the model from C# application to Inkscape, the PDFsharp library is used. PDFsharp is the Open Source .NET library that easily creates and processes PDF documents on the fly from any .NET language. The same drawing routines can be used to create PDF documents, draw on the screen, or send output to any printer [24]. With this library, it would be possible to directly send the created model to the laser cutter or 3D printer.

4.4.4 Result

With the full application, the user can create models from physical objects with added specifications in augmented reality and get real-time feedback. In the next chapters some use cases are proposed and a user study is conducted to determine if this application helps non-experienced users to fabricate objects.

5 Use Cases

To demonstrate that the developed system can be of great use, a few use cases are presented.

5.1 Capture Handmade Drawings

When people design a digital drawing that needs to be printed in full size, it is difficult to estimate or measure the right dimensions. For example, when a logo is created as a digital drawing to print on a shirt, the design often needs some scaling to fit before actual printing. Using the developed system can prevent this problem: the desired area for printing can be manually indicated and exported through the application to a digital model. The use of the system can be further exploited by capturing handmade sketches and drawings to convert to digital models. Examples are creative artefacts like stickers and decorative items. One can do rapid prototyping by making sketches and drawings by hand with the desired dimensions. Once captured by the system and exported to a digital model, it can be digitally finished before creating the physical object.

5.2 Reconstruct Objects

If someone has an object that is broken and wants to manufacture it again, the presented system can offer an helping hand. When the broken parts can be kept together, they can be scanned and capture them as a whole. Then, in one step, a model can be made ready to fabricate and reconstruct the physical object. If it is not possible to hold the broken parts together and captured as a whole, the system can scan the individual parts with possible random shapes and create models from them. With CAD/CAM software, it is possible to combine the models of the broken pieces together as a whole again. When some parts are missing from the broken physical object, this can still help the reconstructing process because with the available parts it can be easier and less time consuming to rebuild it.

5.3 Adjust Models

The system can also be used to change the sizes of a model. For example, when a miniature prototype is made and it needs scaling to real size. The smaller physical object can then be measured and scaled in the modelling part of the application, or the model can be loaded and then changed. It can also be useful in the same way in an iteration where the created object and its model need some adjustments. If some material need to be removed from the physical object, it is a good confirmation to see what will be removed projected on the object before the actual removement.

5.4 Fitting Objects

To create objects that fit into each other, it is very important that they are measured correctly. The proposed system does this in a convenient way and is therefore very suitable to create mating items. When a cover plate must be made where cylinders come through, the plate and the cylinders can be manufactured both independently. The cylinders can be placed on the crafting table of the system and be measured. The resulting model is then ready to be fabricated from the plate material. When creating an enclosure for custom made circuit boards, the application makes it easy to test it before manufacturing. Not only to test if the circuit board fits, but also if the electronic components have enough space left over and to test if possible expansion components will fit. An industrial application is found in the making of moulds. Often an example object is created and the mould is fabricated around it. With the system, this can be done by measuring the example object and directly specify the thickness of the walls of the mould in the modelling part of the application.

5.5 Assembly fittings

As seen in the user study, many smaller parts are fabricated in the assembly phase of fabricating projects. Additional attachments are sometimes required to achieve a sturdy end product. These parts are hard to draw digitally because measuring is harder when the product is partly composed. The system supports the creation of assembly fittings by capturing the partly composed product. In the modelling tool, it is possible to select the part that has to be fabricated as an extension of what already exists. This allows to quickly create assembly fittings.

6 Evaluation

During the development of the measuring and modelling application, user tests were organised. To check if the prototype satisfies the requirements, a usability test with the intended end-users is conducted. They are both users with and without technical experience. Qualitative data on the usability was collected. To know if the system let you achieve tasks it was designed for and to know how to further develop the application, quantitative data was collected.

6.1 Participants

The user tests were conducted with the following participant groups:

The first test group consists of unexperienced users without a corresponding technical background. For this group of users, it is important that the system is self-explanatory and easy to use. Because these people don't have experience, they don't know the steps that need to be followed in the process. The application should support this by only showing the next logical step. It is also important to give the user feedback so he knows what he is doing and what are the results of his actions.

The second group of testers are users with some technical background and previous fabrication experience. For them it is important that there is not too much overhead of steps to follow in the application. The system should not frustrate these users or make them feel limited, it should help them to fabricate in an easy and supportive way. That's why a clear structure of steps in the application is necessary. Feedback is also very important, it can help to strengthen trust in the application.

Users that want to fabricate prototypes for their business form the last type of testers. They can come with or without fabrication experience, but their main goal is to experiment while they get immediate feedback of the results of their fabricated products. These people want to experiment, not to learn a new technology, but to develop a well-formed end product. They want to validate of their idea of the prototype fits into their business. Therefore, the system should have a clear guiding and intuitive user interface. Feedback will also be important, so the user knows what is going on, and eventually where to differ in the next iteration of fabricating.

6.2 Procedure

6.2.1 Test Preparation

The user tests were conducted in a controlled environment with the facilitator and observer being one person. That is why the sessions were recorded to review them later. A facilitator document was composed so he could introduce every test user consistently. After an introduction of the application and the purpose of the process, it was made clear that the aim of the test was evaluating the system and not the user. A consent document is signed, that gives permission to use test recordings and results anonymous.

The test users received some tasks to execute with the system. They were encouraged to think out aloud, to help the analysis of the results later on. It was made clear to the participants that not all the functionality of the final application were already available. Before actual executing of the tasks, the participants filled in a demography questionnaire. That made it possible to set out their experience and demographics relative to the rest of the test users. The application was also initialised for them, because this is only part of the prototype. In a final application, this should no longer be necessary anytime you start up the system, but still can be a needed feature to align camera and projector for example.

6.2.2 Measuring the Object

When starting the test, the first step was to make sure the system was initialised. If not yet initialised, this was done for the participant. The introductory story was told: the objective is to fabricate something to keep your desk organised. For example, something to put your phone, USB-sticks, pens... in. The object of choice by the tester is then placed at the measurement table. The best spot to place the object is at the centre focus point of the camera. In the application, this place is marked with a coordinate axes. When the user is satisfied of the position of the object to measure, he needed to stop the live video preview. Then the user could choose to see extensive feedback or not. With extensive feedback, all measured pixels are coloured. The regular feedback places a rectangle around measured pixels and shows measured data later in the process. After that the tester needed to measure the object, and evaluate if this was done well. If it was not measured well, the user of the application can adjust the threshold depending on the environment light in the room. When the measuring succeeded, the user can choose to proceed to the second part: model creation and editing with use of augmented reality.

6.2.3 Model Editing in Augmented Reality

When the model is created, it is shown on screen in the application and projected on the table. With the abstract model editing tool in the application, the tester made changes to the model. He could see and test the model with augmented reality, through the projection on top of the physical object. The final step during testing was exporting the model through vector data stored in a pdf file, when the test person was satisfied of the created model. The participant finally could open the resulting model in any modelling tool of choice. After that, the user was free to 3D print or laser cut his model, but that was no longer part of the usability test procedure.

6.2.4 Objective and Subjective User Measuring

During the tests, objective measurements have been made, e.g.: time to complete a task, number of errors, number of times tried again, number of navigations, number of users making a particular error, number of users completing a task successfully and time to complete a task again. Subjective measurements are done through observation and a small questionnaire with an interview.

Finally, after using the application, the users filled in the questionnaire about the usability and answered some more open questions about the usage and possible further improvements of the system.

6.3 Results

6.3.1 Background of the testers

To thoroughly test the system, eleven participants conducted in the usability test. ten of them were in their early twenties, and one in his early thirties. Five of them had never participated in a focus group or usability study, while six of them did it once or twice before. Four of the testers came with technical education and seven without. In these numbers about technical education, only finished studies are counted. Six of the participants are studying an engineering program.

The user study at the Makerspace has shown that most of the makers are students and entrepreneurs. Both groups have their own skills and needs, and the two groups have different interests. Therefore eight full-time students were recruited, and three entrepreneurs. Two entrepreneurs are combining entrepreneurship with their studies and one of them is full-time working in his own company for seven years. One of the participants has only concluded high school, while three have obtained the diploma “Professional bachelor” and seven have obtained the diploma “Academic bachelor”.

Except one user who only uses his computer during work days, they all use their computer every day. School and work related usage like document editing, programming and other professional tasks were most common. Some of them also use the computer from time to time to draw technical models and designs. All the testers are accustomed to use a computer and they use it also in their free time to manage social media, read the news, browse the internet, and other entertainment.

The system that has been tested must support people without previous technical experience, but should also support experienced makers. Four participants came without experience, but six already used the laser cutter and four did use the 3D printer in the past to self-fabricate. Some of them have used both, and some are used to develop electronic circuits. One also mentioned previous usage of the sticker machine. In summary, the biggest difficulties came with imagining the real sizes of the drawn dimensions and with being time efficient.

6.3.2 Flow through the process

The participants were all satisfied with the flow throughout the process and found it clear and intuitive to follow. Two of them made some small user interface suggestions and two made some small suggestions to change the process a little bit. The user interface missed some inconsistency and was sometimes placed in front of important aspects of the work field on-screen. If the user measured wrongly and wants to start over, a restart option would be nice instead of starting the live video again and then stopping it again to measure. Even better would be live processing, without the need to stop the live video.

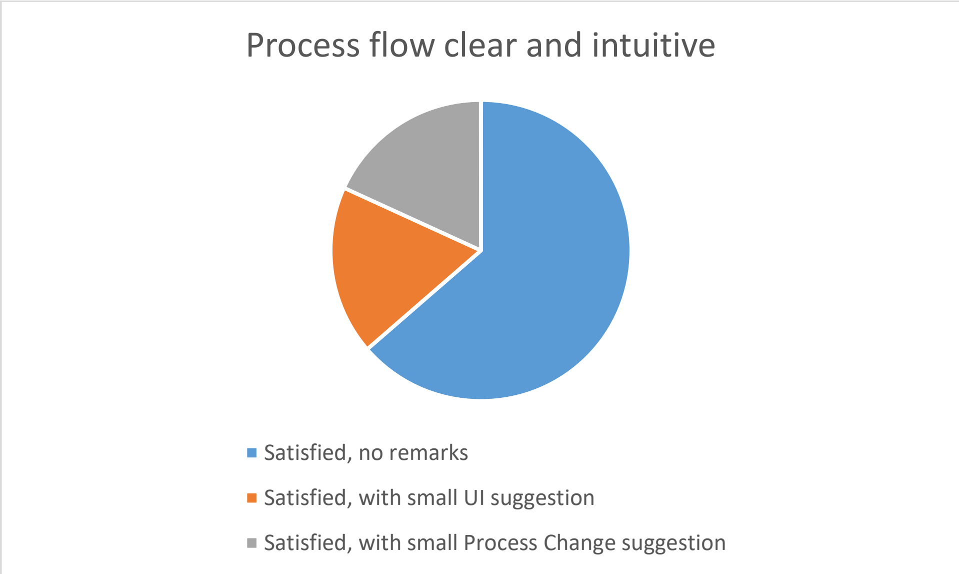

Figure 42. Process flow clear and intuitive.

6.3.3 Missing some aspects

Six of the test users did not miss anything expected in the application, but five did. The missing aspects would both help to get a better view of the end result. On one hand three users wanted to see the resulting model they have created in 3D. On the other hand, two users wanted to see the object outlines added to the abstract presentation on top of the physical model in augmented reality.

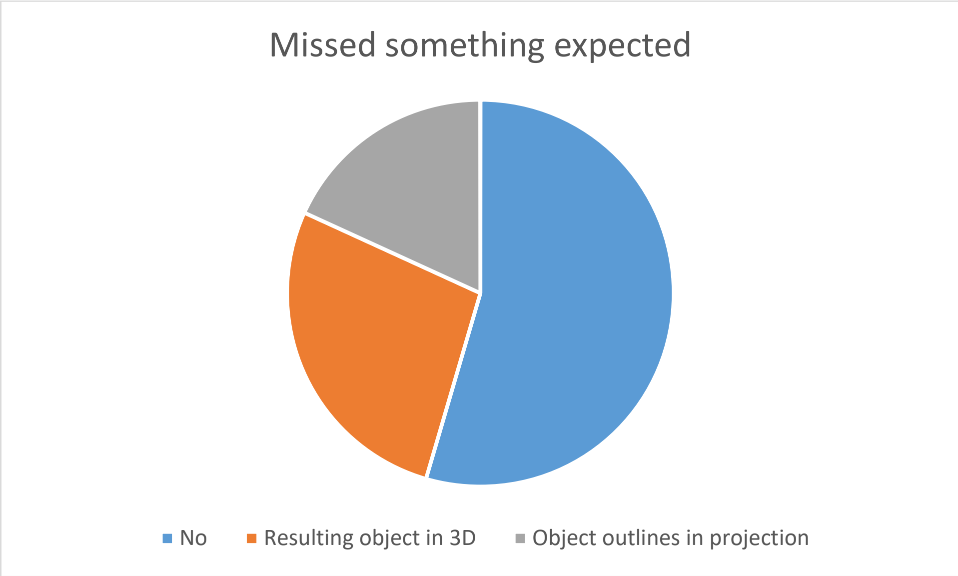

Figure 43. Missed something expected in the application.

6.3.4 Ease of measuring

The measuring process was easy enough for everyone, only two participants had to adjust the contrast manually to measure their physical object properly. Six persons had no suggestions when asked if something could be added to make measuring even more easy. The others had one more suggestions, so the total amount of answers exceeded the total of participants for this question. Three requests for more feedback were made. The users would like to see the measured dimensions presented in the drawing itself, instead of popping up in a message box. One participant asked again to change the start and stop process. Two small user interface changes were proposed. One to make the user interface clearer, and one to make it more usable. To change the contrast, a slider was proposed. In that way, it is very easy and convenient to change. One person suggested some guidance to place the object in the best way, but this is only applicable in the prototype. In the final application, it should not matter where or in what orientation you place the physical object. One experienced maker suggested to make a nice feature, a setting to specify in what unit and precision dimensions should be shown.

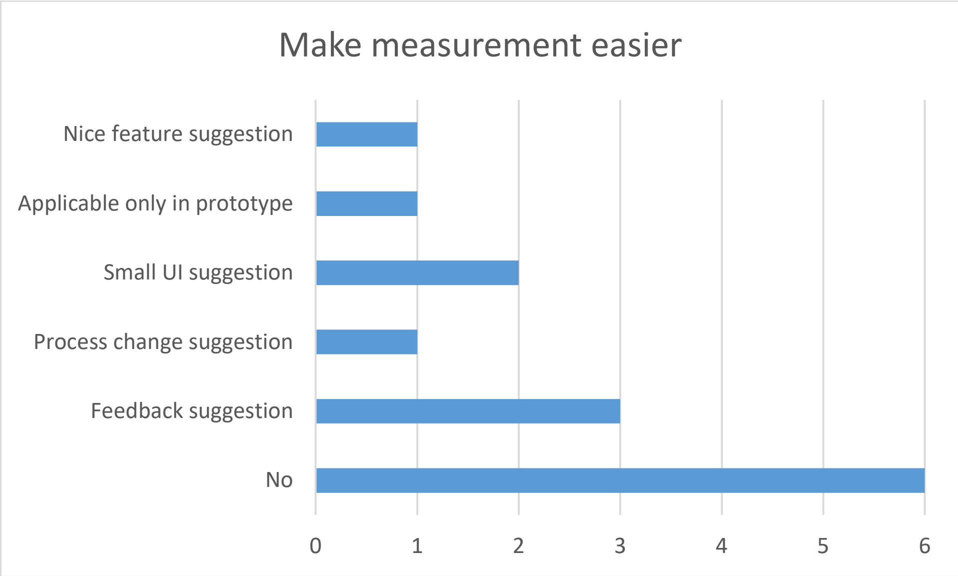

Figure 44. How to make measuring easier.

6.3.5 Ease of model editing

When asked if it was easy enough to edit the created model in the application, only three users requested some extensions to the application. What they want, is changing the offset more specific for each side independently of the other sides. This is something that is added to the future work in the development process of the application. All the other persons found it very easy to edit the model. The simple procedure and direct feedback in augmented reality were both twice the reason why it was very easy and useful. Two users liked to use the slider to change the offset size, and liked the choice of input with the slider or with the numeric input.

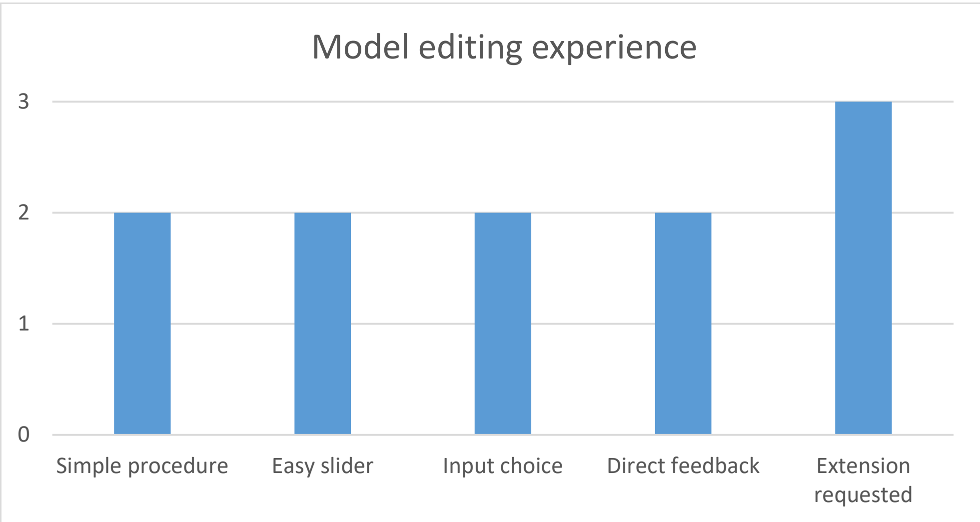

Figure 45. Model editing experience.

6.3.6 Presentation in projection

For everyone, the projection of the offset in augmented reality was very clear and useful to imagine the usability of the end-product. Five participants stressed out that especially the live changes of offset adjustments in the projection are very helpful. Four persons suggested that it would even be better to also show the numbers of the sizes of the offset in the projection, to also support experienced makers.

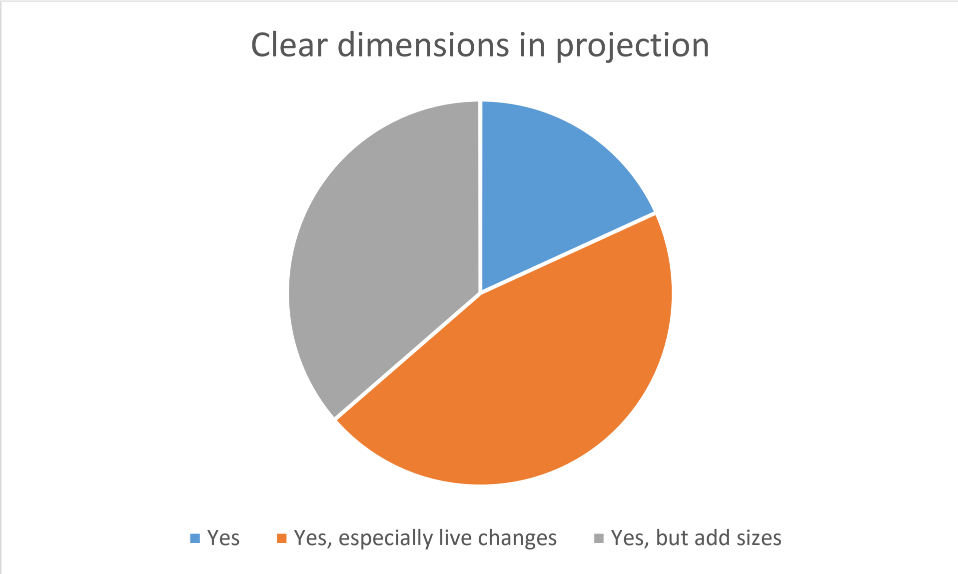

Figure 46. Clear dimension presentation in projection.

6.3.7 Future usage of the application

One of the participants would only use the proposed application to fabricate if he is sure about the accuracy. Another participant would only use the application if 3D representation of the model is available. All the others would definitely use the application. Some gave more than one reason, so the total amount of reasons exceeds the number of participants. 4 users found it very convenient to measure, and 4 more liked it because of the speed of the whole process. 3 people without technical experience told that they liked the application especially because no prior knowledge is required, so they are also able to do some fabricating. 2 business users liked the application because of the direct feedback you get throughout the whole process.

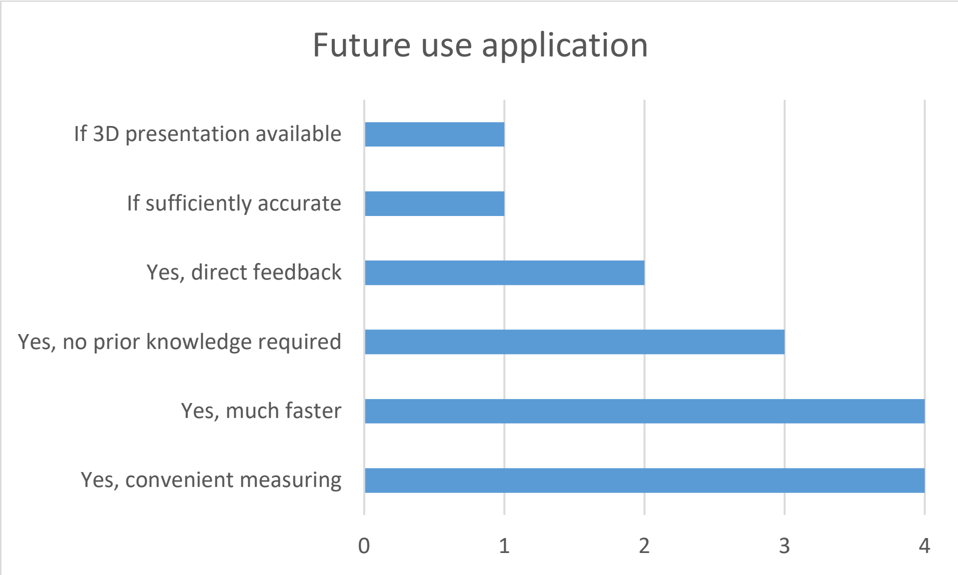

Figure 47. Future use of the application.

6.3.8 Suggested changes

All the test users thought the steps in the process and in the application are followed in a logical order. Only one participant suggested to show the steps that need to be followed also in the application, and not only on a sheet for the user. This was indeed a good suggestion. At the moment, the test person received a task list to follow, to conduct the test. But in normal usage, this sheet should not be provided. The steps could be integrated into a wizard throughout the application itself.

When asked what the users would change if only one change could be made to the application, Two persons proposed very task related changes that would not be helpful for other tasks. Two participants proposed some more smaller interface changes. The six others made suggestions of which some were already included to future work, and some were later included after analysing them.

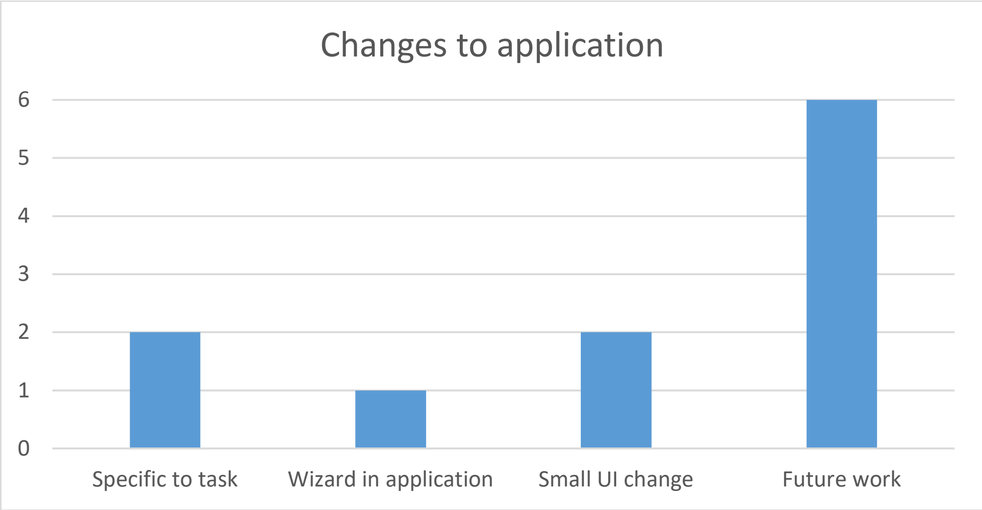

Figure 48. Suggested changes to the application.

The future work suggestions were further analysed and divided into four categories. Two participants suggested that you should be able to add offset to more specific places, and not everywhere the same size. One user came again with the 3D representation. One experienced maker suggested to include fabrication settings in a menu. In that way, it is not necessary anymore to make changes to the model in another modelling or drawing package. Two participants would like more enhancement of the feedback in the application.

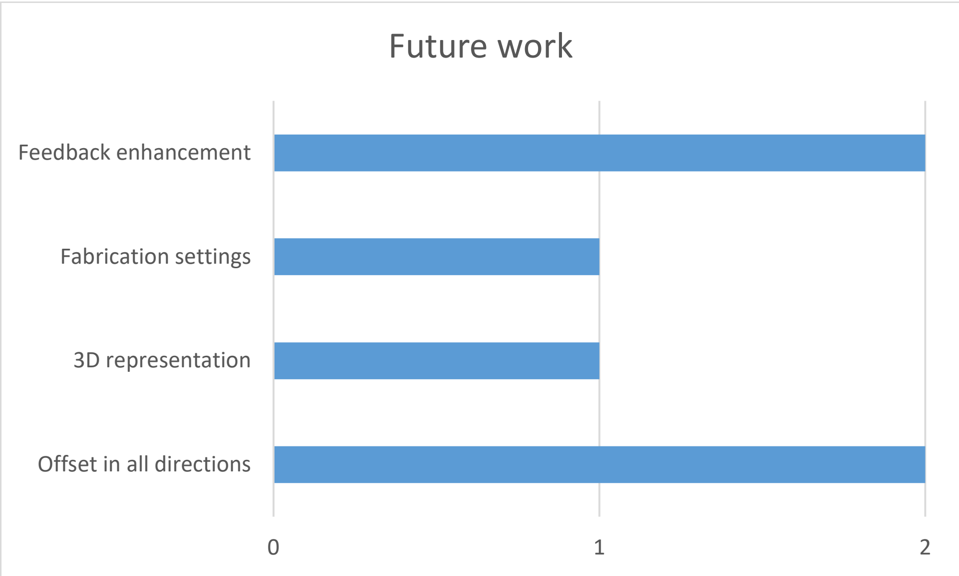

Figure 49. Suggested future work to the application.

7 Conclusion and Future Work

In this thesis, a system to make independent work in fabrication laboratories more accessible without the need of previous technical experience is presented. This system helps the user to measure physical objects and to create and edit a model in augmented reality.

An initial exploration of fabrication laboratories was done in the Makerspace @ PXL/UHasselt. The Makerspace is an open, multidisciplinary, technological and personal fabrication space. The goal of this thesis was to make fabrication laboratories more approachable and usable with less or no assistance from a supervisor, even for users with little or no experience in the field. Users of the Makerspace were observed and interviewed to know about their pains. With these insights and a literature study, a user centred design of a digital assistant application was created. Two big difficulties of the Makerspace visitors were measuring and creating digital models, for example to print in 3D of cut out with the laser cutter. The prototype of the created application consists of an easy measuring method with a camera and object modelling in augmented reality. Measuring objects in the traditional way is much harder and more time consuming. Drawing models in a digital drawing package would also be more time consuming and previous knowledge is necessary. Digital assistance is given through this model creating application, with a natural flow throughout the process. This system allows very rapid prototyping without previous technical knowledge or the help of supervisor. It makes independent work more accessible in fabrication laboratories and gives an easy introduction and approach to complicated and complex technologies like 3D printing and laser cutting.

The usability test showed that the measuring and modelling system was a useful and handy tool for personal fabrication. The group of test users without technical experience were satisfied because this tool made them able to fabricate something without technical issues. The more technical experienced users are also convinced of the application, because it is far easier and less complicated to measure and create a model. Also, it does not necessary exclude traditional model editing in other specialised software. Finally, the business users liked to work with the application and would use it in the future because it gives direct feedback and less iterations of the fabricated products should be made.

During the usability tests, after the first round of tests, some smaller user interface changes were made. These changes made the application more consistent, and the next tests showed that these changes were very helpful for the user to better use the application. Buttons in the measuring menu were all given text and image, and other elements were given a descriptive label. The user interface can still use some enhancements, for example the keyboard controls can be implemented to control the video at the measurement step. Another example is the representation of dimensions throughout the application. They are now displayed in different forms, but it would be more convenient to see them placed on the specific places of the measured object or the presented model.

To fully support independent fabricating, some more steps need to be taken. A wizard should be made in the application, replacing the paper sheet with tasks that the user now received during their test. Extensive editing of the model and support for all kinds of possible physical objects should be added. These are described in the future work section.

It is concluded, and stressed out by an experienced tester, that while there is still future work to do, it is very important to keep the application clean and simple as it is now.

7.1 Future Work

The system can further be extended with more features and has the potential use for other technologies and machinery. This was also shown by suggestions of the usability study participants. To finalise, some possible directions in which the system could be extended are proposed.

7.1.1 Completed System

The next logical step of this thesis is to develop and to complete the system, evolved from the prototype application. The shortcuts made in the prototype will be replaced with full functionality. For example, in the actual model, the offset is simply calculated by adding offset around the outer borders of the simple shapes. Some testers suggested that it would be nice to choose freely which borders you want to give an offset. In that way objects can be hold more firmly in the end-product to keep a desk clean and organised, while the object remains removable by some cut out offset where desired. To set an offset to more complex models, another algorithm can be used. Presented in 2D, a brush with the width of the desired offset can be used to go over every pixel. In that way, the most complex models can get offsets. Another example is the object detecting method with the vision camera that is used. At the moment, this is done by scanning for pixels that are darker than the background colour of the table. This pixel scanning can be replaced by image comparing and background subtraction. It will give a more precise indication of the physical object's placement, provided that the background has not been changed after placing the object. Also, some improvements found and suggested by users during the usability test can be implemented to make the application more useful. The participants came up with some scenarios where they would like to use the completed system. The hardware setup must be aligned with the camera and the projector having the same focus point. To enhance the performance of the initialising step and measuring objects, environmental light can be neutralized by adding a light source. With the right kind of projector, this light source can even be the projector itself. If the hardware is aligned well and the system's specifications are fixed, the initialising step can be done automatically when booting. This system is then ready to use in fabrication laboratories and allows makers to work independently without supervisor.

7.1.2 Integrated System

The better use of the proposed system, would be integrated in an environment where more self-explanatory systems can be used. When this is the case, the user will be stimulated even more to try and discover new technologies and possibilities. A good combination would be with the Smart Makerspace with a smart workbench, toolbox and power-tools [1]. Both the Smart Makerspace and the measuring and modelling in augmented reality application guides makers through the completion of tasks, while providing detailed contextually-relevant assistance, domain knowledge and advice. This makes them complementary to each other.

7.1.3 Mobile Application

If the system is made with a complementary mobile application, the user could carry it around while working in a fabrication laboratory, especially in the previous described environment where multiple smart maker devices are stationed. A location aware mobile application can enhance usability by only giving instructions that goes with the machinery you are using at the moment. Also, when editing the created model on a big table, it can be very helpful if you are able to walk around it freely and not to be bound to a desktop screen.

7.1.4 Extended Model Scanning

In this thesis, measuring the physical object is done by initializing the system, detecting the pixels of the object and calculating the dimensions with the use of a vision camera. The vision camera can be replaced with a device that can scan the physical object and return a detailed 3D model. For example, the use of the Microsoft Kinect with the Fusion library was examined but not implemented yet. The Kinect can also enable extended model editing in augmented reality, as described in the next possible future step.

7.1.5 Extended Model Editing

So far only the model and the changes to it are shown in augmented reality, by projecting the digital model on top of the physical object. But with the Kinect it is also possible to show user interface components on top of the working table. In this way, it becomes even more flexible and usable. Even better, finger movements and gestures can be tracked and enable precisely editing very specific parts of the model.

7.1.6 Augmented Fabrication

Another approach of integration is putting the system together with the actual machinery, for example on top of a laser cutter. Then the application can produce a model in augmented reality and give the preview of cut out material. When the user is satisfied, the model doesn’t need to be exported to a file again, but laser cutting can be done directly on the physical object.

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