ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

DESIGN AS MAKING:
INTEGRATION OF DESIGN DEVELOPMENT AND FABRICATION THROUGH HUMAN-COMPUTER INTERACTION

Ph.D. THESIS

Serdar AŞUT

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Architectural Design Computing Program

SEPTEMBER 2016

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YAPARAK TASARLAMA: İNSAN BİLGİSAYAR ETKİLEŞİMİ İLE TASARIM VE İMALAT SÜREÇLERİNİ BÜTÜNLEŞTİRME

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Serdar AŞUT, a Ph.D. student of ITU Graduate School of Science, Engineering and Technology, student ID 523092015, successfully defended the dissertation entitled " DESIGN AS MAKING: INTEGRATION OF DESIGN DEVELOPMENT AND FABRICATION THROUGH HUMAN-COMPUTER INTERACTION", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

I had particular interest in using CAD software during my bachelor's studies in architecture between 2000 and 2005 –the period which computers have started to become widespread at the schools in Turkey. I remember having many arguments with my teachers who disagree that computers are actually good for us and who even forbid to use them at the studio. Such an argument seems quite naive today –even though it may exist at some places. However, what is very evident is that there is a strong relationship between the qualities of what we are doing and the tools that we are using.

My interest in CAD started to turn into a more serious academic focus when I started to work as a research assistant in 2005 at Anadolu University. Since then, I have been working in teaching and research in architectural design, with a particular focus on the use of computer systems, but as well developing a critical approach on them.

The journey fairly started at CITA (Center for IT and Architecture), where I worked as a research assistant in Copenhagen. There, I had the chance to work in hands-on research projects in which we used several cutting edge tools and methods in digital crafting. Then, I submitted my MSc thesis which was titled "Open Source Initiative Within the Contemporary Architectural Design Tools" at ITU in 2010. The objective of my thesis was to argue the potentials for developing flexible CAD tools by using open source systems. After the graduation, I started to teach in Izmir University of Economics for tutoring the senior semesters' architectural design studio for 4 years, which were focused on computational design in an avant-garde form. This teaching experience was a great case study for me. I had the chance to observe the tight relationships between the introduced CAD methods and students' design thinking, and the necessity of the notion of making in design development. These observations fairly influenced the content of my PhD study as well. In order to gain more skills and knowledge on the notion of making, I went to Bern University of Applied Sciences in Switzerland to work as a researcher with the support of Swiss Government's Excellence Scholarship for 12 months. This research study enabled me to apply many experiments using the CAD/CAM machinery towards the idea of making. And it is evident that this thesis fairly benefits from these experiments. Moreover, they influenced the research practice which I am currently working on besides this thesis. I established a research and teaching laboratory named yumak (Yaşar University MakerLab) after I came back from Switzerland and started to work as a lecturer at Yaşar University Faculty of Architecture. This lab which I coordinate is equipped with the typical MakerLab infrastructure and an industrial robot arm. It supports teaching at the faculty through hands-on practices and several interdisciplinary scientific research projects where the notion of making is essential. I hope to be able to improve yumak for better and make it an environment of my research interests which I have been developing since the start of my academic journey.

Unsurprisingly, writing this thesis was a hard process –possibly just like any other PhD thesis. I am sure that it would be even more difficult without the support of my advisor Prof. Dr. Arzu ERDEM. I would sincerely like to thank her for inspiring,

motivating and teaching me all the time. Also, I would like to thank Prof. Dr. Odilo SCHOCH at Bern University of Applied Sciences for supporting and supervising my research in Switzerland. And I would like to thank Assoc. Prof. Dr Meltem AKSOY and Prof. Dr. Şebnem Yalınay ÇİNİCİ for their valuable input since I started to work on this thesis. I hope that my work is going to inspire some other people and contribute to the knowledge in our field.

June 2016

Serdar AŞUT
Architect

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ABBREVIATIONS

2D	: 2 Dimensional
3D	: 3 Dimensional
AmI	: Ambient Intelligence
API	: Application Program Interface
AR	: Augmented Reality
BFH	: Bern University of Applied Sciences
CAAD	: Computer Aided Architectural Design
CAD	: Computer Aided Design
CAM	: Computer Aided Manufacturing
CLI	: Command-Line Interface
CUI	: Console User Interface / Character User Interface
DOF	: Degree of Freedom
FDM	: Fused Deposition Modelling
GUI	: Graphical User Interface
HCI	: Human-Computer Interaction
iHCI	: Implicit Human-Computer Interaction
IE	: Intelligent Environments
IM	: Interactive Manufacturing
IT	: Information Technologies
LM	: Leap Motion Controller
NUI	: Natural User Interface
NURBS	: Non-Uniform Rational Basis Spline
RE	: Reverse Engineering
RFID	: Radio-Frequency Identification
SDK	: Software Development Kit
TIM	: Tactile Interaction for Making
ubicomp	: Ubiquitous Computing / Pervasive Computing
VR	: Virtual Reality

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DESIGN AS MAKING:
INTEGRATION OF DESIGN DEVELOPMENT AND FABRICATION THROUGH HUMAN-COMPUTER INTERACTION

SUMMARY

This research claims that that the benefits of the digital design environments are not limited to representative qualities or computational support to design thinking. It puts forward that the digital environments contain profound potentials towards integrating with the material world and that the improvements in information technologies can enable us to develop digital design tools which can suit the very nature of the act of design. To this end, it first argues a critical discourse within design thinking and methods towards an understanding of design as a form of making. Then, it introduces the key concepts and recent approaches in Human-Computer Interaction (HCI) research from a designerly perspective and reviews them within design knowledge. Eventually it demonstrates how to bridge the gap between the physical and digital environments in design process by using the existing tools and methods through an applied project.

The research consists of three main parts. The first part provides a theoretical framework on the research objectives. It presents a critical discourse within design thinking and methods mainly from a phenomenological perspective and quotes the related literature. Eventually, it puts forward that intuitive skills and tactile interaction are important notions in the design process and they have profound impact in design studies. Also, it broadly introduces the recent developments in HCI research in order to quote the fundamental know-how in HCI and to guide the designers towards developing better digital design tools. This part is based on a literature review and the theoretical discussions on it and it introduces certain concepts and approaches to the field of design, in which these concepts and approaches are relatively new.

The second part presents a comprehensive review of the state of the art in HCI studies which focus on design development and fabrication in order to point out the potentials in relation with the research objectives. The review starts with the early examples in 1960s and focuses on the most relevant ones which were held in the last 15 years. Accordingly, it presents a chart which lists 68 projects in a taxonomic categorization. The review points out that there is recently a significant increase in the number of HCI systems which are developed to be used in design development or fabrication. Also, there is a particular increase in the HCI systems which address fabrication in the recent years. It is suggested that the reason for this situation is that the computer aided manufacturing systems have been becoming more flexible and widespread since a couple of years. One may argue that the HCI systems which address the notion of craft will become even more widespread and efficient in the near future due to the improvements in these technologies.

After the broad review, 12 projects from the list were selected for having stronger relationships with the objectives of this research. These 12 projects were analyzed for the mode of interaction they contain, the means of interaction they provide, their outputs, and their performance for providing materiality, affordance, multimodality and intuitiveness. This analysis points out the relationships between the modes and means of interaction and the properties of the outputs and performance in each

project. Therefore, it points out the benefits and drawbacks in each approach and indicates the possible future directions towards developing better interactions. This part is based on a comprehensive literature review and analysis.

The third part is conducted as an applied research project. In this part, an HCI application for design is developed following a series of experiments using Computer Aided Design and Manufacturing (CAD/CAM) techniques. The application is named TIM (Tactile Interaction for Making) and it is a hybrid design medium which connects physical and digital environments in order to integrate design development and fabrication towards the conception of design as an activity of making. It is developed in order to test the applicability of the research objectives and to demonstrate a potential strategy for developing better interaction systems which can suit the very nature of design thinking.

TIM enables the user to build a model by using physical materials. This process is monitored by an optic motion controller device. By this means, a digital representation of the model is simultaneously generated. Additionally, the representation can be scaled and optimized following certain parameters with the help of a computer algorithm. This digital representation communicates with a desktop scale 3 axis robot arm. Therefore, the robot arm can duplicate the movements of the hands of the designer based on the optimization values and produces a physical copy of the model in the desired scale.

The application which is developed in this research is a small prototype. Its main objective is to demonstrate how to realize the interaction which is proposed in this research. Eventually it embodies; the potential of tactile and bodily interactions with the digital design environment; the possibility of practicing design thinking through the object and physical materials; the benefit of optimization of design decisions with computational support; and the conception of design as an activity of making with the support of robotic systems.

The conclusion of the research is mainly focused on the evaluation of TIM and the review of the research objectives and methods in relation with the qualities of the application. It argues the scenarios which can benefit from the form of hybrid interaction which is provided by TIM. For example, the first scenario appears in a form of linear workflow from the designer to the robot in which the robot identically duplicates the behaviors of the designer and derives the actual object from a three dimensional sketchy physical model. In another scenario, the designer and the robot collaborates through sequential and synchronous turns in order to produce an object together. In a third scenario, more than one designer and robot can establish remote collaboration and coordinate a design development or fabrication process together.

The fields which can benefit from hybrid tools which are embodied by TIM are described and discussed in this part. It is proposed that mainly the creative fields such as design and arts can profoundly benefit from such direct, organic and mutual interactions between the physical and digital environments. Particularly design fields which are subject to the production of three dimensional objects such as architecture, product design, interior architecture and fashion design; and artistic applications from interactive installations to performing arts can make use of such hybrid media. Additionally, not only the practice but also the education in these fields can benefit from such interactions. It can particularly serve to remote collaboration in teaching and distance learning applications. On the other hand, it is suggested that this interaction can be developed towards addressing certain fields which are subject to hazardous work and still require the intuitive skills of the human. For example, fields like construction, mining, aviation, submarine and medical operations can benefit from this integration of the humanly intuitiveness and robotic functionalities. Besides these evaluations, a methodological discussion is presented towards improving the capabilities of the medium in order to guide the following research.

Both the review of the state of the art and the applied research phase are able put forward and prove that digital design media is not only representative but also profoundly related with materiality. They demonstrate that particularly the new developments in HCI technologies enable direct, organic and mutual interactions between the physical and digital environments; which is a key aspect to develop better design tools. By this means, it becomes possible to reframe design as an activity of making. So that the qualities of traditional and typical craftsmanship are re-integrated into design thinking and the tacit dimensions of design knowledge are involved with the help of computer systems.

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ÖZET

Bu araştırma, sayısal tasarım ortamlarının sunduğu faydaların sadece tasarımın temsiline ilişkin olanaklarla veya tasarım sürecinin işlemsel (hesaplamalı) yöntemlerle desteklenmesi ile sınırlı olmadığı görüşüne dayanmaktadır. Sayısal ortamın somut olan ile doğrudan ilişkiler kurmak adına da verimli olanaklar barındırdığı ve bilişim teknolojilerinin bu doğrultuda ele alınıp geliştirilmesi sayesinde tasarım eyleminin doğasına uygun sayısal tasarım araçlarının geliştirilebileceğini savunur. Bu amaçla öncelikle tasarımın bir yapma eylemi olduğu savı doğrultusunda tasarım düşüncesine ve tasarlama yöntemlerine yönelik eleştirel bir söylem önermektedir. Bu savla ilişkili olarak İnsan-Bilgisayar Etkileşimi (İBE) alanındaki güncel yaklaşımları ve anahtar kavramları tasarım perspektifinden değerlendirerek bu yaklaşım ve kavramları tasarım bilgisi bağlamında tartışır. Sonuç olarak da mevcut araç ve yöntemleri kullanarak tasarım sürecinde somut ile sayısal ortam arasında ilişkiler kuran olası bir yaklaşımı uygulamalı olarak örneklendirir.

Araştırma üç ana kısımdan oluşmaktadır. Birinci kısım araştırma hedefleri ile ilgili kavramsal bir çerçeve sunar. Özellikle fenomenolojik bir bakış açısı ile tasarım sürecinde kullanılan düşünme biçimleri ve yöntemlere ilişkin eleştirel bir söylem ortaya koyar ve bu söylemle ilişkili literatüre atıfta bulunur. Sonuç olarak sezgisel becerilerin ve dokunsal etkileşimin tasarım sürecinde çok önemli hususlar olduğunu ve tasarım araştırmaları literatüründe bu kavramların önemli etkilerinin olduğunu savunur. Bunun yanı sıra daha iyi tasarım araçları geliştirilmesine yol gösterebilmek amacıyla bu kavramlar ışığında İBE araştırmalarının sunduğu temel bilgi birikimini ve bu alandaki güncel yaklaşımları aktarır. Bu kısım literatür araştırmasına dayalı kavramsal bir tartışma içermekte ve tasarım alanında görece yeni olan bazı kavram ve yaklaşımları bu alanın bilgisine dahil etmeyi hedeflemektedir.

İkinci kısım İBE alanında geliştirilen uygulamaların son durumunu ortaya koyan kapsamlı bir değerlendirme sunmaktadır. Bu değerlendirme özel olarak tasarım geliştirme ve imalat alanlarında kullanılmak üzere geliştirilmiş uygulamalara odaklanır. 1960'lı yıllarda ortaya çıkan ilk örnekleri ele aldıktan sonra son 15 sene içinde geliştirilen uygulamaları tarar ve bu taramanın sonucunda taksonomik bir sınıflandırma altında analiz edilen 68 uygulamayı bir tablo halinde sunar. Tasarım geliştirme ve imalat uygulamalarında kullanılmak üzere geliştirilen İBE sistemlerinde özellikle son beş yılda önemli bir artış olduğu bu değerlendirme sonucunda gözlenmektedir. Özellikle imalat süreçlerini destekleyen İBE uygulamalarında son yıllarda önemli bir artış yaşanmıştır. Bu durumun, bilgisayar destekli imalat sistemlerinin git gide esnekleşmesi ve yaygınlaşmasından kaynaklandığı düşünülmekte ve bu sistemlerdeki gelişmelere bağlı olarak yakın gelecekte zanaat fikrini desteleyen İBE uygulamalarının daha da verimli sonuçlar otaya koyacağı öngörülmektedir.

Bu genel değerlendirmenin ardından, bu uygulamalar arasında bu araştırmanın hedefleri ile en yakından ilgili olan 12 uygulamaya ilişkin daha kapsamlı bir çözümleme de yine bu kısımda yapılmıştır. Bu amaçla, özgün bir çözümleme yöntemi kullanılmış, uygulamalar barındırdıkları etkileşim tipi, kullanıcıya sundukları etkileşim

yöntemleri, sundukları çıktılar ve bu araştırmanın hedefleri ile ilişkili olarak sahip oldukları maddesellik, sağlarlık, çok yönlülük ve sezgisellik değerleri göz önünde bulundurularak ele alınmıştır. Bu çözümleme sayesinde her bir etkileşim tipi ve yönteminin çıktılar ve bahsedilen değerler ile arasındaki ilişkileri gözlemek mümkün olmaktadır. Bu sayede her bir uygulamanın barındırdığı yaklaşımın fayda ve eksikleri görünür kılınarak yakın gelecekte yeni uygulamaların ilerleyebileceği olası yönler işaret edilir. Bu kısım kapsamlı bir literatür taramasına dayalı bir değerlendirme ve çözümleme içermektedir.

Üçüncü kısım uygulamalı bir araştırma projesi olarak yürütülmüştür. Bu kısımda Bilgisayar Destekli Tasarım ve İmalat (CAD/CAM) teknolojilerinin kullanıldığı bir dizi deney yapılarak tasarımda kullanılabilecek yeni bir İBE uygulaması geliştirilmiştir. TIM (Tactile Interaction for Making / Yapma İçin Dokunsal Etkileşim) adı verilen bu uygulama, *bir yapma eylemi olarak tasarım* önerisi doğrultusunda tasarım geliştirme ve imalat aşamalarını bütünleştirmek amacıyla somut ve sayısal ortam arasında karşılıklı ilişkiler kuran melez bir tasarım aracıdır. Araştırmanın hedeflerinin uygulanabilirliğini sınamak ve tasarım eyleminin doğasına uygun etkileşim sistemleri geliştirebilmek için kullanılabilecek olası bir stratejiyi örneklemek amacıyla geliştirilmiştir.

TIM sayesinde tasarımcı, somut malzemeler kullanarak bir model inşa eder. Bu süreç bir hareket kontrol aygıtı tarafından optik olarak izlenmektedir. Bu sayede tasarımcının elleri ile inşa ettiği modelin bir kopyası sayısal ortamda eş zamanlı olarak üretilir. Bununla birlikte modelin şekli sayısal ortamda geliştirilen bir algoritma sayesinde belirli parametrelere bağlı olarak optimize edilebilir ve yeniden ölçeklendirebilir. Bu şekilde üretilen sayısal model ise 3 eksenli bir masa üstü robot kola veri aktarmaktadır. Bu sayede robot kol da tasarımcının el hareketlerini verilen optimizasyon değerlerine bağlı olarak tekrar eder ve benzer bir somut modeli istenilen ölçekte tekrar üretir.

Burada geliştirilen uygulama küçük ölçekli bir prototiptir ve esas amacı araştırma kapsamında öne sürülen etkileşim biçiminin nasıl gerçekleştirilebileceğini örneklemektir. Bu kapsamda tasarımcının sayısal tasarım ortamı ile dokunsal ve bedensel etkileşim kurma imkânı, tasarım düşünme süreçlerini doğrudan nesne üzerinden ve somut maddeler aracılığı ile gerçekleştirme olanağı, sayısal ortamın işlemsel becerilerini kullanarak tasarım kararlarının optimize edilmesi ve robotik imalat tekniklerinin sisteme dahil edilmesi ile tasarımın bir yapma eylemine dönüşmesi önerileri somutlaşmış olur.

Araştırmanın sonuç kısmı yoğun olarak TIM'in değerlendirilmesine ve bu sayede araştırma hedeflerinin ve yönteminin gözden geçirilmesine dayanmaktadır. TIM aracılığıyla sağlanan melez etkileşim biçimlerinin kullanılabileceği olası senaryoları tartışır. Örneğin, tasarımcının davranışlarının robot tarafından bire bir tekrar edilmesi ile sonuçlanan tek yönlü bir akış sayesinde eskiz niteliğindeki üç boyutlu somut bir modelin gerçek ürüne dönüşmesi olası senaryolardan biri olarak belirmektedir. Bir diğer senaryo, tasarımcı ve robotun ardışık ve eş zamanlı hamlelerle bir ürünü birlikte üretmesini sağlayacak biçimde karşılıklı bir etkileşim kurulması şeklindedir. Üçüncü bir senaryo ise birden çok tasarımcı ve robotun, paylaşılan bir sayısal model aracılığı ile uzaktan iş birliği kurması ve birlikte bir tasarım ve imalat sürecini yürütmesi şeklinde belirmektedir.

TIM aracılığı ile örneklendirilen melez araçların hangi kullanım alanlarında faydalı olabileceği de bu kısımda öne sürülmekte ve tartışılmaktadır. Bu şekilde somut ve sayısal ortamlar arasında doğrudan, organik ve karşılıklı ilişkiler kurmayı sağlayabilecek araçların öncelikle tasarım ve sanat gibi yaratıcı alanlarda kullanım alanı bulacağı öngörülmektedir. Özellikle mimarlık, ürün tasarımı, iç mimarlık veya moda tasarımı gibi 3 boyutlu somut nesnelerin üretimine odaklanan tasarım alanları ile etkileşimli yerleştirmelerden sahne sanatlarına uzanan sanat çalışmalarında bu tür etkileşim olanaklarının kullanışlı olacağı düşünülmektedir. Ayrıca yine bu alanlardaki eğitim uygulamalarının da bu tür ortamlardan beslenebileceği, özellikle eğitimde uzaktan iş birliği ve uzaktan öğrenme uygulamalarının sanat ve tasarım alanlarında da hayata geçirilmesini kolaylaştıracağı öngörülmektedir. Öte yandan bu tip araçlar insanın sezgisel becerileri ile robotik teknolojinin sunduğu pratik faydaları bir araya getirdikleri için insanın doğrudan müdahalesini gerektiren tehlikeli çalışma alanlarında da kullanılabilir. Örneğin inşaat, madencilik, havacılık, su altı çalışmaları ve tıp gibi alanlarda bu araştırmada örneklenen etkileşim biçiminin faydalı olacağı öngörülmektedir. Tüm bu değerlendirmelerin yanı sıra, ilerleyen araştırmalara yön verebilmek amacıyla uygulamanın nasıl daha da iyileştirilebileceğine yönelik yöntemsel bir tartışma da yine bu kısımda sunulmaktadır.

Hem ikinci kısımda gerçekleştirilen literatür taraması ve bununla ilişkili yapılan değerlendirme, hem de üçüncü kısımda gerçekleştirilen uygulamalı araştırma projesi sayısal tasarım ortamının sadece temsili bir ortam olmadığı, ayrıca somut olan ile de derinden ilgili olduğu tezini öne sürmekte ve ispatlayabilmektedir. Özellikle İBE teknolojilerindeki güncel gelişmelerin somut ve sayısal ortamlar arasında doğrudan, organik ve karşılıklı ilişkileri mümkün kıldığını göstermektedirler. Bu sayede tasarımı bir yapma biçimi olarak tanımlamak mümkün olabilmektedir. Böylece zanaata ilişkin geleneksel ve karakteristik nitelikler tasarım düşünme süreçlerine yeniden dahil edilebilmekte ve tasarım bilgisinin örtük kısımlarının bilgisayar sistemleri desteğiyle kapsanması mümkün olabilmektedir.

1. INTRODUCTION

1.1 Motivation, Hypothesis and Research Objectives

Weiser (1991) starts his influential paper by claiming that the most profound technologies are those that disappear and weave themselves into the fabric of everyday life until they are indistinguishable from it. The motivation of this research is to seek potentials for developing digital design tools which weave themselves into the fabric of designerly practices.

Within the context of this research, design refers to the creative form-giving practices. It addresses the fields which are subject to the production of 3 dimensional (3D) physical objects; such as architectural, product, interior, landscape or fashion design. In these fields, an understanding of designing as a form of creative crafting in which the designer works with physical materials through bodily and intuitive means is constructive.

This research proposes that the benefits of the digital design environments are not limited to representative qualities or computational support to design thinking. Further to that, digital media contain profound potentials towards directly integrating with the material world. One may claim that, design will benefit from building organic and direct interactions between the digital and physical environments by providing new design methods via new tools. To this end, the objectives of this research are as follows:

- To argue a critical discourse within design thinking and design methods towards an understanding of design as a form of making.
- To introduce the key concepts and recent approaches in Human-Computer Interaction (HCI) studies from a designerly perspective.
- To demonstrate how to bridge the gap between the physical and digital environments in design process by using the existing tools and methods.

Eventually, this research aims to provide two important outputs. The first output is a comprehensive review and analysis of the related studies which aim at developing interaction systems to be used in different phases of design development and fabrication. It is important to provide this review, because, the know-how in HCI field is relatively new to design fields. Moreover, the analyses of this review are useful as they point out the benefits and drawbacks of the approaches in each reviewed project. By this means, they indicate a roadmap to designers who aim at developing new systems which provide better interactions with digital media.

The second output is a prototype application named Tactile Interaction for Making (TIM). TIM is developed in this research in order to demonstrate a potential approach for developing interaction systems to be used in design development and fabrication. In fact, TIM is a demonstration of the integration of design development and fabrication as argued within the critical discourse towards the understanding of design as an activity of making. Therefore, it is a proof of the concept which demonstrates the potentials of the existing tools and methods and it indicates the future needs and solutions towards the research objectives.

Both the review and the application point out that it is possible to re-integrate the qualities of craftsmanship into design thinking and to involve the tacit dimensions of design knowledge more efficiently with the help of computer systems. In this context, designing is considered as a form of creative crafting. Eventually, the notion of "design as making" is rooted on this consideration.

1.2 Research Methods

The research consists of three main parts. The first part presents a critical discourse within design thinking mainly from a phenomenological perspective. The second part presents a review of the literature and state of the art in HCI studies, starting with the early examples in 1960s and focusing on the most relevant studies which were held in the last 15 years. Accordingly, 68 projects were analysed through a taxonomic categorization in order to point out the benefits and drawbacks, as well as the future directions.

The third part is conducted as an applied research project. In this part, an application is developed following a series of experiments using Computer Aided Design and Manufacturing (CAD/CAM) technologies. These experiments were held at Bern University of Applied Sciences (BFH) in Switzerland with the supervision of Prof. Dr. Odilo Schoch and the support of the Swiss Government Excellence Scholarship for Foreign Scholars and Artists for 12 months between September 2013 and September 2014. Following these experiments, TIM is developed as a prototype set-up by building new relations between the existing tools in order to provide a better interaction system which can sustain materiality, integrate design development and fabrication and enable intuitiveness in design process. Moreover, it is a proof of the concept which can be developed further in order to address the real world applications in design development or fabrication.

1.3 Outline

Chapter 2 aims at providing a theoretical framework on the research question. It addresses the most fundamental literature and key concepts in order to claim that intuitiveness and tactility are important notions in design thinking which have profound impact in design studies particularly from a phenomenological perspective. Moreover, it broadly introduces the recent developments in HCI studies in order to quote the fundamental know-how in HCI and to guide the designers towards developing better digital design tools within the research objectives. Chapter 2.1 aims at idealizing the concept of “design media” in the way it is used in this research. In this context, it refers to the diverse toolset of the designer, including both material and immaterial entities. It conflates brains, bodies and things by synchronizing the actions and perceptions of the designer. To this end, it is claimed that it needs to be developed for incorporating the bodily senses of the designer and tactile aspects of designing, while sustaining the intuitive skills of the human. Chapter 2.2 broadly addresses the developments in HCI technologies towards the research objectives. It underlines the key concepts which guide the recent developments and designates a conceptual road map towards developing digital design media which can sustain tactility and intuitiveness during design thinking. Chapter 2.3 addresses the most important key concepts and the fundamental literature within the third-wave in HCI, which is called the phenomenological matrix. Here, these studies are presented as both guides and inspirations towards tactile and intuitive interactions with the digital design media.

Chapter 3 aims at presenting the state of the art in order to point out the potentials in relation with the research objectives on concrete basis. Chapter 3.1 addresses the pioneering studies in the realm of intuitive HCI. Here, the Sketchpad (Sutherland, 1964) as being the first Graphical User Interface (GUI) system developed for Computer Aided Design (CAD), and the Seek (Negroponte, 1973) and 3D Modelling System (Aish and Noakes, 1984) projects as being the important early examples of direct relation between the physical and digital environments are described. Chapter 3.2 presents a comprehensive literature review of the related studies which were held between 2000 and 2015. It includes an overview of 68 projects which aim at building a bridge between physical and digital environments for design development or fabrication. Chapter 3.3 presents a detailed analysis of the most relevant 12 projects through a taxonomy of the features which they perform. The analysis proves the applicability of the research objectives and aim at guiding the designers towards developing better design tools.

Chapter 4 introduces the applied research which is conducted in order to test the applicability of the research objectives, to demonstrate the strategies for developing better interaction systems, and to point out the future directions. Chapter 4.1 presents the exploratory experiments which were conducted using the existing tools and methods within gestural modelling and reverse engineering applications in order to understand the potentials they provide. The benefits and drawbacks of each tool and method is defined following the experiments. Chapter 4.2 presents the application named TIM, which is developed in this research in order to point out a strategy for developing better interaction systems towards the research objectives using existing tools and methods. It is presented as a proof of the concept and is able to provide insight towards developing hybrid design media which can sustain tactility and intuitiveness during designing. Also, the limitations of the developed system and the means of improvement are described in this chapter in details.

Finally, Chapter 5 presents the evaluation of the research by describing its outputs, defining the possible forms of interactions using TIM and the possible fields which can benefit from such hybrid media.

2. A CRITICAL DISCOURSE TOWARDS DESIGN AS MAKING

2.1 Design as Rhetoric and Hegemony of the Eye

The motivation of this research stems initially from questioning the role of tool use on design cognition. As put forward by Dahlbom and Janlert (unpublished), just as you cannot do very much carpentry with your bare hands, there is not much thinking you can do with your bare brain (Dennett, 2000). One uses tools to perform physical and mental activities. In both cases, there are cognitive engagements between the user and his/her tools. They arise on two associated bases. Firstly, tool embodies certain knowledge which affects and is affected by human knowledge. Secondly, there exist conceptual tools as well as physical ones. Baber (2003) illustrates the first basis by mentioning the cognitive change when adapting a shoe heel for banging in a nail instead of using a hammer. Here, the hammer possesses a potential for achieving the goal, which becomes a gained knowledge by its user and is then adapted to a new manner of working with another tool. The second basis is defined by Vygotsky (1986) as the tools of the mind. They are symbolic cultural artefacts, such as signs, symbols, texts, formulae, maps, diagrams and language, which enable us to think and create (Vygotsky, 1986).

The act of design involves performing both physical and mental activities. It requires various forms of engagements with both material and immaterial artefacts, and is fully engaged with tool use; both physical and psychological ones, and the distinction between the two is often unclear. Hence, *design media* is a better phrase for addressing this diversity and complexity of designer's tool set. Design media is the environment of the act of design, which is subject to design thinking and execution. It involves the designer himself/herself, as well as his/her interactions with various types of tools. Its inherent qualities and economies are encouraged to shape both process and products in a condition of craft (McCullough, 1998); therefore is an actuator. In this research, the frequently coined concept of media refers to such a content.

Representation tools constitute the most common realm of design media. Modern disciplinary design methods, unlike vernacular forms of making, are in close engagement with representation tools. Indeed, modern understanding of design fairly addresses the production and processing of representation tools; just like Schön (1984a) defines design as an activity of producing the representations of the things to be built. According to him, design is a reflection-in-action with talking backs which emerge as the spontaneous reciprocal reflections between the maker and representations (Schön, 1984a). Though, his precious definition does not address the materiality of design artefacts as a potential participant of the reflective conversation.

Representation is abstraction. Typically, design representation is considered as the visual abstraction, an imagery of the things to be built. Therefore, sense of sight is hegemonic in our relationships with artefacts in design development and evaluation, through their representations. Modernist design methods celebrate the eye as a superior sense organ above the others. They emphasize a praise of sight. Herewith, they constrain our relationships with things to what is visual in an abstract sense. Moreover, they distinctly separate design and making. Because, in the age of professionalism and expertise, designer is responsible for the production of rhetoric. And this rhetoric is principally produced by and for the eye, because, like Pallasmaa (1996) mentions, the only sense that is fast enough to keep pace with the astounding increase of speed in the technological world is sight. The modern praise of sight is mentioned by Sontag (1977) too, with an emphasis on image. She claims that; the reality has come to seem more like what is shown by the camera; and the people of the industrialized countries seek to have their photographs taken because they feel that they are images, and are made real by photographs. That is; the image is the reality in modern world; and to see is to believe in it.

Steiner (1958) claims that the five classical senses fuse into each other in several ways and generate a complex perception system which eventually constitutes twelve senses such as the senses of sight, taste, smell, balance, movement, life, touch, ego, thought, speech, hearing and warmth. He categorizes them as the outward and the inward senses (Figure 2.1). The ones which are directed more towards the outside are adapted more to penetrate the outer world. The inward senses let us perceive ourselves in the things, and the effect of things upon us (Steiner, 1981). In this regard, the sense of sight is outward, whereas the sense of touch is inward.

Also, Gibson's (1983) definition of senses as being aggressively seeking mechanisms rather than passive receivers considers the perceptual system as a continuously operating actor. This is strongly related with Merleau-Ponty's (1962) definition of embodied perception, which is not a passive receptor activity but an active involvement of the whole body. Neglecting this complex system of perception of the involving body, and letting the sight be hegemonic over the other senses will disable most of the capabilities of the individual and constrain his/her existence to a witness who has nothing but eyes to perceive; in Pallasmaa's (1996) terms, a bodiless observer.

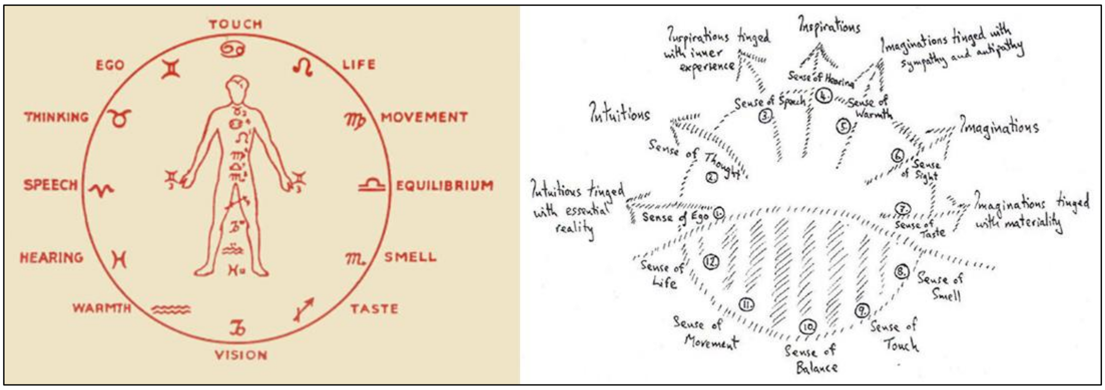

Figure 2.1 : Human's 12 Senses as defined by Steiner (1981).

We need to consider design as a practice which involves the complex mechanisms of perception and enables various forms of engagements, both bodily and cognitively, between material and immaterial entities. Therefore, we need to develop design media which can perform as actuators in collaboration with the designer. In other words, diverse tools which are the aids of imagination and instruments of thinking tied to the body (Latour and Yaneva, 2008). Thus, they will perform as the extensions of one's bodily range and the bodily synthesis like defined by Merleau-Ponty (1962).

Our relationships with the material world are not always based on explicit knowledge. Polanyi (1966) claims that we can know more than we can tell, in order to refer to the realm of knowledge which is not possible to express by verbal means. Many of such engagements are rooted on tacit knowledge. Also, the tacit knowledge that many physical situations afford plays an important role in expert behaviour (Klemmer et al., 2006). So, the knowledge which is required for a successful work is not always explicit. Likewise, a significant part of design knowledge is tacit. According to Cross (1982), what designers know about their own problem-solving processes remains largely tacit knowledge -ie they know it in the same way that a skilled person 'knows' how to perform that skill. And as mentioned by Schön (1984b), knowledge comes from our action. We know 'it' by acting and perceiving.

Within the knowledge acquired by perception, Diderot (1916; originally published in 1749) claims that the eye is the most superficial, the ear is the haughtiest, smell is the most voluptuous, taste is the most superstitious and inconstant, and touch is the most profound and philosophical (Diderot, 1916). What is profound about touch is that, it is not only a way of receiving but also a way of transmitting. Moreover, Pallasmaa (1996) claims that all the senses including vision are extensions of the sense of touch and the senses are specializations of the skin; and all sensory experiences are related to tactility. Tactility enables mutual engagements with things. It allows the hybrid assemblage of brains, bodies and things, which is defined as the way we think by Malafouris (2013).

While the primacy for sight is witnessing; for touch it is making. This research principally aims at proposing hypothetical framework for design as making. To this end, it seeks potentials for developing design media, which can incorporate brains, bodies and things in a hybrid environment and enable material engagements with the design object in order to involve the tacit dimensions of design knowledge with the help of digital design media.

2.2 On Tactility within Digital Design Media

Bourguet (2009) claims that people are good at sensing and manipulating physical objects, but these skills seldom are used in HCI. Similarly, according to Waterworth (1997), who suggests that computer systems are better at directly supporting sensation than cognition (rational problem-solving) in their users, the purpose of the computer technologies should be to broaden our channels of sensation (and communication), allowing us to experience reality more fully and making us more creative in the face of life's challenges. However, as pointed out by Preece et al. (1994), there has been a lack of consideration of other aspects of behaviour besides how users process information at the interface –namely, how people interact with each other, and other objects besides computer systems, in the environment they are in. As a consequence, what we need is not to withdraw from our physical relationship with things, but to sustain and enhance it by the help of novel technologies, tools and paradigms.

There are two crucial notions towards developing actuator design media which can sustain and enhance our physical relationship with things: the theory of affordances and the synchronization of action and perception. The theory of affordances was originally introduced by psychologist Gibson (1977) in order to address the possibilities of actions which are formed by the relationship between an agent and its environment. Norman (1990) introduces this notion into design, in order to address the relationship between a physical object and a person (or for that matter, any interacting agent, whether animal or human, or even machines and robots). He claims that, an affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used (Norman, 1990). Towards the objectives of this research, the term can relate to both software and input systems within digital design media. This research focuses on the latter. In this sense, the common input devices are not capable of performing affordance. The lack of affordance of the most common computer interaction techniques cause uncertainties about the functionalities of input devices (Sharlin et al., 2004). For instance, a mouse, which is the most common input device which can perform various functions in a computer system, is far from affording its functionalities. It is a versatile apparatus, which is able to perform various tasks, ranging from working with a text editor to playing video games. However, its generic form and the way the user operates it do not differ much towards addressing the variety of the tasks of which it can execute.

Sutphen et al. (2000) seek interface affordances as well as the synchronization of the perception space and the action space for better interactions. They claim that, the spatial and temporal natural synchronization of our perception space and our action space enables us to perform complex tasks (Sutphen et al., 2000). This notion addresses a real-time interaction with the medium, which is the environment of both the perception and the action. Such interactions are present in traditional form-giving work, which is coined as the source of inspiration by McCullough (1998) for developing more engaging technology, as well as developing more receptive attitude towards new opportunities raised by technology. Perception and action are temporally and spatially synchronized in traditional form-giving work. The synchronization enables direct and immediate reflections between the maker and the object. Hence, making becomes a dialogue between the object and the maker.

The actuator design media need to afford the user and to synchronize the actions and perceptions. To this end, we need to develop multimodal interaction systems. Multimodality refers to interaction with the virtual and physical environment through natural modes of communication such as speech, body gestures, handwriting, graphics or gaze (M. Bourguet, 2003). Therefore, they incorporate the senses of the human. In this regard, the interface becomes a natural and organic layer. Actually, in its ultimate sense, this layer entirely dissolves.

Involving the senses of the human is becoming more achievable by the evolution of HCI technologies. The modern HCI systems consider three manners within this evolution; Command-Line Interfaces (CLI) (also referred as Command Language Interpreter, Console User Interface or Character User Interface (CUI)), Graphical User Interfaces (GUI) and Natural User Interfaces (NUI).

CLI refers to the form of interaction where the user inputs commands to the system through consecutive lines of text (Figure 2.2). This mode of interaction distinctly separates the perception space and the action space. It requires the use of symbolic systems; therefore, it requires cognitively advanced abstraction.

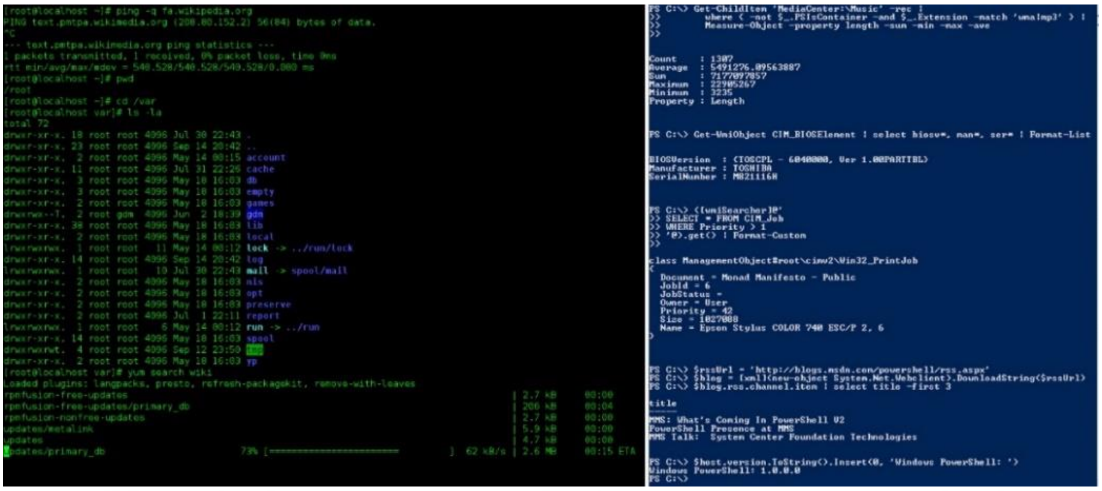

Figure 2.2 : Examples of CUI. Left: Linux command-line (Url-1); Right: Windows PowerShell (Url-2).

GUI allows the user to interact through graphics on a screen (Figure 2.3). The interaction is achieved by means of Windows/Icons/Menus/Pointer (WIMP) (Figure 2.4). Yet, many of the natural abilities of human are being blocked by the common Keyboard/Mouse/Monitor interface and the WIMP interaction (Sharlin et al., 2001). Also, as 3D object manipulation and movement requires much more than a 2 DOF interface, a WIMP method of object interaction tends to interfere with fluidity (Gauldie et al., 2004). In such interactions, the pointer is controlled by using generic devices such as the mouse or the fingers on touch screens. Such devices do not perform affordance as they do not naturally guide the user towards their functional characteristics. They are functionalized by not their form but the software used. The use of fingers may have both pros and cons in terms of enhancing the interaction. However, in either way, GUI-based HCI displays all information as “painted-bits” on rectangular screens in the foreground, thus restricting itself to very limited communication channels; and they fall short of embracing the richness of human senses and skills people have developed through a lifetime of interaction with the physical world (Ishii and Ullmer, 1997).

The still hypothetical concept of NUI aims at providing more intuitive interaction modes. Principally, NUI need to be multimodal, invisible and intuitive. Affordance is key to intuition. So, a novice user can intuitively start using the system and experience a steep learning curve. NUI is relevant to most of our everyday interactions with material world through tactile engagements. Indeed, the most seamless interaction with computer systems could emerge by, in Ishii and Ullmer’s (1997) words, changing the world itself into an interface. And by moving the interface out of the screen we move it closer to the human world (Svanæs, 2001). In other words, the better interaction shall happen in the physical environment of the designer, rather than on the screen. This is way the more recent studies in HCI mention the interaction itself instead of the interface.

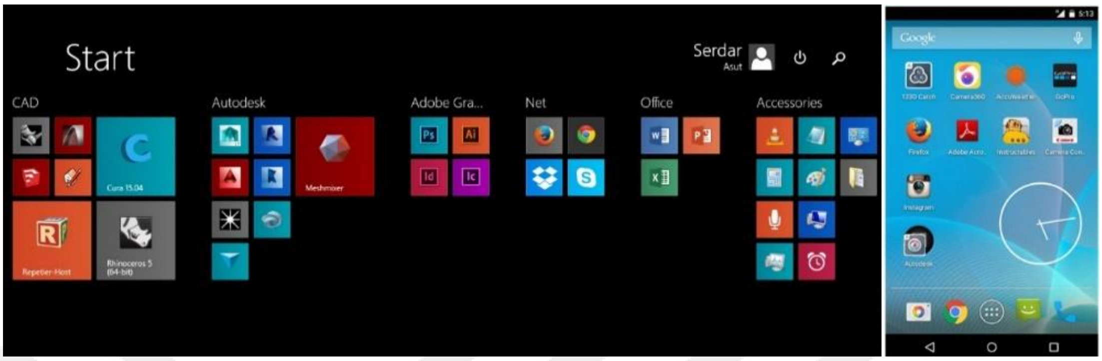

Figure 2.3 : Examples of GUI. Left-side: Windows; Right-side: Android.

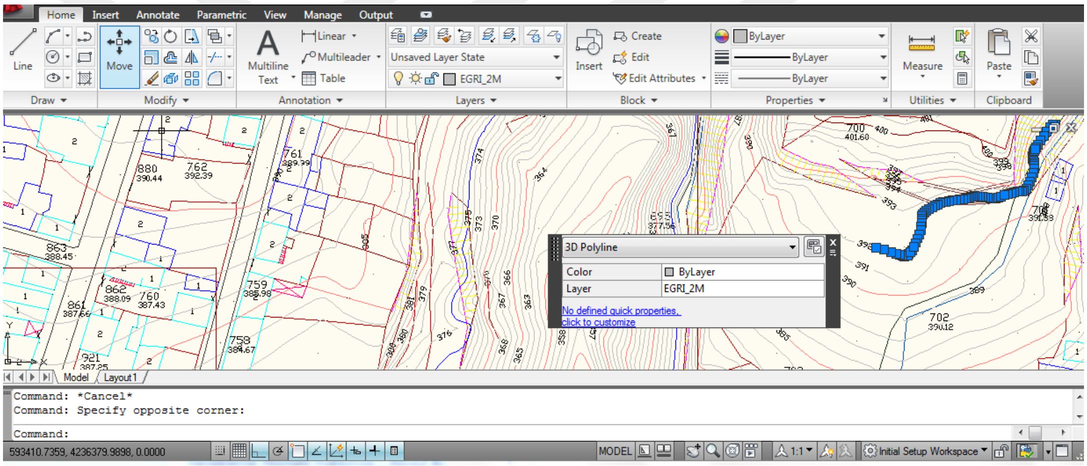

Figure 2.4 : The WIMP Interface of a typical CAD application.

The improvements in HCI technologies towards developing multimodal and intuitive NUI systems will enable us to integrate the tactile dimensions of design thinking into our engagements with digital design media in the near future. By this means, we will be able to develop computer systems which can fit into human environments by enhancing the existing world (Weiser, 1999) instead of simulating it by making a world inside the computer (Weiser, 1991) (Figure 2.5). To this end, we need to transfer the knowledge and techniques which are being developed in HCI studies into design.

Figure 2.5 : Left-side: Oculus Rift Virtual Reality Headset (Url-3); Right-side: The Incredulity of Saint Thomas by Caravaggio, 1601-1602 (Url-4).

2.3 Potentials for Enhanced Interactions

One can find potentials for enhanced, bodily and intuitive interactions with digital design media through certain key concepts of the so-called third-wave HCI, which is named as the phenomenological matrix by Harrison et al. (2007). They claim that the third-wave treats interaction not as a form of information processing but as a form of meaning making in which the artefact and its context at all levels are mutually defining and subject to multiple interpretations. Similarly, Bødker (2006) claims that the third wave in HCI includes new elements of human life, such as culture, emotion and experience by conceptually and theoretically focusing on the cultural level, expansion of the cognitive to the emotional, or a pragmatic/cultural-historical focus on experience.

Schmidt (2000) defines the concept of Implicit Human-Computer Interaction (iHCI) as an action performed by the user that is not primarily aimed to interact with a computerised system but which such a system understands as input. The implicit dimension to HCI is rooted on certain concepts within the discipline of Human-Centered Computing, such as Ubiquitous Computing (ubicomp; also called Pervasive Computing), Calm Technology, Context Awareness, Intelligent Environments (IE), and Ambient Intelligence (AmI). Each of these concepts is strongly related with each other while having minor differences.

Satyanarayanan (2001) characterizes a ubicomp environment as one saturated with computing and communication capability, yet so gracefully integrated with users that it becomes a ‘‘technology that disappears”. Calm technology refers to the computer systems which engage both the centre and the periphery of our attention; while periphery stands for what we are attuned to without attending to explicitly (Weiser and Brown, 1997). Context-aware computing is the ability of a mobile user's applications to discover and react to changes in the environment they are situated in (Schilit and Theimer, 1994). Augusto et al. (2013) define IE as environments in which the actions of numerous networked controllers are orchestrated by self-programming pre-emptive processes in such a way as to create an interactive holistic functionality that enhances occupants experiences. AmI refers to electronic environments that are sensitive and responsive to the presence of people (Aarts and Encarnação, 2006).

As a result, the hybrid design media of intuitive interactions is a matter of environment in which the computer system disappears. It is programmed and functionalized in a way that is aware of the user and the particularities of the context of use. This notion addresses Norman's (1993) definition of soft technology. He argues that; soft technology refers to compliant, yielding systems that informate, that provide a richer set of information and options than would otherwise be available, and most important of all, that acknowledge the initiative and flexibility of the person; whereas hard technology refers to those systems that put technology first, with inflexible, hard, rigid requirements for the human (Norman, 1994).

One may address the traditional understanding of craftsmanship in order to challenge with HCI systems which are compliant in design. Luckily, like claimed by Golsteijn et al (2014), craft has recently started to gain interest from the HCI community, and over the past years, a number of studies have looked at craft practice to inform design or have developed ways to combine technology with more traditional means of crafting to support new craft practices with digital technology. Craftsmanship simply means workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works (Pye, 1978). Pye (1978) claims that, the quality of the result is continually at risk during the process of making; and so he calls it the workmanship of risk. Similarly, Dutta's (2007) definition of felicitous error refers to a variation from the programmed and indeterminacies in physical processes, and is defined as being essential to craft. Both felicitous error and workmanship of risk are rooted on the tacit and inarticulable dimensions of craft skills, and are not to be afraid of. Sennett (2009) addresses this by claiming that the craftsman's desire for quality poses a motivational danger: the obsession with getting things perfectly right may deform the work itself.

The tacit dimension of craftsmanship is based on many aspects of the interactions between the craftsman and his/her environment. One of these aspects is the material. Material embeds its content through its qualities, behaviours and demands into craftsmanship, which are not fully predictable and computable. Hence, there is need to associate materiality with design thinking during our interactions. This association is addressed by Gramazio and Kohler (2012) as “digital materiality” towards integrating design development and fabrication within the use of digital media. They claim that, design and execution are no longer phases in a temporal sequence and design sketches do not need to be converted into execution drawings anymore; and accordingly, the design incorporates the idea and knowledge of its production already at its moment of conception (Gramazio and Kohler, 2012). In fact, this approach re-celebrates material qualities as actors in design thinking. Thus, material, with the medium, becomes the message. Designing becomes a direct interaction with the material rather than processing its abstract representations. Referring back to Schön (1984), design becomes a reflective conversation with talking-backs between the designer and the material. The material provides input for design development and the output is perceived by the designer through bodily interactions. In this sense, the act of design is upgraded to a whole practice of making which integrates design development and fabrication. This framework corresponds to vernacular forms of making, in terms of not the economic or legal context but design knowledge. Therefore, one may claim that, design as making through actuator hybrid media which enable intuitive and multimodal interactions with the material will herald a contemporary vernacular.

3. A CRITICAL REVIEW OF THE RELATED STUDIES

3.1 Pioneering Studies towards Hybrid Environments

Around half a century ago, Sutherland (1964) have mentioned that most interaction between man and computers has been slowed down by the need to reduce all communication to written statements that can be typed. He developed a system called Sketchpad, which was in favor of line drawings instead of typed statements in early 1960s. It was the pioneering demonstration of direct user input into digital design environment. Therefore, it is often coined as the first GUI or HCI application for CAD. What Sutherland proposed was a tangible device; a light pen integrated with a control box which contains command buttons like draw, move or rotate (Figure 3.1). The device allowed the user to use his/her hands in real 3D for performing certain functions. It enabled a spatial interaction through a handheld device, while today's most common input devices like the mouse or touchpad is able to operate only on 2D surfaces.

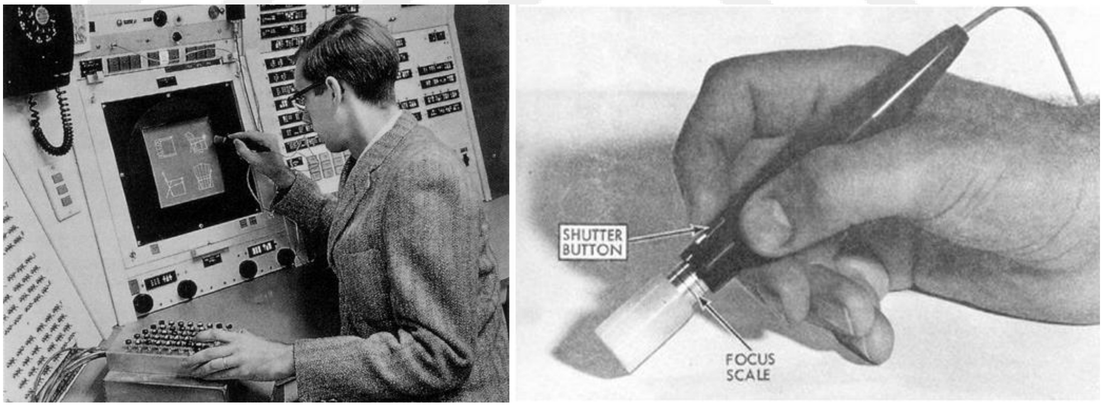

Figure 3.1 : Sketchpad (Url-5; Url-6).

Studies towards more enhanced interactions date back to 1970s. The Architecture Machine Group of Nicholas Negroponte was one of the pioneers who worked on outstanding projects such as the Seek (Negroponte, 1973). It was demonstrating a possibility of a direct relationship between the model world and the real world. It included 500 metal plated cubes of 5 cm dimension and curious gerbils inside an enclosed space (Figure 3.2). The cubes were constantly being moved by the gerbils. These movements were being recorded and repeated by a robot arm. Negroponte (1975) defines the output of Seek as a constantly changing architecture that reflects the way the little animals used the place. Now after 40 years, it must be possible to integrate intellect with curiosity and provide opportunities for the reflection of the way the humans make places.

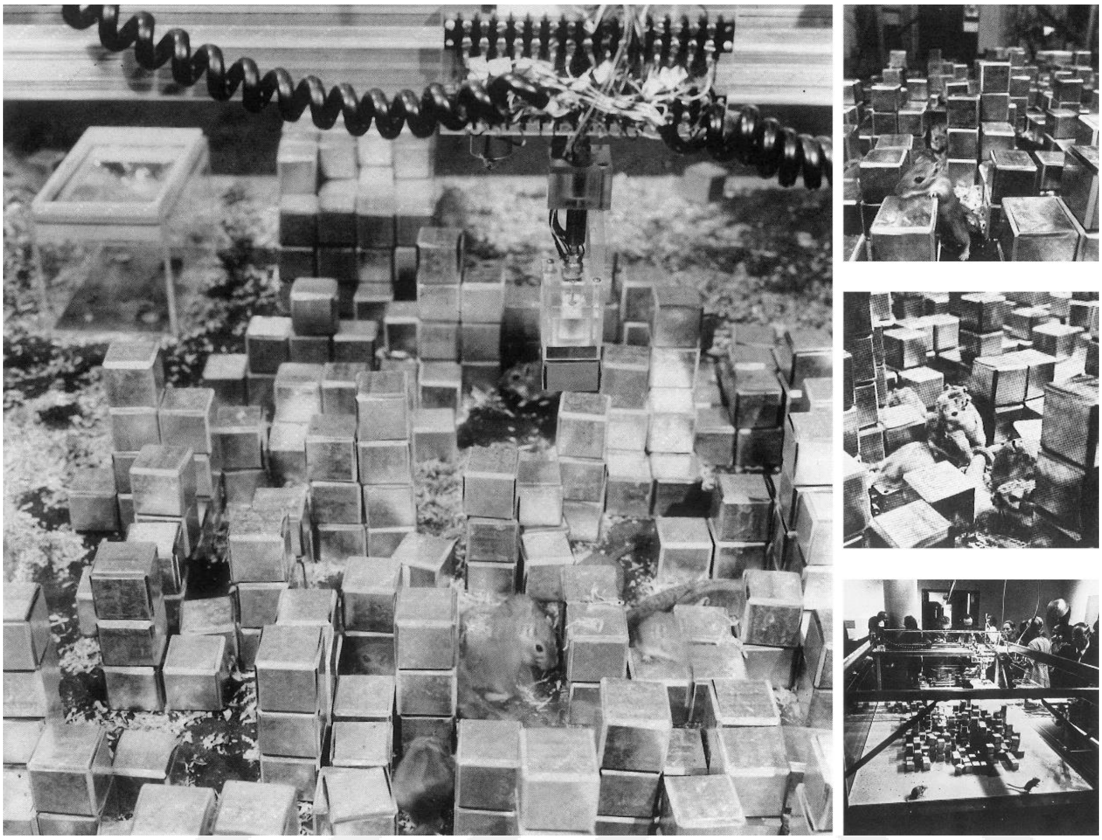

Figure 3.2 : Seek exhibit at New York Jewish Museum (Negroponte, 1975).

Aish (1979) claimed that it is often difficult for the user of conventional graphic computer aided architectural design (CAAD) systems to conceptualize the building being designed by only inspecting and manipulating drawings displayed on the screen. He proposed a 3D input method for CAAD systems to complement the graphical channel of man-machine communication by enabling much of the 3D information to be communicated by the designer directly to the system (Aish, 1979). The system allowed the user to directly pick up the blocks and build a model without the need to learn operating commands (Aish and Noakes, 1984). It was an early significant demonstration of the applicability of hybrid design media which naturally complement the intuitive skills of the human and the capabilities of the computer (Figure 3.3).

Both projects profoundly relate with the hypothetical proposal of hybrid design media, which is presented in this research. They seek reciprocal, direct and organic interactions between the physical and digital environments; or, in Negroponte's words, between the real and the model worlds. Yet, they propose interaction via generic agents; simple blocks which perform as abstract representations of design artefacts. Therefore, their capabilities constrain the performance of the system. On the other hand, they are not capable of and are not aiming at putting forward a comprehensive framework for an approach to design as making. They rather aim to provide better functionalities for the use of digital platforms.

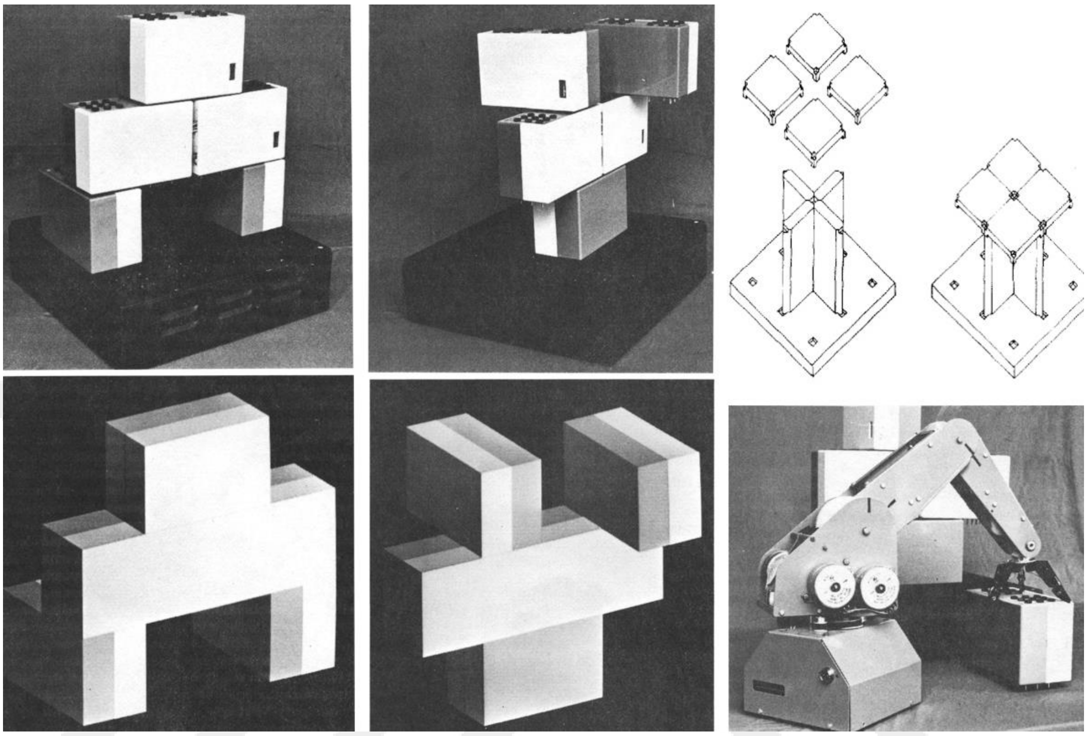

Figure 3.3 : 3D Modelling System (Aish and Noakes, 1984).

3.2 Emerging Approaches towards Direct Interactions

Recent improvements in HCI technologies enable us to develop more enhanced interactions towards achieving seamless workflows and debating critical frameworks for the act and discourses of design. All of the related works would constitute a very long list. Therefore, this review is limited to the projects held since 2000. The ones which have relevance within this critical discourse towards its motivations, intentions or objectives are listed in Table 3.1.

Table 3.1 : Overview of the related work.

Name of the Project	Year	Field of Use	Main Objective	Addressed Audience
Human-Assisted Additive Manufacturing (Yoshida et al., 2015)	*2015*	*Architecture*	*Fabrication*	*Craftsman*
ReForm (Weichel et al., 2015)	*2015*	*Design (General)*	*Fabrication*	*Designer*
Being the Machine (Devendorf and Ryokai, 2015)	*2015*	*Design (General)*	*Fabrication*	*Designer*
CAD Interaction Lab (Beattie et al., 2015)	2015	Design (General)	CAD Visualization	End user
TADCAD (Te, 2015)	2015	Design (General)	Digital Modelling	End user
WrapIt (Iarussi et al., 2015)	2015	Fashion Design	Fabrication	Craftsman
Kinetic Blocks (Schoessler et al., 2015)	2015	Universal	Object Manipulation	End user
SPATA (Weichel et al., 2015)	2015	Design (General)	Digital Modelling	Designer
Fusilli (Zheng, 2015)	2015	Fashion Design	Digital Modelling	End user
Computer Aided Painting (Shilkrot et al., 2015)	2015	Art	Fabrication	End user
Roly-Poly Mouse (Perelman et al., 2015)	2015	Universal	Universal	End user
T(ether) (Lakatos et al., 2014)	2014	Design (General)	Digital Modelling	Designer
MixFab (Weichel et al., 2014)	2014	Design (General)	Fabrication	End user
Nishanchi (Goyal et al., 2014)	2014	Design (General)	Fabrication	Craftsman
FreeD (Zoran and Paradiso, 2013)	*2013*	*Design (General)*	*Fabrication*	*Designer*
Hand Gestures in CAD Systems (Tumkor et al., 2013)	*2013*	*Design (General)*	*Digital Modelling*	*Designer*
Mockup Builder (Araújo et al., 2013)	*2013*	*Design (General)*	*Digital Modelling*	*Designer*
SpaceTop (Jinha et al., 2013)	2013	Design (General)	Digital Modelling	Designer
inFORM (Follmer et al., 2013)	2013	Universal	Object Manipulation	End user

Table 3.1 (continued) : Overview of the related work.

Name of the Project	Year	Field of Use	Main Objective	Addressed Audience
Easigami (Huang and Eisenberg, 2012)	*2012*	*Design (General)*	*Digital Modelling*	*Designer*
KidCAD (Follmer and Ishii, 2012)	*2012*	*Design (General)*	*Digital Modelling*	*End user*
Fabrication of Gestural Form (Johns, 2012)	*2012*	*Architecture*	*Fabrication*	*Designer*
Constructable (Mueller et al., 2012)	2012	Design (General)	Fabrication	Craftsman
DressUp (Wibowo et al., 2012)	2012	Fashion Design	Digital Modelling	Designer
Position-Correcting Tools (Rivers et al., 2012)	2012	Design (General)	Fabrication	Craftsman
ToolDevice (Arisandi et al., 2012)	2012	Design (General)	Digital Modelling	Designer
Turn (Cho et al., 2012)	2012	Design (General)	Digital Modelling	Designer
SIMI (Johnson et al., 2012)	2012	Design (General)	Fabrication	Craftsman
Cutter (Willis et al., 2011)	*2011*	*Design (General)*	*Digital Modelling*	*Designer*
Fabric 3D (Leal et al., 2011)	*2011*	*Design (General)*	*Digital Modelling*	*Designer*
Five-Axis Robotic Motion Controller (Payne, 2011)	*2011*	*Universal*	*Fabrication*	*Craftsman*
6D Hands (Wang et al., 2011)	2011	Design (General)	Digital Modelling	Designer
Recompose (Blackshaw et al., 2011)	2011	Universal	Object Manipulation	End user
Collaborative Design Platform (Schubert et al., 2011)	2011	Architecture	CAD Visualization	Designer
2.5D Shape Display (Leithinger et al., 2011)	2011	Universal	Object Manipulation	End user
Actuated Puppet (Yoshizaki et al., 2011)	2011	Art	Digital Modelling	Designer
MozArt (Sharma et al., 2011)	2011	Design (General)	Digital Modelling	Designer
Raw Shaping Form Finding (Wendrich, 2010)	2010	Design (General)	Digital Modelling	Designer
Spatial Sketch (Willis et al., 2010)	2010	Design (General)	Digital Modelling	Designer

Table 3.1 (continued) : Overview of the related work.

Name of the Project	Year	Field of Use	Main Objective	Addressed Audience
Relief (Leithinger and Ishii, 2010)	2010	Universal	Object Manipulation	End user
CopyCAD (Follmer et al., 2010)	2010	Design (General)	Digital Modelling	End user
Imaginary Interfaces (Gustafson et al., 2010)	2010	Design (General)	Digital Modelling	End user
Tangible Design Support System (Hosokawa et al., 2008)	2008	Architecture	Digital Modelling	End user
MxR (Belcher and Johnson, 2008)	2008	Design (General)	Digital Modelling	Designer
ASTOR (Olwal et al., 2008)	2008	Industry	Fabrication	Craftsman
ShapeShift (Skeels and Rehg, 2007)	2007	Art	Fabrication	Craftsman
iSphere (Lee et al., 2005)	2006	Universal	Digital Modelling	Designer
Virtual 3D Sculpting (Sheng et al., 2006)	2006	Art	Digital Modelling	Designer
FlexM (Eng et al., 2006)	2006	Design (General)	Digital Modelling	Designer
3D Tractus (Lapides et al., 2006)	2006	Design (General)	Digital Modelling	Designer
ModelCraft (Song et al., 2006)	2006	Design (General)	Digital Modelling	Designer
Projector-Guided Painting (Flagg and Rehg, 2006)	2006	Art	Fabrication	Craftsman
Illuminating Clay (Ishii et al., 2004)	2004	Landscape Design	CAD Visualization	Designer
ActiveCube (Watanabe et al., 2004)	2004	Design (General)	Digital Modelling	Designer
Virtual DesignWorks (Liu et al., 2004)	2004	Design (General)	Digital Modelling	Designer
Benchworks (Seichter, 2004)	2004	Urban Design	Digital Modelling	Designer

Table 3.1 (continued) : Overview of the related work.

Name of the Project	Year	Field of Use	Main Objective	Addressed Audience
I/O Brush (Ryokai et al., 2004)	2004	Universal	Digital Modelling	End user
Tangible NURBS-curve Manipulation (Bae et al., 2004)	2004	Design (General)	Digital Modelling	Designer
Twister (Llamas et al., 2003)	2003	Design (General)	Digital Modelling	Designer
iNavigator (Ma et al., 2003)	2003	Architecture	CAD Visualization	Designer
CUBIK (Lertsithichai and Seegmiller, 2002)	2002	Design (General)	Digital Modelling	Designer
Gesture Modelling (Gross and Kemp, 2001)	2001	Design (General)	Digital Modelling	Designer
CavePainting (Keefe et al., 2001)	2001	Art	Digital Modelling	Designer
Surface Drawing (Schkolne et al., 2001)	2001	Design (General)	Digital Modelling	Designer
FEELEX (Iwata et al., 2001)	2001	Universal	Object Manipulation	End user
DAB (Baxter et al., 2001)	2001	Art	Digital Modelling	Designer
Tangible Interaction + Graphical Interpretation (Anderson et al., 2000)	2000	Design (General)	Digital Modelling	Designer
Cubic Mouse (Fröhlich and Plate, 2000)	2000	Universal	Universal	End user

The overview in Table 3.1 presents 68 projects sorted by year in descending order and by classifying them within their fields of use, main objectives and audiences. The classification within the field of use refers to the most relevant field which the project is developed for, as addressed by its developers. In this sense, the projects are addressing either; general design (practices which are subject to creative production of 3D physical objects), fashion design, urban design, architecture, art, industry or universal practices. The classification within the main objective refers to the primary functionality which the project is intended for. In this sense; digital modelling refers to producing or modifying 3D geometries in the digital environment; fabrication refers to producing or modifying the physical artefacts; CAD visualization refers to viewing or investigating a digital model; object manipulation refers to manipulating an actuated physical object through a computer system; and universal refers to miscellaneous HCI functionalities which do not fit into the previous 4 definitions. Finally, the classification within the addressed audience refers to the target user who is addressed as the main user of the projects. In this sense; designer refers to the person who takes design decisions and generates design solutions; craftsman refers to the person who works on the fabrication of the physical artefacts; and end user refers to the person who is simply the non-professional client. Figure 3.4 presents the distributions in each classification.

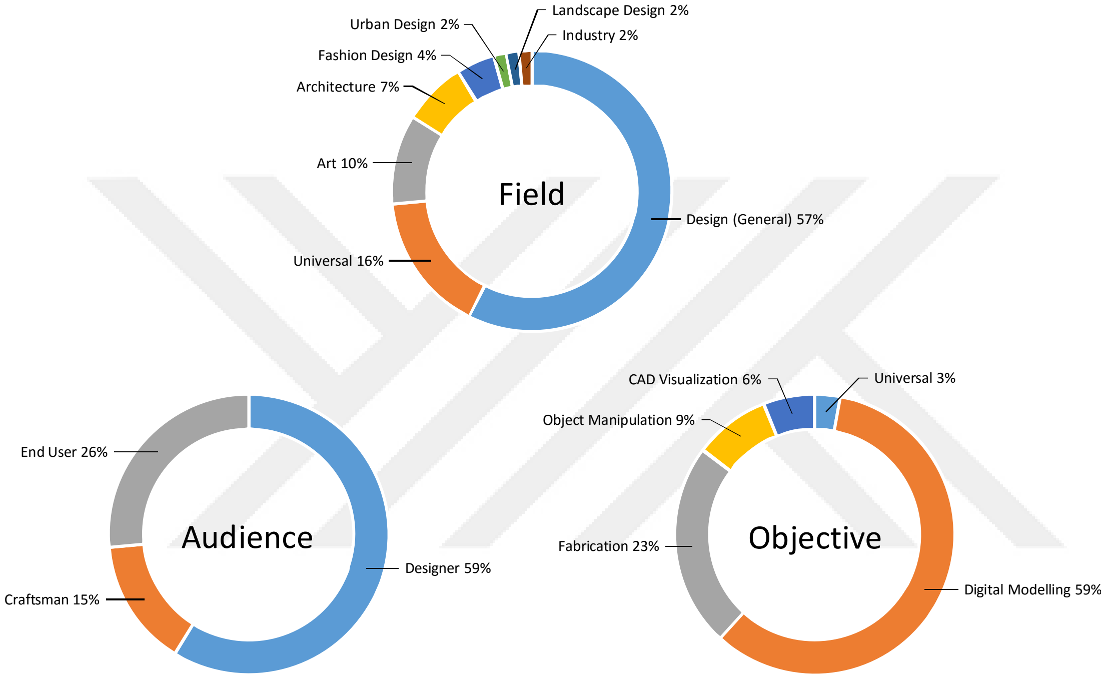

Figure 3.4 : Analysis on the comparison of related work.

The analyses of the overview, as seen in Figure 3.4, indicate the following remarks:

• More than half (62%) of the projects are developed after 2010.

• The projects are mostly (57%) developed to be used in general design fields, whereas the ones which address specific fields are rare.

• The projects are mostly (59%) developed to be used for digital modelling.

• Most of the projects (59%) are developed to be used by designers.

• There is an increase in the projects which address the craftsmen in more recent years. 70% of these projects are developed in the last 5 years, whereas there are no such projects developed before 2006.

• There is a significant increase in the projects which address end users. 33% of these projects are developed in the last year. While there is usually 1 such project per year (with exception of 2 in 2001 and 3 in 2010), there are 6 projects developed for end users in 2015.

• The projects which address fabrication are becoming more common in the recent years. 43% of the projects which address fabrication are developed in the last 2 years, while there is no such project before 2006.

• The projects which address the end users are mostly developed for either Digital Modelling (39%) or Object Manipulation (33%), while only 11% address fabrication.

• 83% of the projects which address designers are developed to be used for Digital Modelling.

• 63% of the projects which address fabrication are developed to be used by craftsmen.

Following these remarks one can claim that, there is an increasing interest in studies which aim at enhanced HCI systems in CAD. The studies are yet not field-specific. As the systems improve, they will be able to provide specific solutions tailored for specific fields.

Even though most of the projects are aimed to be used for modelling in virtual environments, there is an increasing interest to integrate tactile aspects into the interaction. This aspect will get more common practice as immersive environments get better. On the other hand, there is a significant interest in projects which aim at integrating fabrication and addressing the craftsmen as the fabrication tools become more integrated with the computer systems. Applications which incorporate design and fabrication, as well as the designer and the craftsmen, will become more feasible to realize in near future.

Even though the projects yet usually address designers, there is recently an increasing interest in providing solutions for end users as well. This is mainly because of the fact that design and fabrication tools are becoming popularized towards the idea of personalized fabrication such as the maker movement phenomena which aims at democratizing the design practices. One can claim that, such applications will get even more common in near future as personalized fabrication systems become more popular and accessible. On the other hand, the projects which integrate fabrication for the use of the end users are yet very rare. This means that there is still room to explore this relationship within HCI.

In Table 3.1, the rows with light gray background and italic text indicate the projects which have more profound relevance with this research within its motivations or methods and are accordingly inspirational. These 12 projects aim to bridge the gap between digital representation and materiality in different ways and each of them provide important aspects which can lead to develop better interaction tools for designers. Therefore, the following text presents more detailed descriptions of these projects. Also, an in-depth taxonomic analysis of these projects are presented in the following chapter.

The contents of these 12 projects are as follows:

Human-Assisted Additive Manufacturing [1]: The aim of the project is to propose a new method for printing architecture-scale objects out of chopsticks and glue, with the help of a printing guidance system that uses projection mapping (Yoshida et al., 2015). In this project, the digital media serve as a real-time co-operator for the fabrication, which guides the craftsmen through images that are projected onto the object being built (Figure 3.5).

Figure 3.5 : STIK: Architecture-Scale Human-Assisted Additive Manufacturing (Yoshida et al., 2015).

ReForm [2]: The aim of the project is to integrate digital modelling with shape input, shape output, annotation for machine commands, and visual output by continually synchronizing the physical object and digital model (Weichel et al., 2015). The system embeds digital and physical environments into each other by integrating additive manufacturing, subtractive manufacturing and light scanning (Figure 3.6).

Figure 3.6 : ReForm: Integrating Physical and Digital Design through Bidirectional Fabrication (Url-7).

Being the Machine [3]: The aim of the project is to place digital fabrication activity outside of the traditional fab lab environment (Devendorf and Ryokai, 2015). The system helps us to question the thresholds between the user and the machine by enabling the user to manually experience an additive manufacturing practice following G-Code instructions (Figure 3.7).

Figure 3.7 : Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication (Devendorf and Ryokai, 2015).

FreeD [4]: The aim of the project is to develop a hand-held digital milling device in order to combine digital fabrication and craft (Zoran and Paradiso, 2013). It enhances the capabilities of the user through a system which guides him/her during production while preserving his/her intuitions and freedom (Figure 3.8).

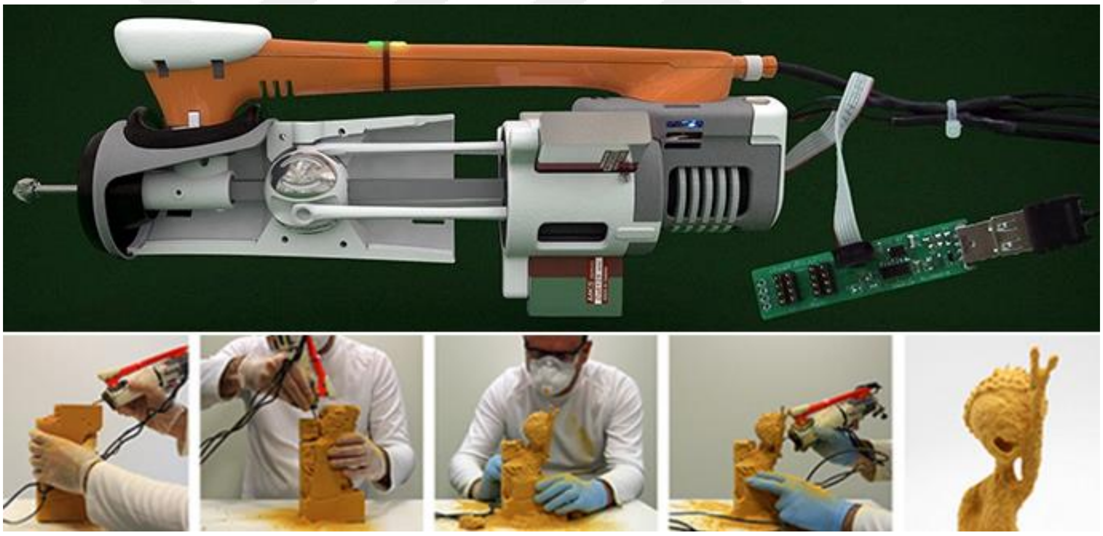

Figure 3.8 : FreeD: A Freehand Digital Sculpting Tool (Zoran and Paradiso, 2013).

Hand Gestures in CAD Systems [5]: The aim of the project is to enable gesture recognition for manipulating and disassembling CAD models by integrating two Kinect depth cameras with Solidworks API and a Windows API (Tumkor et al., 2013). The system enables a spatial and bodily interaction with the digital model which is performed through hand gestures (Figure 3.9).

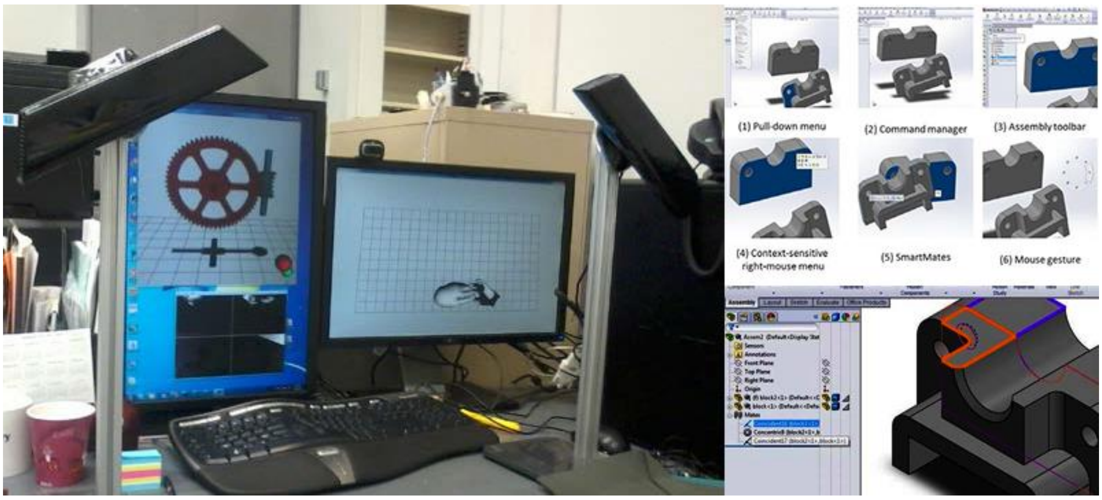

Figure 3.9 : Hand Gestures in CAD Systems (Tumkor et al., 2013).

Mockup Builder [6]: The aim of the project is to allow virtual mockups to be created using gestures (Araújo et al., 2013). The system is able to provide a flexibility in use as it enables spatial interactions while it provides certain functionalities on a multi-touch screen (Figure 3.10).

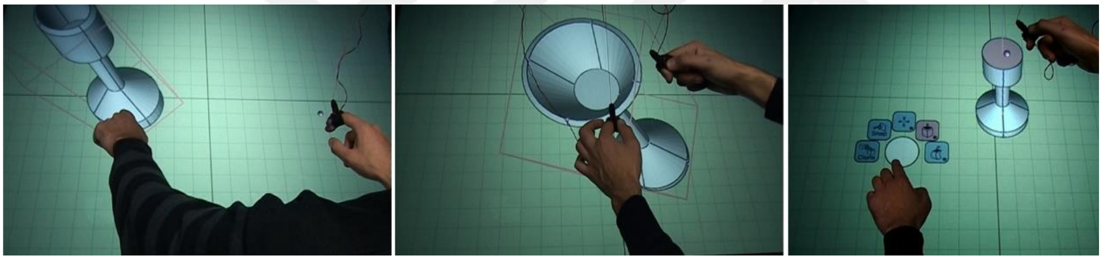

Figure 3.10 : Mockup Builder: 3D Modeling on and Above the Surface (Araújo et al., 2013).

Easigami [7]: The aim of the project is to overcome the 2D bottleneck of the standard computer screen and associated conventional input devices by providing a 3D sketching tool which permits user to assemble polyhedral objects by connecting and folding polygonal shapes (Huang and Eisenberg, 2012). The system provides organic and direct input through the tangible device-object (Figure 3.11).

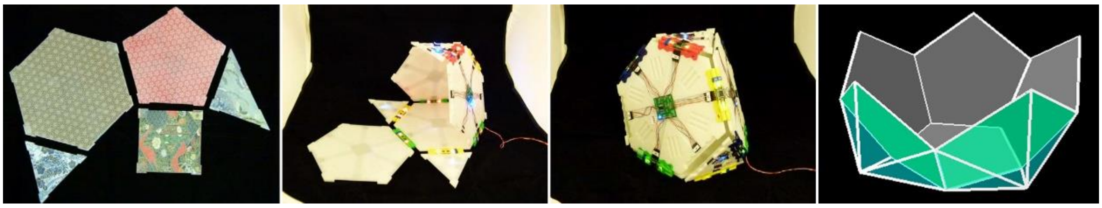

Figure 3.11 : Easigami: Virtual Creation by Physical Folding (Huang and Eisenberg, 2012).

KidCAD [8]: The aim of the project is to enable children to make new toys by transforming physical objects with the help of digital tools. It uses a digital clay interface (deForm) for the interaction with digital environment (Follmer and Ishii, 2012). The system is a good example of intuitive making which is enhanced with the help of digital media (Figure 3.12).

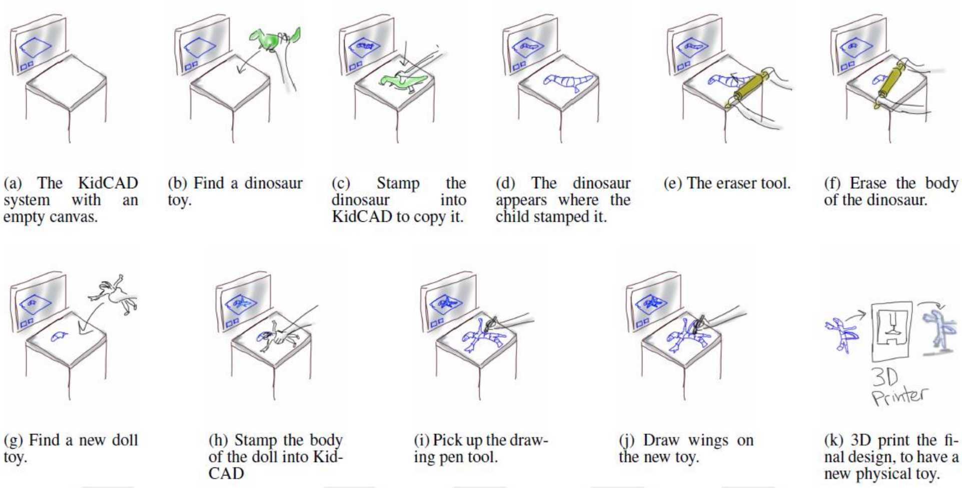

Figure 3.12 : kidCAD: Digitally Remixing Toys Through Tangible Tools (Follmer and Ishii, 2012).

Fabrication of Gestural Form [9]: The aim of the project is to explore the design potential of using robotic fabrication tools in conjunction with a specially developed low-cost augmented reality system (Johns, 2012). The system provides good insight towards the use of intuitive gestures in robotic manufacturing (Figure 3.13).

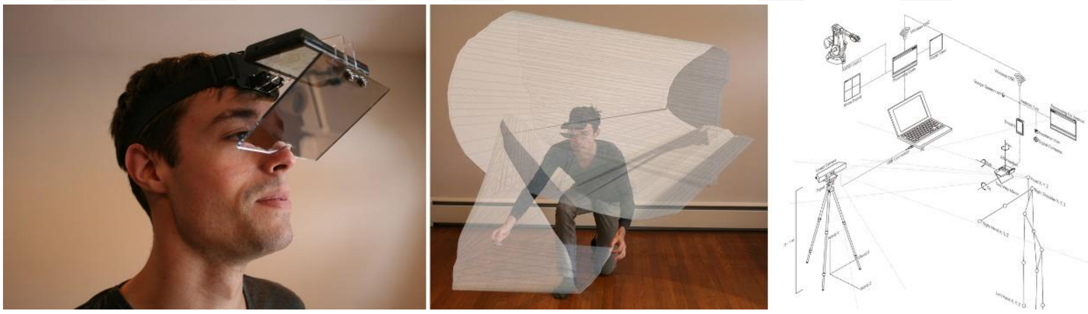

Figure 3.13 : Augmented Reality and the Fabrication of Gestural Form (Url-8).

Cutter [10]: The aim of the project is to provide a tangible interface for generating 3D digital models by hand crafting polystyrene foam. The user pulls, pushes, and rotates a custom hotwire cutter to sculpt, cut, and shape foam cubes (Willis et al., 2011). The system enables the material performance during digital modelling by allowing the user to make digital 3D models by manually shaping a physical object (Figure 3.14).

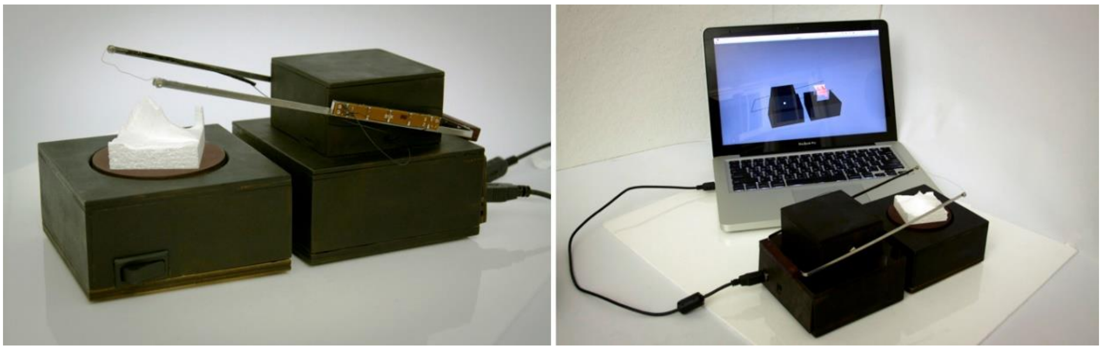

Figure 3.14 : Interactive Fabrication with Cutter (Willis et al., 2011).

Fabric 3D [11]: The aim of the project is to explore the potentials of fabric as an input device for 3D modelling. It uses a vision system with eight cameras and marker input devices located on a fabric which is intuitively shaped by the user (Leal et al., 2011). The system enables the user to make digital 3D models through intuitive and expressive performances including the material performance (Figure 3.15).

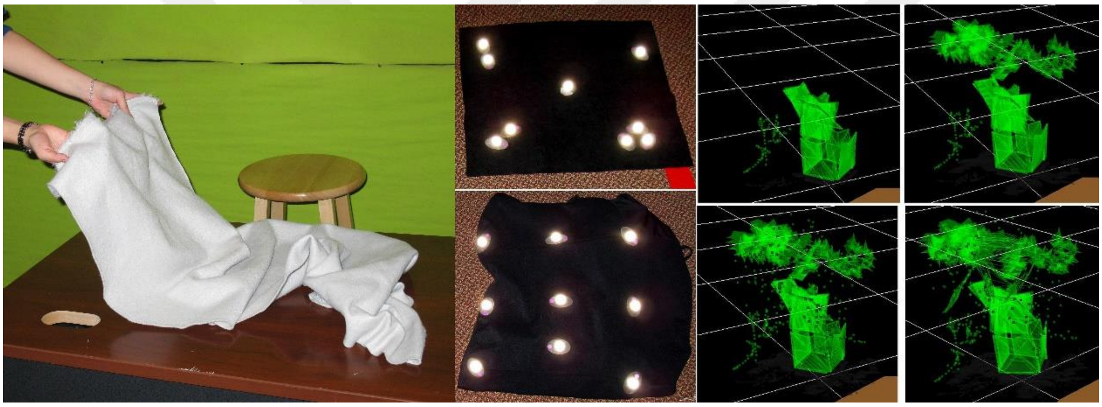

Figure 3.15 : Fabric 3: 3D Sketching Using Interactive Fabric for Tangible and Bimanual Input (Leal et al., 2011).

Five-Axis Robotic Motion Controller [12]: The aim of the project is to enable manual control of the movements of an industrial robot arm. It provides an HCI tool named Firefly, which works with Rhino 3D and Grasshopper software in order to communicate with micro controllers through CAD interface (Payne, 2011). The system provides good insight towards the use of intuitive and organic control of robotic fabrication practices (Figure 3.16).

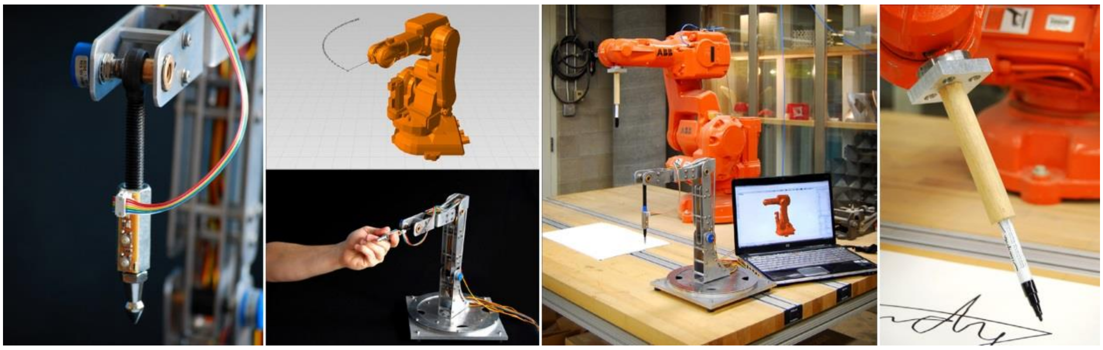

Figure 3.16 : A Five-axis Robotic Motion Controller for Designers (Payne, 2011).

3.3 Remarks on the State of the Art

Table 3.2 presents an in-depth analysis of these projects which are listed and briefly described in Chapter 3.2. The numbers on the first column of the table indicate the list numbers of the projects as presented in the previous chapter. The projects are reviewed through a taxonomic classification under four categories; interaction mode, interaction means, outputs and inherent features. In each category, there are certain features which relate to the objectives of this research. The projects were explored for their performance of providing these features and the exploration is presented in the table.

There are three features in “interaction mode” category; spatial, tactile and gestural. “Spatial” refers to the use of real 3D space, “tactile” refers to the use of a tangible object (except the screen or common input devices), and “gestural” refers to the use of hand or body gestures for interacting with the computer system. In this sense, all of the projects perform spatiality since the use of real 3D space for the interaction is the most common feature of similar studies in HCI field. On the other hand, while 8 projects (67%) provide tactile interaction, only 3 (25%) provide interaction through gestures. This is most likely because of the fact that, interaction through the use of hand gestures without any physical touch is not considered efficient in professional tasks because of ergonomic reasons. Therefore, there is significant interest in providing better interactions through tangible input methods. Further, there is no project which integrates all three features; or both tactile and gestural features in the same system. Because, each of these projects explore the potentials of certain modes of interactions; therefore, they focus on particular aspects. Still, one can claim that, integrating as many modes as possible inside the same system will provide multimodality in more efficient ways.

Table 3.2 : In-depth analysis of the related work.

	Interaction Mode			Interaction Means					Outputs			Inherent Features			
	Spatial	Tactile	Gestural (Hand / Body)	Through Object	Through Device	Through Gestures	Vision-based	Computational Guidance	Fabricated Object	Physical Model	Digital Representation	Materiality	Affordance	Multimodality	Intuitiveness
1	•	•		•			•	•	•						
2	•	•		•			•		•		•				
3	•	•		•			•	•	•						
4	•	•		•	•			•	•						
5	•		•			•	•				•				
6	•		•			•	•				•				
7	•	•			•					•	•				
8	•	•		•	•				•		•				
9	•		•			•	•		•		•				
10	•	•		•	•					•	•				
11	•	•			•		•				•				
12	•				•				•		•				

The “interaction means” category indicate the genres of tools and techniques used for the interaction and it includes five features:

• Through Object: The interaction is performed via the design object itself or its physical prototype.

• Through Device: The interaction is performed via tangible input devices (except the screen or common input devices) which are developed specifically for the project.

• Through Gestures: The interaction is performed via the gestures of the hand or body.

• Vision-based: The system uses vision based devices (such as cameras, depth sensors or laser scanners) for inputs or outputs.

• Computational Guidance: The system guides the user for performing actions through computational support systems.

The analyses point out that performing interaction through object (50%) or through devices (50%) is the most common practice. Because, either the object itself or a specifically developed tangible interaction device enables tactility, which, as stated earlier, provide benefits for better interaction. On the other hand, there is seen a rise in utilizing vision-based and computational guidance systems in recent years. The systems get more functional as such smart devices are developed towards integrating with each other and exchanging data more efficiently.

The “outputs” category points out the outputs which are produced during the interaction. In this category, “fabricated object” refers to the actual scale and completed physical object to be used. “Physical model” refers to a physical prototype of the object, which contains some of its physical characteristics. “Digital representation” refers to the digitally stored representations of any kind of information related with the object. Most of the projects (75%) output a digital model thanks to the very nature of the technology. By this means, even when the main goal of the interaction is not to develop digital models, the systems are able to produce digital data in several forms of representation which can be stored and proceed further. Also, fabricated object as output is recently getting more common because, computer assisted fabrication technologies are getting more flexible. On the other hand, physical model as output is fairly rare (17%). Because, the goal of using the fabrication tools is usually fabricating the object rather than a physical model. Further, there is no project which provides all three outputs on the same system as they focus on explorations on certain means of production. However, achieving a synchronization between the production of different phases of a design, such as digital representations, information sheets, physical models and prototypes, would strongly support creative and efficient design practices.

The “inherent features” category contains a more subjective realm of evaluation. Here I analyzed the projects for their capabilities of providing materiality, affordance, multimodality and intuitiveness during interaction. In this part of the table, the black cells indicate the features which profoundly exist, and the grey cells indicate the features which exist to some extent. Materiality refers to tactile interactions. It is profound when the user is able to touch the material which constitutes the design object itself. Promisingly, it is more achievable in the more recent projects. Affordance refers to system’s capability of informing its use. While all of the projects provide affordance to some extent, it profoundly exists fairly where the interaction is achieved through device. Because, the devices are tailored for specific uses and they are able to afford the user better than generic devices. Multimodality is the rarest feature found in this category as the project focus on investigating the potentials of certain finite modes of input. Finally, intuitiveness refers to system’s capability of being perceivable by intuition and providing steep learning curve for its use. Intuitiveness, as discussed in Chapter 2, is one of the most important aspects which this research is focused on. Among the analyzed projects, most of them provide intuitiveness at least to some extent, as this is one of the common objectives of the reviewed field. The only projects which do not provide intuitive use are the ones which aim at developing systems to guide the user for certain pre-defined tasks. And it is at the highest degree especially when the user is able to work in a freehand sketching-like fashion.

As seen in these examples and as claimed by Golsteijn et al (2014), craft has recently started to gain interest from the HCI community, and over the past years, a number of studies have looked at craft practice to inform design or have developed ways to combine technology with more traditional means of crafting to support new craft practices with digital technology. The analyses provide promising outcomes and inspirations towards developing hybrid design media which integrate design development and fabrication through bodily interactions with computer systems and sustain materiality and intuitiveness in design cycle. In other words, they fairly point out that the objectives of this research are already applicable at least to some extent and will be more feasible to realize in near future with the help of the developments in HCI. The field provides us new solutions which can seamlessly be integrated into the digital design cycle and indicate the future directions.

Looking at the bigger picture within the state of the art, each feature which was sought in these analyses has various benefits and drawbacks. Like, gestural interaction can provide a high degree of freedom for the spatial and intuitive use of the body and hands. Also, it is technically fairly easy to apply as vision–based gesture recognition systems are already fairly advanced. The recent developments in these systems enable more organic and direct relationships between the physical and digital worlds reciprocally. However, moving hands in the air without any physical touch is exhausting and is not doable for long durations especially for professional and serious tasks. Moreover, a sole gesture-based system lacks of materiality. Yet, tangible input devices provide better ergonomic solutions in which materiality exists to some extent. Also, they are able to afford their user efficiently for being tailored for specific uses. However, such generic devices are still representative and abstract. They are not able to embody all the material aspects which the design object would have in the material word. They rather simulate their materiality. On the other hand, as fabrication tools become more flexible and integrated with computer systems, it is becoming more possible to include aspects related with the materiality of design artefacts into our interaction with computer systems, which is still one of the biggest challenges of HCI studies.

4. APPLIED RESEARCH TOWARDS DESIGN AS MAKING

The applied research phase aims at testing the potentials of existing tools and technologies and proposing a new interaction method towards the research objectives. The primary aim of the applied research is to demonstrate a proof of the concept by utilizing the existing tools and technologies while building new relations between them. Following the exploratory experiments which are presented in Chapter 4.1, the details of the developed application are presented in Chapter 4.2.

4.1 Exploratory Experiments

Svanæs (2001) argues that, an important research challenge is how to make the technology that exists in the labs today available to interaction designers in a form that enables them to seamlessly include it in the design of new systems and services. As illustrated in Chapter 3, there already exist several tools and methods which can enable better interaction if utilized through designerly perspectives. The aim of the exploratory experiments in this research was to understand the potentials of these existing tools and technologies towards developing hybrid design environments. To this end, a set of experiments, which focus on gesture recognition and reverse engineering technologies were performed.

4.1.1 Gestural modelling

The first set of experiments were conducted by utilizing gesture recognition technologies for digital modelling. Gesture recognition is commonly achieved by depth cameras such as the Leap Motion Controller (LM) (Url-9), Kinect (Url-10), DUO3D (Url-11) and Intel Perceptual Computing SDK 2103 (Url-12). These devices use various image-based 3D reconstructions in order to capture the movements of the objects. Within HCI, they track the user's body, body parts or associated instruments and detect their gestures through a natural user interface (NUI), and allow the user the hands-free control of computer systems. Additionally, there are wearable gesture sensing devices such as Myo Gesture Control Armband (Url-13), Nod Gesture Control Ring (Url-14), Fin Wearable Ring (Url-15), Stompz Foot Controller (Url-16) and Reemo Smart Home Wristband (Url-17). Similar to the depth cameras, these devices track the movements and recognize the gestures of the body. However, they are physically connected to certain body parts, such as the hands or feet, whereas the depth cameras do not require any physical touch.

In this project, I have tested not the wearable devices but the vision-based gesture recognition systems such as Kinect and LM. Such systems have initially been developed for the entertainment industry. Then, the technology has spread into various fields such as healthcare, education and data visualization. Among the existing depth cameras, LM appears to be a more convenient device for this project because of its lower cost, smaller size, higher precision in detecting the movements and gestures of the hands and fingers, and more user friendly software development kit which supports several programming languages (Figure 4.1). Moreover, LM can currently recognize and track pen-like devices as well. Therefore, the focus of the experiments was on LM.

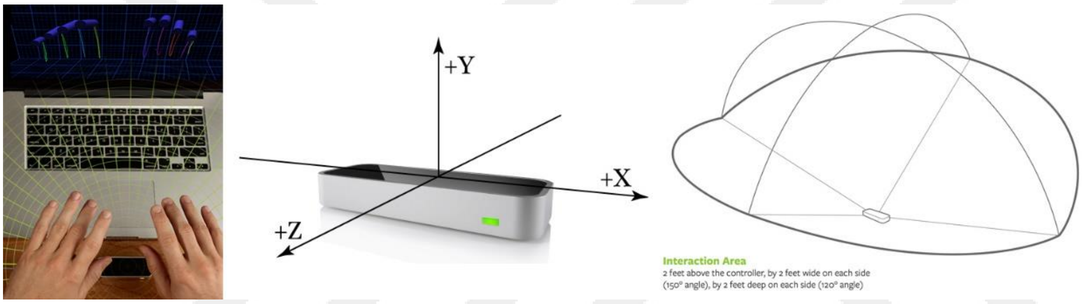

Figure 4.1 : Leap Motion Controller (Url-18).

There are several studies, some of which are listed in Chapter 3.2, which aim at integrating such vision-based gesture recognition technologies with CAD systems. These studies typically demonstrate two methods; the use of third party desktop control applications, and the use of specific plug-ins for CAD software.

Desktop control applications allow the user to interact with the computer's desktop in a mouse-like fashion by using hand movements and gestures with the help of sensor devices without any physical touch. The user moves his/her hands to control the cursor position and performs certain hand gestures to activate certain operations such as mouse clicks or pre-defined keyboard shortcuts. Some of these applications allow the user to customize the gestures and operations. Therefore, they can be used with CAD software with varying degrees of functionality. The most common ones which are developed for LM are BetterTouchTool (Url-19), Pointable (Url-20), GameWAVE (Url-21), AirInput (Url-22), AirControl(Url-23) and Touchless(Url-24).

Also, there are plug-ins which are developed for certain CAD software for LM integration. Unlike the desktop control applications, these plug-ins have better communication with the CAD software as they provide tailored solutions particularly for CAD use. The most common ones are Primat (Url-25), Leap Motion Plug-in for Autodesk Maya (Url-26), Ossewa SolidWorks Plug-in (Url-27), Sculpting (Url-28). All of these applications and plug-ins provide digital design experiences in which the viewing of the object (such as pan, orbit and zoom) are performed by hand movements and gestures. The user can also perform hand movements and gestures to operate certain modelling functions of the software. What is achieved by these applications and plug-ins is that the user uses his/her hands in real 3 dimensional space for viewing, generating or modifying the digital model. Therefore, the user gains a more realistic 3D control on the geometry of the design object comparing with the use of the input devices which are used in 2D space, such as the mouse and stylus for touch screens. However, they aim at interaction without any physical touch and do not provide any tactile input and materiality. The most common critique against these applications is that moving the hands without any physical touch for long time is not ergonomic and cause tired muscles and reduced precision. The most important challenge in developing plug-ins or CAD applications to work with LM is to provide intuitive use of the hands. An application which allows intuitive gestures to operate the functions will enable a seamless workflow.

The experiments for providing hybrid design media through gestural modelling focuses on possible enhanced interactions with the digital model through hand movements and gestures by integrating LM with existing CAD applications. The simplest approach to this is to use a third party desktop control application as an interface to the CAD software. To this end, I customized the GameWAVE application to be used with SketchUp software for 3D geometric modelling (Figure 4.2).

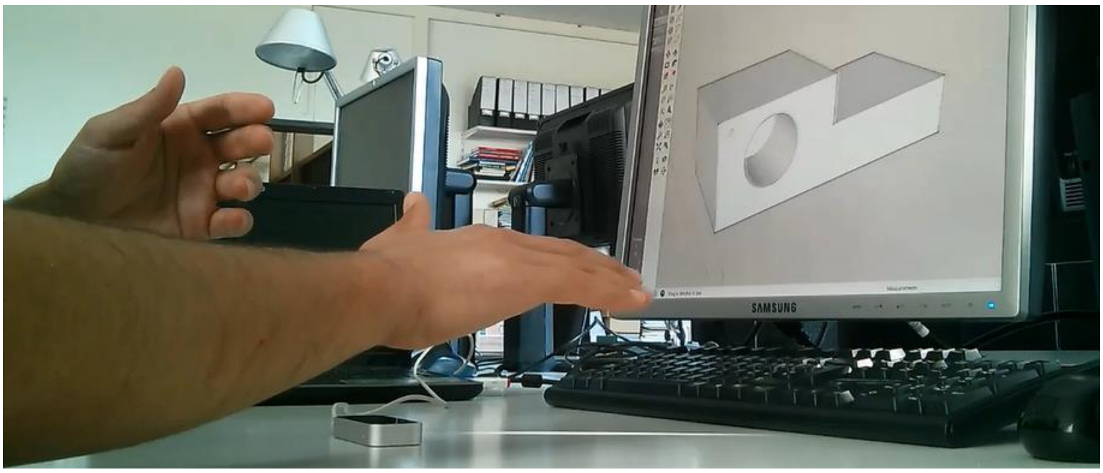

Figure 4.2 : Gestural 3D modelling by using LM, SketchUp and GameWAVE.

This customized application allows 3D digital modelling through hand movements and gestures. The user moves his/her hands in real 3D space and performs certain gestures as if he/she is making a model physically by hands (Figure 4.3). However, there is no physical touch to any tool or material.

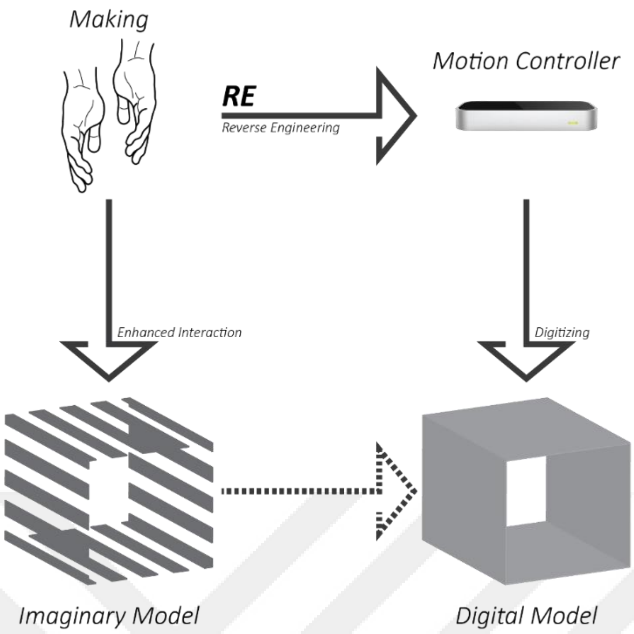

Figure 4.3 : Gestural Modelling on CAD application.

There is no direct integration embedded into the CAD system in this application. The user interacts with the desktop control application, which becomes another interface between the user and the model (Figure 4.4). Therefore, the capabilities of the interaction are naturally constrained with the capabilities of the desktop control application.

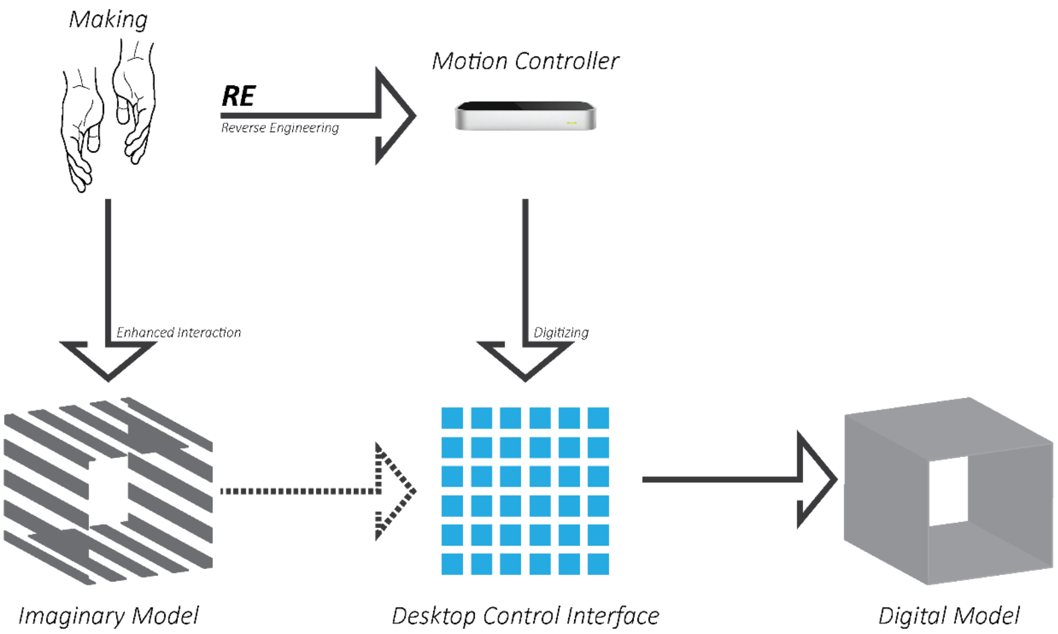

Figure 4.4 : Interaction through desktop control interface.

Two configurations are developed in the desktop control application; interaction with two modes and interaction with three modes. The interaction with two modes allows the user to interact with the CAD model mostly in a mouse-like fashion, by just moving his/her hands in real 3D space in order to reach the menus and toolbars on the CAD software interface. Therefore, this interaction is not much different than a WIMP interface. The interaction with three modes provides a more direct interaction by allowing the user to activate certain functions of the CAD software through specified hand gestures instead of pointing them on the menus or toolbars.

The configuration with two modes allows the user to mediate the mouse movements and clicks, as well as the *Pan*, *Orbit*, *Zoom*, *Undo* and *Select* functions of the CAD software through the controller. Here, the idea is to let the user reach any function of the CAD software in a mouse-like fashion, while letting him/her activate certain *Camera* and the most used *Tools* and *Edit* functions by hand gestures. For this purpose, the assigned functions are categorized as stable (Trigger Mode) or active (Steering Mode) functions and they are associated with certain gestures of the right or left hand, where the right hand mediates the active functions and the left hand mediates the stable functions (Table 4.1).

Table 4.1 : Gestures and functions for the first two modes.

Mode	Menu	Function	Mode (T/S)	Hand (L/R)	Gesture
1	Mouse	Move Up	Steering	Right	Move/Upward
		Move Down	Steering	Right	Move/Downward
		Move Left	Steering	Right	Move/Leftward
		Move Right	Steering	Right	Move/Rightward
		Left Click	Steering	Right	Thumb/Lift
		Double Click	Steering	Right	Finger/Tap
		Right Click	Steering	Right	Incline/Outward
	-	Escape	Steering	Right	Incline/Inward
	Edit	Undo	Steering	Right	Rapid/Multi Taps
2	Tools	Select	Trigger	Left	Incline Closed/Outward
	Camera	Pan	Trigger	Left	+Fingers/Swipe Left & Swipe Right
		Orbit	Trigger	Left	+Fingers/Circle Left & Circle Right
		Zoom	Trigger	Left	Incline Closed/Upward & Downward
1&2	-	Switch Mode	Steering & Trigger	Right & Left	(SR)Rapid/Multi Taps & (TL)Rapid/Multi Taps

The configuration with three modes is achieved by enriching the previously used two modes with the left hand steering mode. The idea behind providing one more mode is to allow the user to access certain functions of the CAD software by using hand gestures instead of pointing them on the menus or toolbars. This new mode provides access to the *Line*, *Rectangle*, *Circle* and *Arc* functions of the *Draw* menu, and the *Push/Pull*, *Move* and *Rotate* functions of the *Tools* menu through the associated hand gestures (Table 4.2). Similar to the interaction with 2 modes, the categorization of the software functions and their association with the hand gestures through an intuitive manner are essential in this configuration.

Table 4.2 : Gestures and functions for the third mode.

Mode	Menu	Function	Mode (T/S)	Hand (L/R)	Gesture
3	Draw	Line	Steering	Left	Move/Upward
		Rectangle	Steering	Left	Move/Downward
		Circle	Steering	Left	Move/Leftward
		Arc	Steering	Left	Move/Rightward
	Tools	Push/Pull	Steering	Left	Thumb/Lift
		Move	Steering	Left	Finger/Tap
		Rotate	Steering	Left	Incline/Outward

The analyses of the gestural modelling experiments point out that such interaction allows a more organic and direct workflow comparing with mouse use. The use of the hands in real 3D space during modelling provides a more efficient perception of the form. Even though it is imaginary and is without any physical touch, the bodily interaction which is achieved at this phase already provides a more transparent media between design thinking and the design object. Moreover, such an enhanced interaction with the digital object is fun and exciting. Therefore, the outputs of the first phase are promising towards the research objectives.

However, the transparency between the thinking and making is yet not fully achieved. The contents and the orders of the executed operations are not different than what common CAD practices offer. On the other hand, tactility and materiality, which are the other core aspects of the research objectives, are missing. Also, a perfect intuitive relation between the sough CAD operation and the hand gesture cannot always be obtained because of the configuration limitations of the interface application.

4.1.2 Reverse engineering

The common CAD/CAM practices involve sequential steps such as the generation of the digital model first, then its physical fabrication without human intervention. 3D scanners and digitizers are used to digitize the object only when it is necessary to document the object or to perform further digital processing. Digitizing, in this sense is usually coined as reverse engineering (RE) (Figure 4.5).

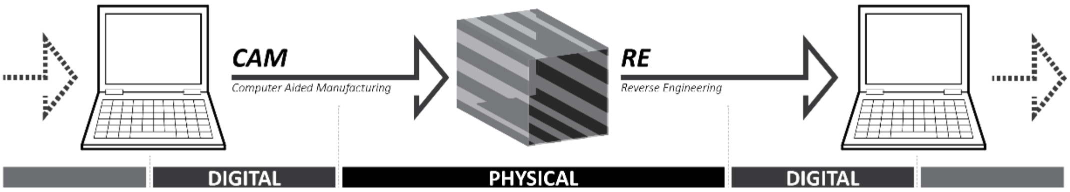

Figure 4.5 : Traditional Reverse Engineering.

RE provides potentials towards developing hybrid environments as it enables information transfer from the physical environment to the digital. It upgrades the linear workflow of design to production into a cycle of making where design and production feed each other. To this end, it is necessary to integrate RE as a component of the design cycle (Figure 4.6) in enhanced HCI systems.

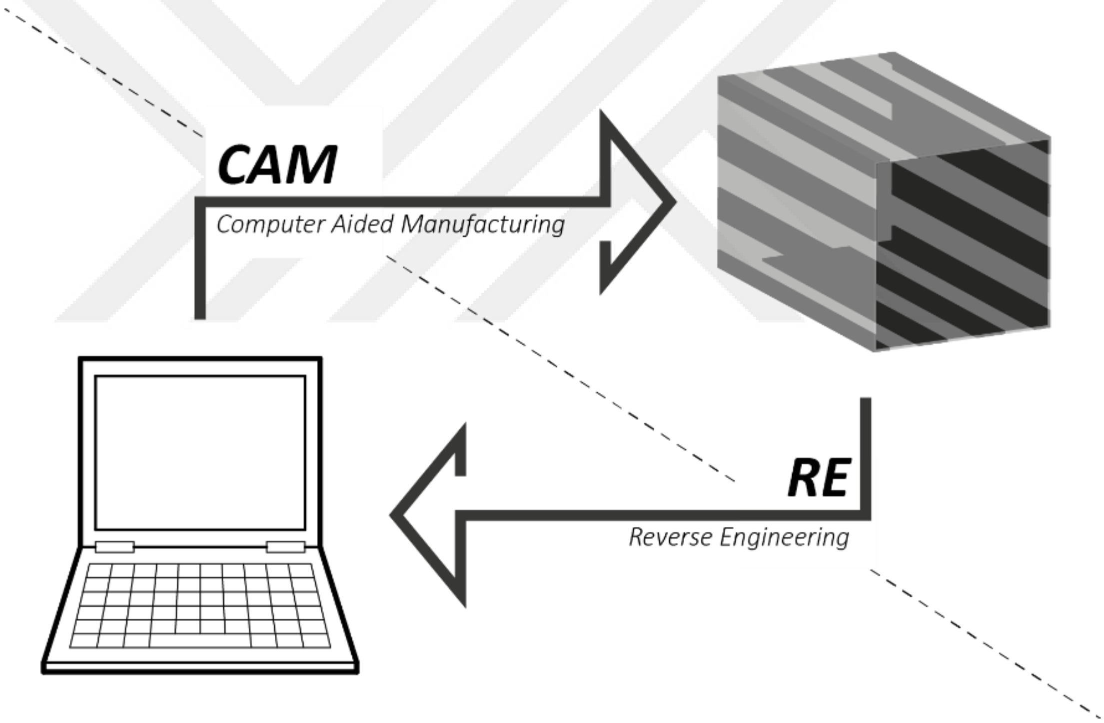

Figure 4.6 : Reverse engineering as a component of the design cycle.

Commonly, RE refers to digitizing the physical object for further digital processing. In this research, the experiments on RE towards developing hybrid design media focus on digitizing the making process instead of the object. So that, the information of making will be digitized, which is then possible to store, reproduce and modify.

I worked with a 3D laser scanner and a digitizer arm in order to investigate the potentials of reverse engineering tools and methods towards digitizing the processes of making in design. 3D laser scanner (Figure 4.7) uses laser beams to analyse the surface of the object in order to construct its digital representation. It is an optic system and is able to analyze the surfaces only which it can see through laser beams. Typically, the user cannot interfere with the scanning system while it is operating.

Figure 4.7 : 3D Laser Scanner.

The 3D digitizer arm (Figure 4.8) is a counterbalanced mechanical arm, which is manually traced over the contours of the object in order to construct its digital representation. It is a mechanical device and is held and operated by the user for scanning the object. Its manual operation provides an organic quality. Its capabilities are directly related with the capabilities of the user's hand.

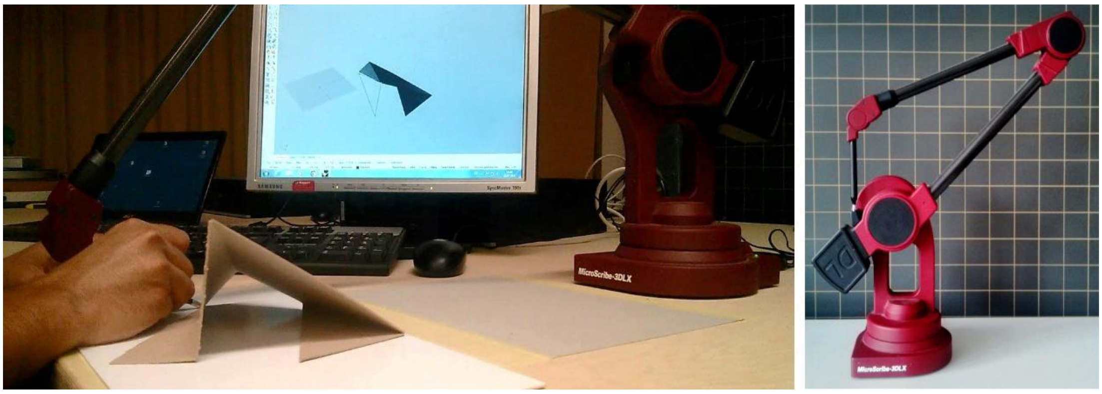

Figure 4.8 : 3D Digitizer Arm.

Comparing the laser scanner and the digitizer arm, the latter better responds to the needs of the experiments on RE towards developing hybrid design media. Because, while the laser scanner analyzes the object qualities, the digitizer arm analyzes the movements of the practicing hand. Typically, the digitizer arm is used for analyzing a physical object. If it is rather used for making the object, it will be possible to digitize the information related to the making. To this end, it is necessary to apply a making technique in which the hand and the digitizer arm can operate in coordination. In other words, it is necessary to use a physical making tool, which can principally move identical with the digitizer arm.

After testing the possible available tools, a 3D printing pen appears as the most convenient device which can be used in coordination with the digitizer arm. Two pen versions of 3Doodler, which have different shapes, were used in these experiments (Figure 4.9). These pens melt and then rapidly cool plastic thread while it is moved in real 3D space. They are able to extrude ABS and PLA plastic filaments like the most common 3D printers which are based on Fused Deposition Modelling (FDM) technology. One may address these pens as being freehand and manual 3D printers, as they provide additive manufacturing and use similar types of materials like 3D printers. However, unlike a 3D printer, the production of the object by using these pends is not necessarily in a layer by layer fashion, but more visual and depictive like freehand sketching. Moreover, there is no digital information or manual followed during the operation. On the contrary, they allow the designer to perform intuitively.

Figure 4.9 : Two versions of the 3Doodler 3D Printing Pen.

Eventually, I developed a hybrid tool simply by connecting the 3D printing pen and the 3D digitizer arm (Figure 4.10). The idea behind it was to test the applicability of the research objectives through a simple tool which outputs physical object while processing digital information using the RE technology.

Figure 4.10 : The hybrid tool which integrates the 3D printing pen and the digitizer arm.

The connection allowed the digitizer arm to move identically with the 3D printing pen while model making (Figure 4.11). Therefore, it enabled the real-time digitization of the form of the object by analyzing the movements of the hand and pen and transferring the information into CAD environment.

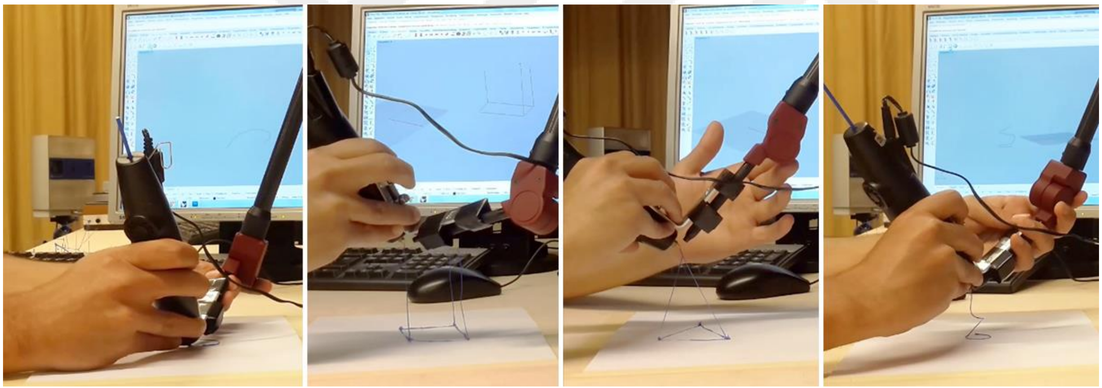

Figure 4.11 : Operation of the hybrid tool.

The outputs of the gestural modelling experiments were promising towards demonstrating the applicability of hybrid design media. The hybrid tool which was developed for these experiments was used to make simple physical shapes. The digitizer was integrated with Rhino 3D software and was transferring data related with its position in real 3D space to the software. Thus, a digital representation of the shape was simultaneously being produced while making. The digital models were almost identical to the shapes of the physical objects (Figure 4.12).

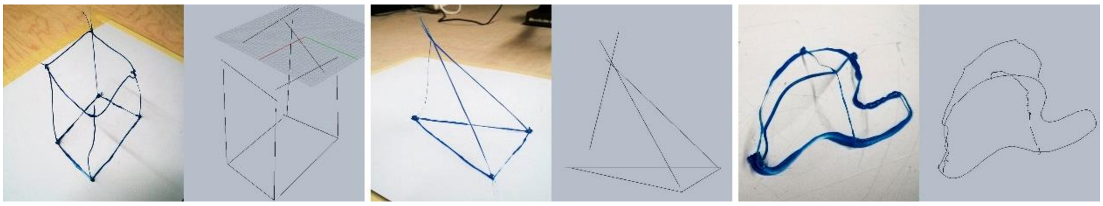

Figure 4.12 : Outputs of the experiments with the hybrid tool.

RE experiments have provided profound outputs which are promising towards the research objectives. First of all, the affordance is more present comparing with typical modelling techniques. Actions and perceptions are spatially and temporally synchronized. The experience is fully spatial, bodily and material. The physical material plays a role in the process. There is continuous tactile feedback. CAD environment performs as the platform for the reproduction of the making process. The digitally stored and processed information is not only the geometry of the object, but also the recorded movements of the hand and the handheld tool.

On the other hand, the hybrid tool is heavy and uncomfortable to use. Its reach is limited to the dimensions of the digitizing arm. Therefore, it is not practically possible to build objects of any size or shape. Also, there is a significant difference between the sensitivities of the hand and the tool.

4.1.3 Remarks on the exploratory experiments

The exploratory experiments principally demonstrate the applicability of the research objectives and guide for developing better tools. The following remarks emerge as outputs of the applied experiments:

- It is possible to develop hybrid design media which enable spatial, bodily and material interactions with the digital environment.
- The use of hands in real 3D space during modelling provides a more efficient perception of the form.
- Making by using tangible objects increases ergonomics.
- RE technologies provide potentials towards enabling hybrid environments.
- Vison-based digitizing systems provide more freedom within the action space.
- Intuitive forms of making, such as sketching, increases affordance.
- Working with physical materials enables tactile feedbacks.
- Materiality integrates material behaviours as actors in design development.

• Materiality synchronizes perception and action both temporally and spatially.

• Materiality provides more transparent interfaces between design thinking and the design object.

4.2 TIM: Tactile Interaction for Making

The review of the related studies in Chapter 1 points out that hybrid design environments has been one of the core interest in CAD research since 1970s, in one respect, since the emergence of CAD applications. The exploratory experiments which are presented in Chapter 4.1 prove that recent developments in HCI technologies provide us tools and methods which enable more feasible and functional solutions towards developing hybrid design media.

In this chapter, I present the application called Tactile Interaction for Making (TIM) which is developed in this research. TIM proposes a new approach for developing hybrid design media by utilizing the existing tools and methods. It aims at extending the content of previously tested experiments by including fabrication. It enables tactile making using handheld tools and physical materials, simultaneous digitizing of the making activity through gesture recognition, and synchronized fabrication of the real object through robotic fabrication systems (Figure 4.13). It is a prototype setup in the form of a proof of the concept which does not aim at providing a robust tool that works seamlessly and outputs complete products. It rather demonstrates the applicability of design as making, which is a hypothetical statement that is presented within the critical discourse in Chapter 2.

TIM incorporates physical model making by using a 3Doodler 3D printing pen (described in Chapter 4.1.2. It will be referred as *Pen*), digitizing through gesture recognition by using a Leap Motion Controller (described in Chapter 4.1.1. It will be referred as *Controller*), and fabrication by a uArm robot arm (will be referred as *Robot*). The software environment of TIM consists of Rhino, Grasshopper and Firefly.

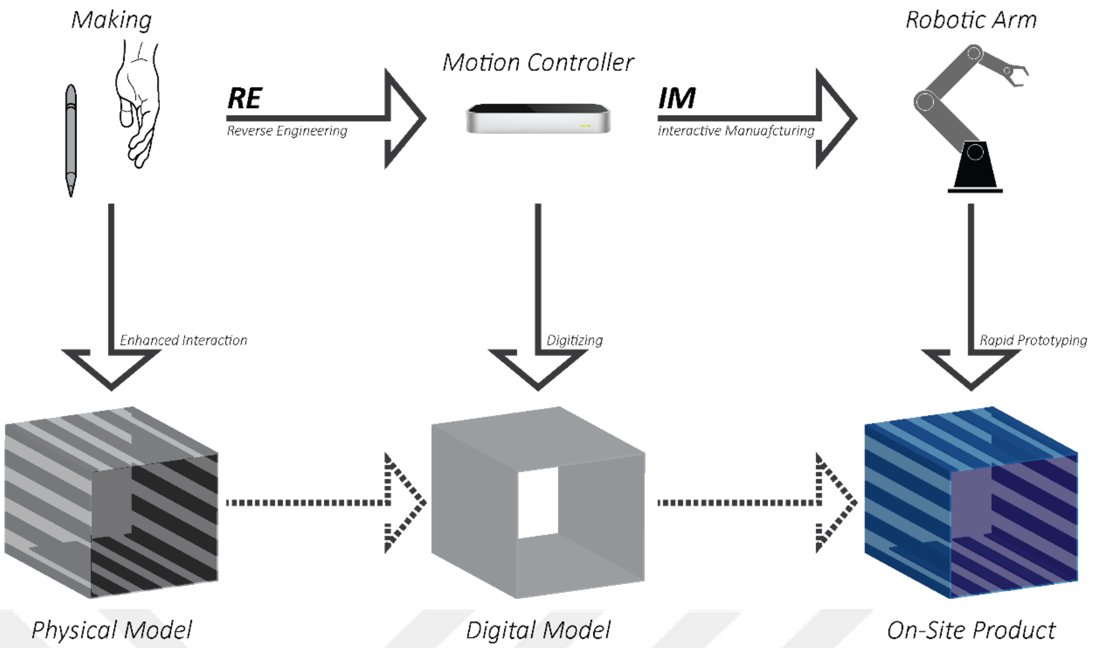

Figure 4.13 : TIM: Tactile Interaction for Making.

4.2.1 Computational workflow

TIM is used intuitively, without any computational task required. However, there is a computational workflow running in the background which connects the devices with each other and exchange data in order to perform digitizing and fabrication. The workflow which starts with physical model making and outputs the digital geometric representation and the fabricated object is shown in Figure 4.14.

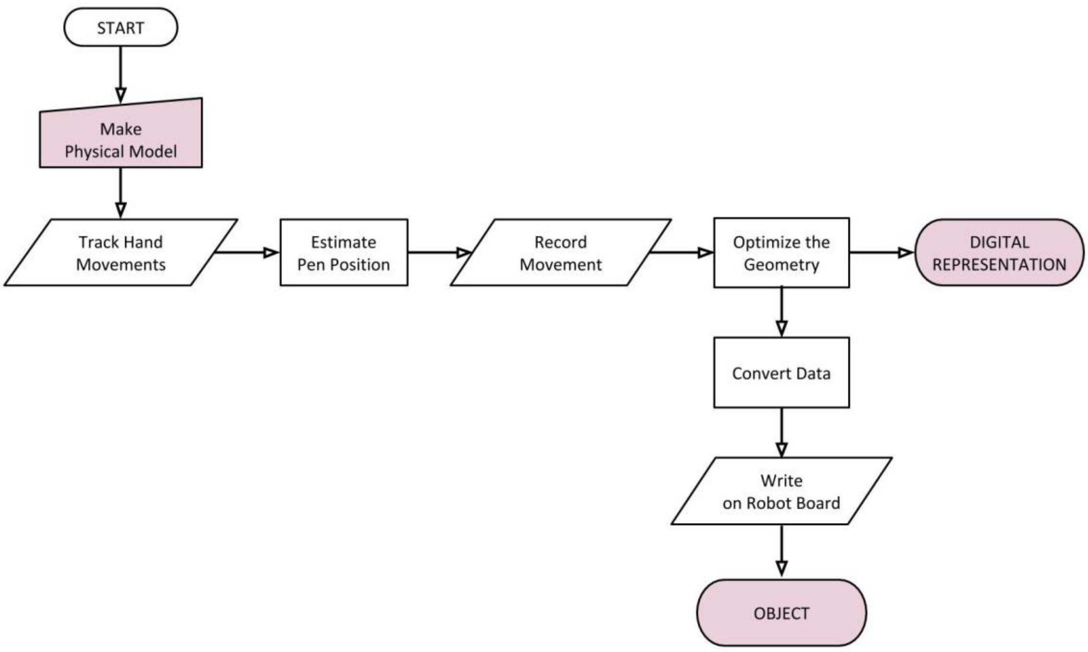

Figure 4.14 : Workflow algorithm.

The steps of the workflow are as follows:

- The designer makes a physical model by using the Pen manually,
- The Controller tracks the hand movements during making,
- The application estimates the orientation of the Pen and the location of its tip point,
- The data related with the Pen location is continuously recorded,
- The recorded data is optimized,
- The optimized data is used to construct the digital representation of the object's geometry,
- The optimized data is converted and written on the Robot board to fabricate the end object.

Eventually, the workflow has three outputs:

- Physical Model: The object which is built by the user manually. The Pen is used to build the object out of extruded plastic. It is a 3D form, made in a sketchy form, through an intuitive and depictive process.
- Digital Representation: The digitally stored information related with the object and its making. The information consists of the movements of the Pen during the production of the physical model. It can be used for further detail processing, reproduction and modification. It is also used to represent the shape of the model in CAD environment.
- Fabricated Object: The end object which is built by the Robot using the digital representation. It is a reproduction of the user's making through the Robot. The Robot is integrated with a plastic extrusion system similar to the Pen (actually, another Pen is used with the Robot in this project). The Robot uses the Pen in the same way as the user, while it is possible to optimize or modify it through certain factors, such as geometric optimization or scaling.

4.2.2 Software environment

The software environment used to develop TIM consists of Rhino, Grasshopper and Firefly. Rhino (also referred as Rhinoceros or Rhino3D) is a commercial CAD application developed by Robert McNeel & Associates (Url-29). It is able to represent freeform curves based on Non-Uniform Rational Basis Spline (NURBS) model. The reason for using Rhino for this application is that its functionalities can easily be extended when using with Grasshopper and its associated plug-ins. Grasshopper (Url-30) is a visual programming language developed by David Rutten at Robert McNeel & Associates. It runs within the Rhino and provides a parametric interface to it. Firefly (Url-31) is a set of comprehensive software tools developed by Andy Payne and Jason K Johnson. It bridges the gap between Grasshopper, the Arduino microcontroller and other input/output devices like web cams, mobile phones, game controllers and more.

TIM uses Firefly to communicate with the Controller and the Robot. The algorithm is developed in Grasshopper. The geometric representations are created in Rhino interface. Communication with the Controller is achieved through the *Leap Finger Tracker* component in Firefly. It tracks the movement of the hands and outputs the following data:

- A list of fingertip point locations,
- A list of vectors representing the finger directions,
- A list of unique identifiers for the fingers,
- A list of finger joint locations,
- A list of lines representing the skeletal bones,
- The plane of the palm.

The component currently is not able to track the Pen, even though the Controller itself is. Therefore, I developed an algorithm which estimates the position and orientation of the Pen by using the data driven from the component. It executes a geometric calculation by using the point location of certain joints on the hand in order to estimate the orientation of the Pen and the location of its tip point.

4.2.3 Hand tracking

The first part of the algorithm is the definition for tracking the hand movements and estimating the Pen position (Figure 4.15).

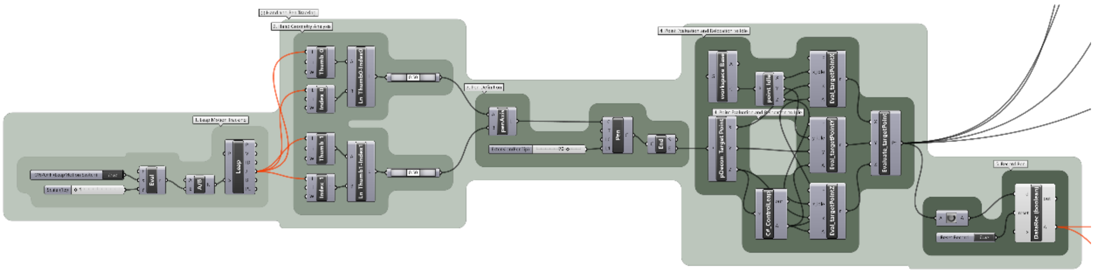

Figure 4.15 : Application Algorithm Part 1: Hand tracking and pen estimation.

The first variable of the algorithm is the scale factor, which allows the user to make physical models in his/her desired scale. He/she may input the scale factor through a *Number Slider*. The algorithm starts by changing a *Boolean Toggle* to *True*. As long as this switch is on, the *Leap Finger Tracker* component reads data from the Controller. While the component is active, the location of 4 joint points (2, 5, 3, and 7) of the hand are being tracked. These points are the first two joint points of the thumb and the index finger. The idea behind this definition is that, the user would hold the pen between his/her thumb and index finger, which is the most common position for holding a pen (Figure 4.16). Therefore, this definition will not work if the Pen is hold in a different position. These points are then used to estimate the position and orientation of the Pen through a geometric calculation. The user inputs the extension parameter through a *Number Slider* in this calculation. It allows to define the location of the tip point of the Pen more precisely. If the user needs to hold the Pen closer or more far away from its tip point, the user may adjust it by changing this parameter.

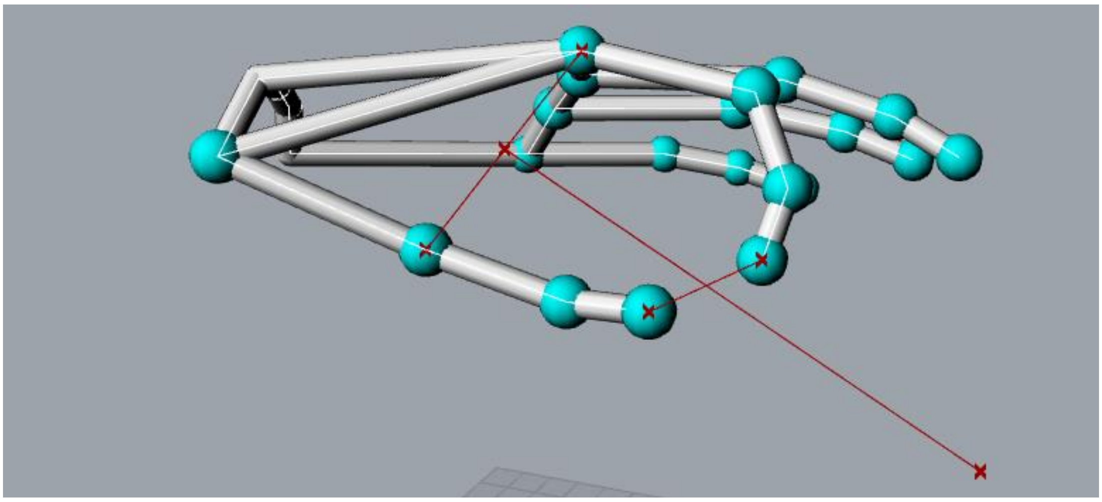

Figure 4.16 : Representation of the hand holding the Pen during physical model making.

The tip point of the Pen is the target point, which will be used for building the digital model and controlling the movements of the Robot. Therefore, an evaluation of the location of the target point is executed. The point is kept active as long as it is inside the Robot workspace. Otherwise it is sent to the idle position which is, by default, the center point of the workspace. The location of the active point is constantly being recorded through a *DataRec* component which outputs a series of target points. The user is able to change the recording time intervals in order to better suit with his/her working speed. He/she may also reset the record when necessary through a *Boolean Toggle*, in order to restart the sketching.

4.2.4 Generating the digital representation and the toolpath curve

The second part of the algorithm is the definition for generating the digital representation and the toolpath curve (Figure 4.17). The recorded target points are used to create the digital model, which is the geometric representation of the physical model and the toolpath curve of the Robot. The model is defined by an *Interpolate* component, which uses the series of the target points as the interpolation points to create an interpolated curve. Then, the algorithm provides two options for optimizing the curve. The first option is to rebuild the curve by changing its degree and number of points. The second option is to convert the curve to a polyline by optionally changing the maximum allowed segment length and the tolerance for removing the least significant vertices. These options for optimization allow the user to get rid of the undesired details of the digital model, which can be caused due to vibrating hands or the unexpected instant reactions of the *Leap Finger Tracker* component.

4.2.5 Robotic fabrication

The Robot which is used in the research is the Metal Alpha version of uArm (Figure 4.18) which is produced by EVOL (Url-32). It is a desktop scale 4-axis robot arm. It has three digital servos which control the segments and an additional mini servo which rotates the end effector. The Robot works with an Arduino Uno compatible board, which is called Uduino. Its arm reach is between 70 and 340 mm; working range is 180°; and the maximum payload is 1 kg.

In this project, the Robot is used in order to provide a prototype set-up for on-site fabrication. Principally, it will simulate the behavior of an actual on-site industrial robot arm on a desktop environment for the fabrication of a scaled product. The procedures for programming and controlling the Robot in this environment will be as same as an actual industrial robot arm. Therefore, it is able to provide insight towards the application in real world conditions. However, the functionalities of the desktop Robot provide much less than the actual one.

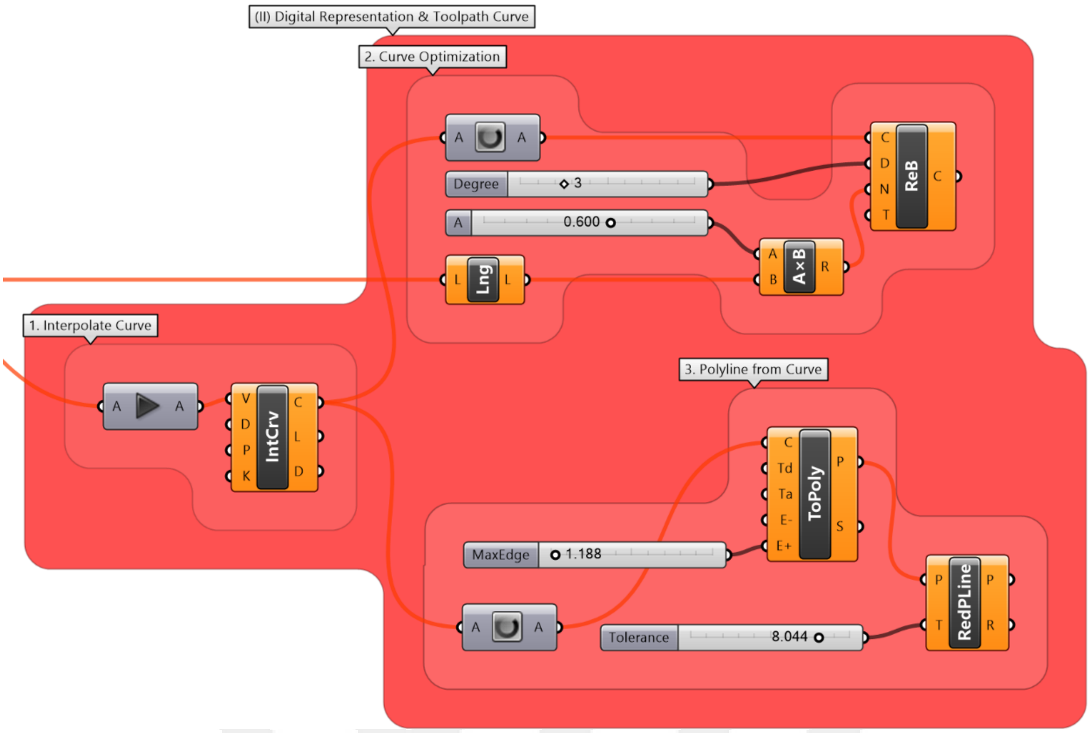

Figure 4.17 : Application Algorithm Part 2: Generating the digital representation and the toolpath curve.

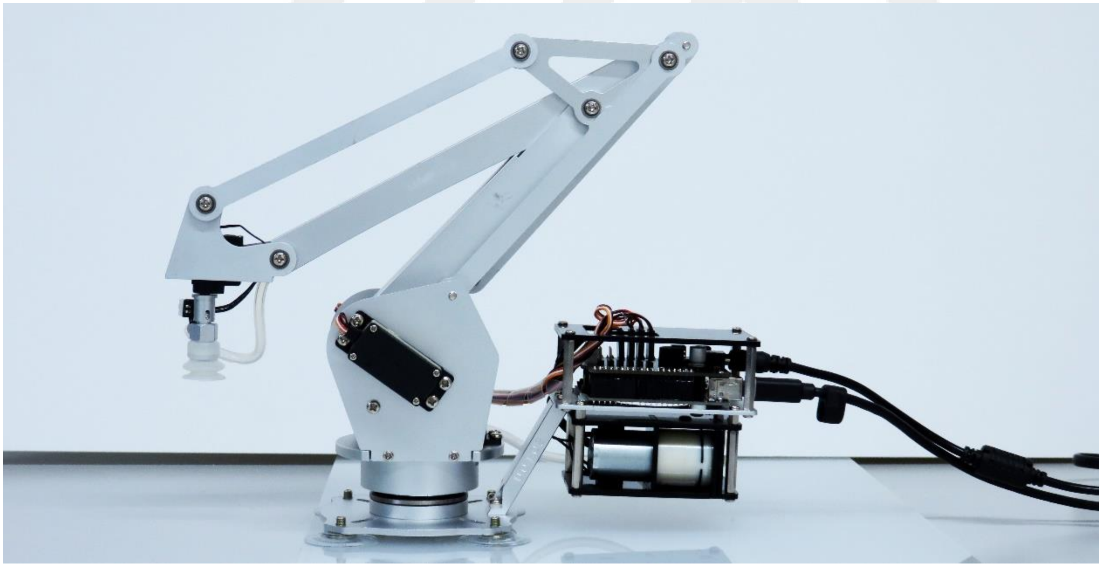

Figure 4.18 : Robot arm (uArm Metal Alpha).

First of all, the rotation angle on each joint of the Robot is limited as follows in relation with the real world axes (Figure 4.19) in order to prevent the arm being stuck on the joints:

• Joint 1 (Linear Joint on XY plane): 180 degrees; from 0° to 180°.

• Joint 2 (Rotary Joint on Shoulder): 90 degrees; from 15° to 105°.

• Joint 3 (Rotary Joint on Elbow): 45 degrees; from 315° to 0°.

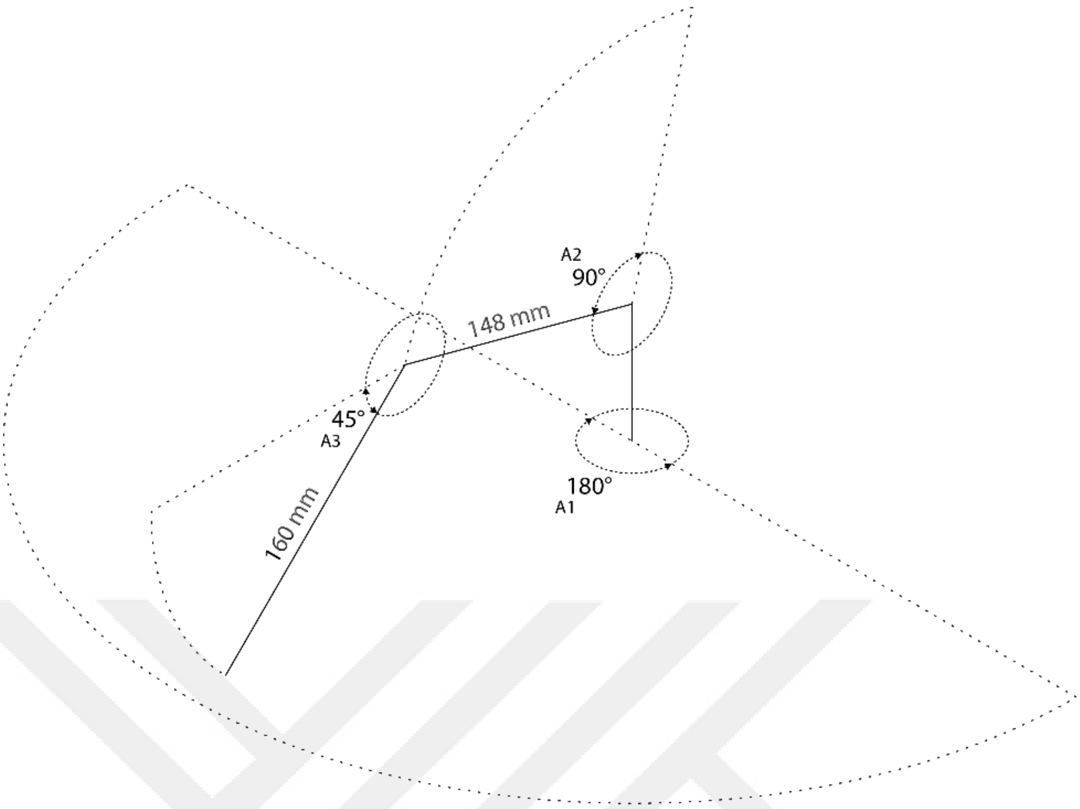

Figure 4.19 : Robot's DOF and the rotation angles on each joint.

According to the defined angles, the work envelope of the Robot is shown in Figure 4.20. The envelope which is shown in this figure is the volume which can be reached by the end effector within the limitations of the stability of the Robot.

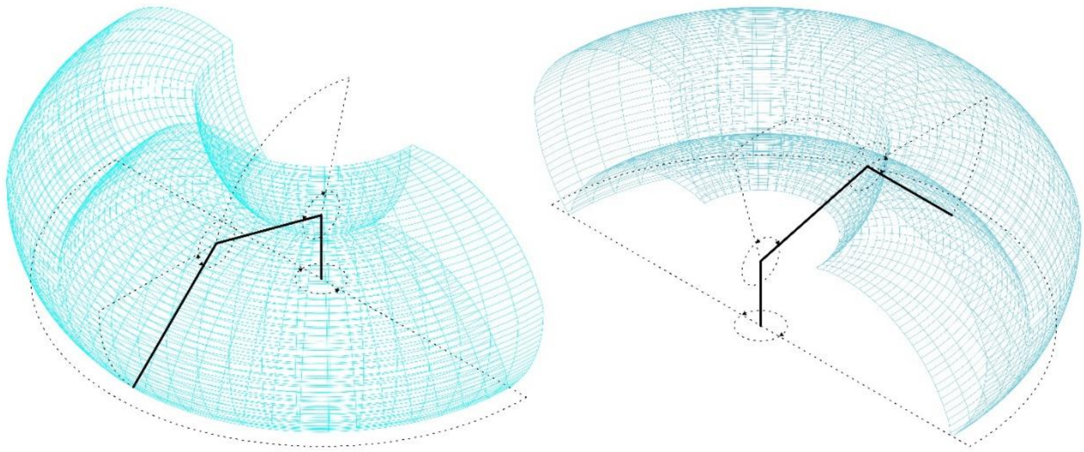

Figure 4.20 : Robot's work envelope.

However, it is not possible to build an object on all parts of this volume as its shape will be limiting. Therefore, an imaginary plane is defined inside the work envelope in order to define a ground for modelling (Figure 4.21). Eventually, the build space of the robot arm is the volume which is inside the work envelope and above the plane. The object needs to be built inside this build space for a more efficient workflow.

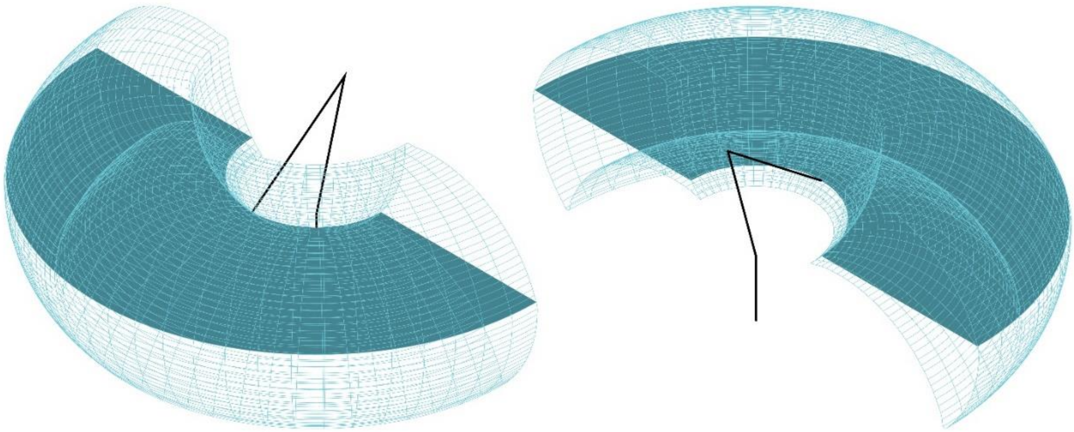

Figure 4.21 : Robot's work envelope and the ground for modelling.

Despite its constraints and limitations, the Robot is able to provide insight towards the goal-oriented use of an actual on-site robot; as the programming and control procedures of the two will not be much different than each other. Therefore, it is sufficient enough to provide an environment which is necessary for the empirical analysis of the research objectives even though it is not fully precise and stable.

Then Pen is integrated with the Robot as seen in Figure 4.22. Eventually, the Pen performs as a fixed end effector. The idea behind this procedure is that, the Pen will extrude material vertically while the Robot moves along the defined toolpath; and create an identical scaled copy of the physical model which is created by the designer using another Pen manually. The operation of the Robot may be either synchronous or asynchronous with the designer, depending on the robot programming and the way he/she prefers to use it. By this means, the designer will be able to control the Robot without physical touch, but through the physical model which he/she manually creates. The link between the two hardware situations is achieved through the software environment.

The third part of the algorithm is the definition for inverse kinematics (Figure 4.23) which works within the physical constraints of the Robot mentioned above. The definition generates a responsive kinematic scheme in order to simulate the movements of the Robot in CAD environment (Figure 4.24) and to generate data to actuate the movements of the Robot in real world.

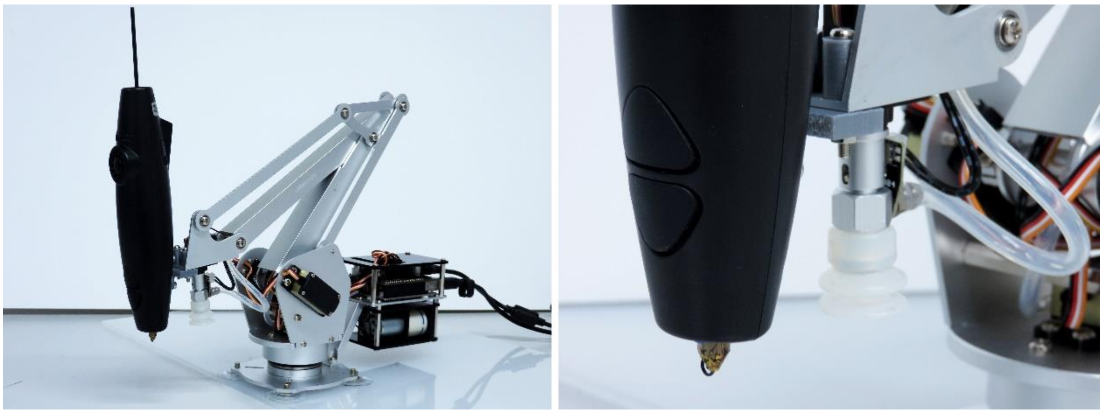

Figure 4.22 : The Pen and Robot integration.

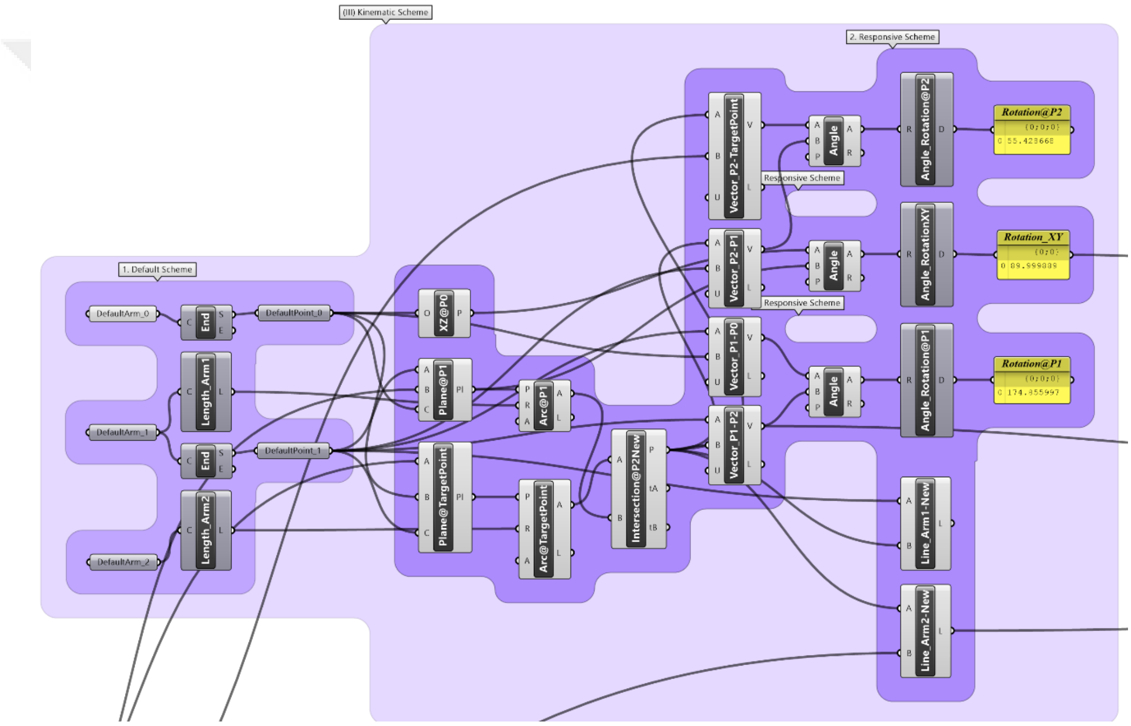

Figure 4.23 : Application Algorithm Part 3: Inverse Kinematics.

The fourth part of the algorithm (Figure 4.25) writes the data from the kinematic scheme onto the Robot board in order to actuate its movements in real world. To this end, the parameters of each joint, which are acquired from the inverse kinematic definition, are converted to match with the features of the Robot. Then, the data is used to write on the pins of the Uduino board of the Robot. The *Uno Write* component is used in order to turn on and off the connection port of the board and write data on it. 3 of the pins, Pin11, Pin12 and Pin 13 are used to rotate the segments at the 3 joints. These pins control the servo motors; therefore, it is necessary to set the pins to *Servo* on the *Uno Write* component.

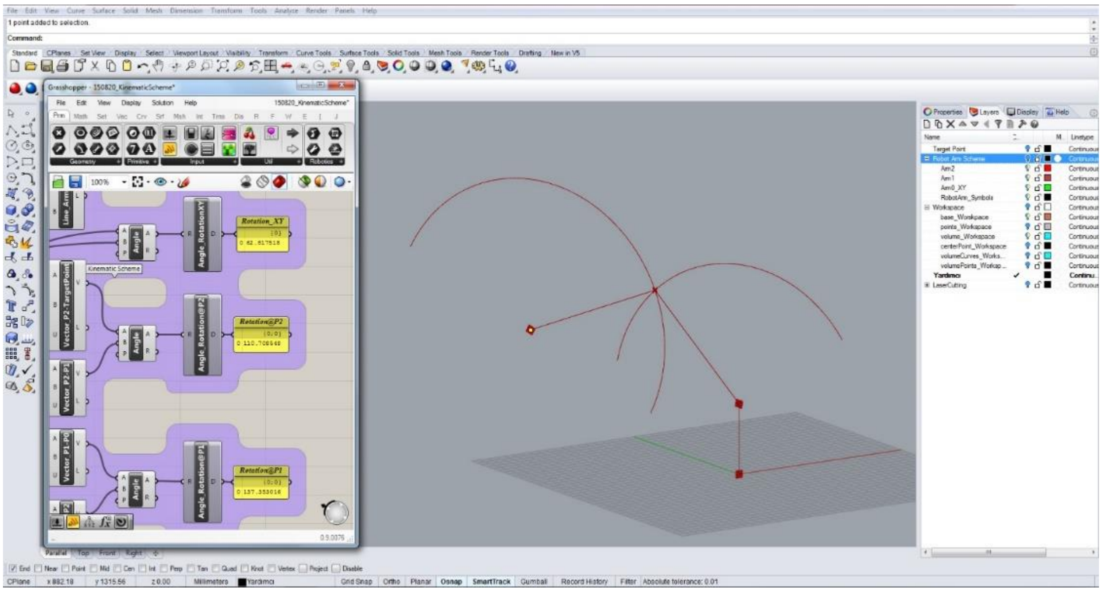

Figure 4.24 : The kinematic scheme.

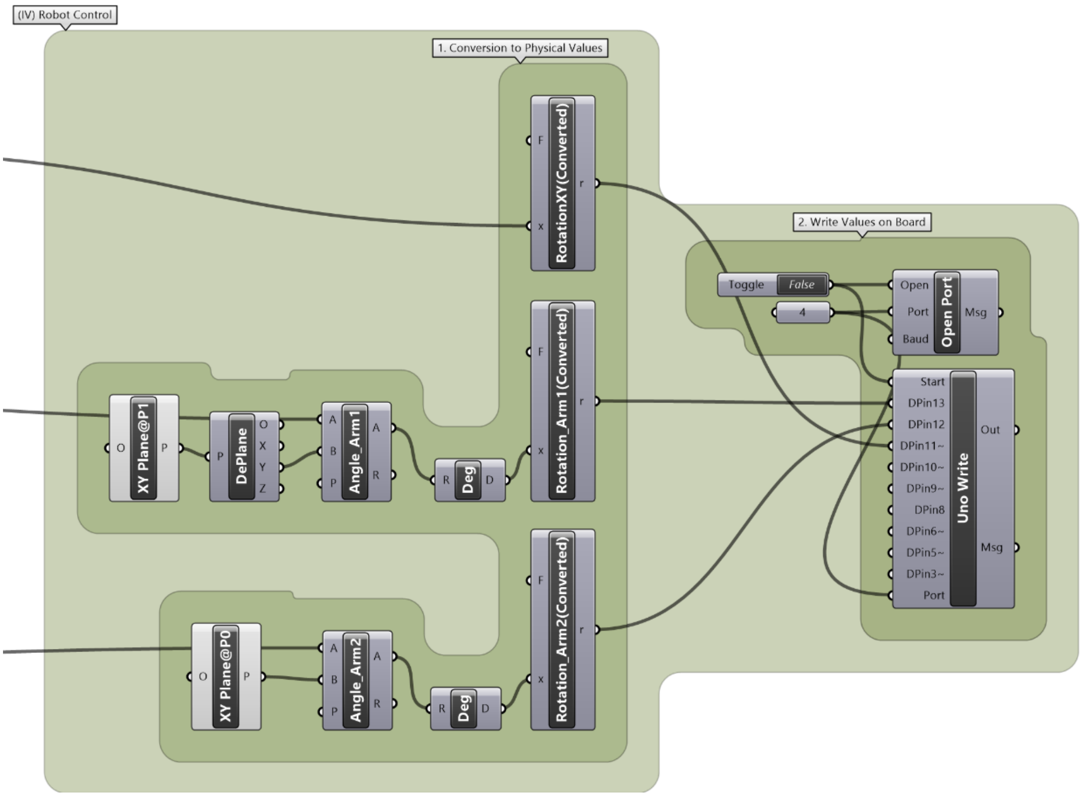

Figure 4.25 : Application Algorithm Part 4: Robot control.

The Robot moves in the physical environment identically with the kinematic scheme in CAD environment. Thus, while the target point is moved in the CAD environment, both the kinematic scheme and the physical robot arm is simultaneously moved; so that the location of the tip point of the robot arm is exactly matched with the location of the target point. This enables the Pen, which is integrated with the Robot, to move identically with the Pen which is used by the designer manually. These two movements may be either synchronous or asynchronous, depending on the preferences of the designer.

4.2.6 Evaluation of the application

TIM, as a prototype set-up (Figure 4.26), is meant to serve as a proof of the concept and to provide insight towards real world applications. It demonstrates the potentials of the existing tools and methods towards developing better interaction systems for designers. It points out the future directions for developing better tools by introducing the studies developed in HCI field into design. Eventually, it is able to prove the applicability of research objectives by demonstrating that digital design environments are not only representative but also contain growing potentials towards integrating materiality.

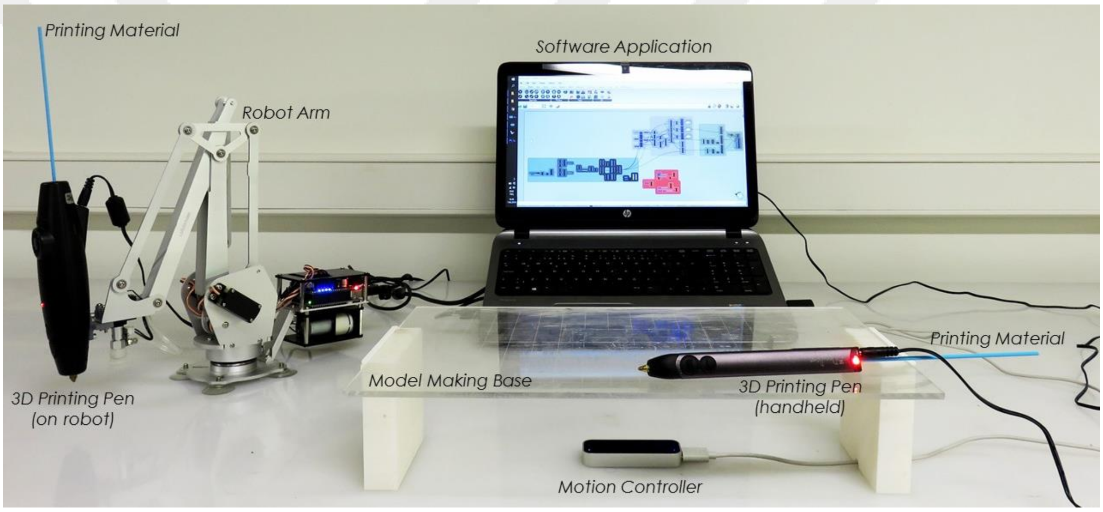

Figure 4.26 : The workspace set-up of TIM.

TIM enables the designer to materialize his/her sketchy design proposals using the Pen, which is a feature that introduces intuitiveness into the process. Do (2002) defines sketching as a natural way for people to explain and understand complex ideas and to perform visual and spatial reasoning. Similarly, the aim of TIM is to allow the designer to analyze the design problems and to illustrate proposals through freehand, 3D and physical depictions. The output of this phase is a physical model made of plastics. In the meantime, the movements and the gestures of the designer's hand are recorded by the system. This phase of the process outputs digital data which is stored and used for computational processing. One of the outputs in the digital environment is a 3D digital model which represents the shape of the design. This shape is identical to the physical model which is created manually. Further, the movements of the Pen are recorded in order to be used to define the toolpath curve for the Robot. Then, the Robot fabricates a scaled copy of the design using plastic by receiving data from the digital model. By this means, the application synchronically produces three outputs; the physical model, the digital model and the fabricated object.

TIM demonstrates a hybrid medium in which physical and digital tools are integrated with each other by exchanging data reciprocally with the help of an application algorithm (Figure 4.27). It enables various forms of engagements, both bodily and cognitively, with material and immaterial entities. It is able to involve the tacit dimensions of design knowledge with the help of digital technologies as being an instrument of thinking tied to the body. It synchronically produces both physical and digital outputs which address different phases of design development and fabrication. It enables the designer to illustrate and materialize his/her design decisions through intuitive and implicit acts while allowing further computational and digital processing such as optimization and pre-rationalization. It enables the designer to develop his/her design decisions by working with physical materials rather than through only representations. It illustrates the hypothetical proposal of “Design as Making” by embedding the inherent qualities of craftsmanship into a digital design practice.

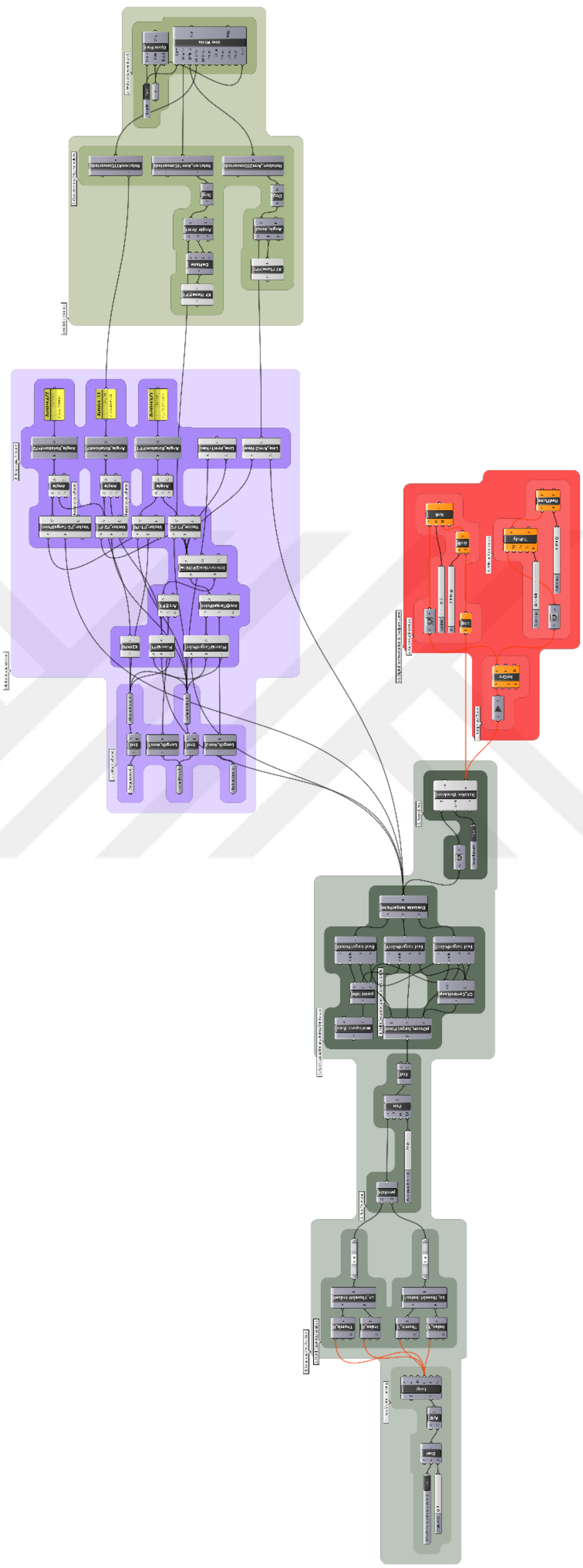

Figure 4.27 : The complete algorithmic definition of the application.

4.2.7 Means of improvement

There is still room for improvement to provide better outputs using the system. This points out the next steps of the future work to improve the system’s functionalities. Particularly, TIM is not a robust tool because of certain limitations of the hardware and software used.

The limitation of the software is that; it is yet not able to track pointable devices even though the Controller itself is. Therefore, the tracking of the Pen is conducted through a computational estimation inside the algorithm. However, the system would function more robust if pointable detection feature is added by working on the Leap SDK into the *Leap Finger Tracker* component. So that the tracking of the Pen would be more precise, correct and solid.

The most important aspect regarding the hardware in order to improve the usability of the medium would be using a more precise and stable robot arm with higher Degree of Freedom (DOF), which was not available in this research. The DOF of the Robot which is used in this research is 4. The fourth axis provides the rotation of the end effector on XY plane. This feature does not have much use in this application, therefore, it is omitted. Thus, the Robot, in the way it is used for this project, has only 3 DOF. On the other hand, the segments of the Robot are not very stable, especially at certain angles. It causes vibrations on the arm, which is another factor which makes it difficult to position the end effector exactly on the defined toolpath. Because of these reasons, the output which is fabricated through the Robot will not be exactly what is defined by the algorithm. Also, the reach of the Robot is very limited. As its maximum reach is 340 mm, the work envelope is not big enough to output objects in any desired scale. On the other hand, it was necessary to limit the rotation angles at each joint in order to keep the Robot within the limits of a safer volume, which is another factor that constrains the work envelope. There exist several brands which produce stable and precise robot arms with up to 6 DOF in different sizes with higher stability and precision. Therefore, they are able to provide better outputs as the end-effector will be able to move on the toolpath without deviations. On the other hand, higher DOF will enable the robot to perform the movements of the Pen more similar to the way the designer uses it manually. This will enable the creation of more complex geometries, as the Pen will be able to reach the target points not only in vertical position but also in diverse positions. Even though such robots provide better functionalities, it is possible to program and control them in principally the same way as it is done in this research. Besides the *Firefly* plug-in, which is used in this research, there are other Grasshopper plug-ins, such as KUKA|prc (Url-33), HAL (Url-34), and IO (Url-35), which enable direct communication between the CAD application and robotic systems. They enable robot programming, simulation and control directly through the CAD interface; and simplify the use of robotic systems for designers who are not specialists in robotics but are able to use such CAD applications. Therefore, one can claim that, design-to-fabrication workflow for industrial robots, which has traditionally been a slow and cumbersome process, and required intimate knowledge of scripting and fabrication processes (Payne, 2011), will be widespread and simple in design disciplines in the near future.

Another improvement would be developing a special extrusion system as the end effector instead of using the Pen integrated with the Robot for the fabrication of the object. The Pen is able to perform extrusion only with PLA or ABS plastics. A specialized extrusion system can enable the use of different materials such as clay, cement, glass, metal or resin. Such extrusion systems are becoming more common along with the improvements in 3D printing technologies with robotic support. One may claim that, the logic of additive manufacturing will be adapted to a more diverse set of materials, which will enable rapid fabrication of complex geometries by using different materials more accessible in the near future. On the other hand, specialized extruders can enable flow in different thicknesses. For example, both very thin materials for the fabrication of small objects such as jewellery, and very thick materials for the fabrication of big objects such as building components, can be used by such extrusion systems. Therefore, the medium can have use in several types of real world problems when equipped with such extrusion systems which are becoming more widespread.

On the other hand, the mode of making which is provided in this research is limited to the capabilities of the Pen. Both the manual physical model making and the robotic fabrication of the object is executed only by plastic extrusion in this prototype setup. However, design activity includes several operations through various tools; such as folding, cutting, assembling, drilling and so on. Therefore, in order to address a more comprehensive spectrum of making activities, the medium needs to include different types of practices and the use of different tools which a designer might need. One of the important aspects of the medium is that it includes the material qualities into the design process and enable material feedbacks while working with digital environment. However, the material to be used for model making is limited to the capabilities of the Pen as well. In order to improve the capabilities of the medium, a material variety is necessary to enable the material complexities which a design might include. So, it will be useful to repeat the research questions and develop techniques towards the research objectives within different types of design crafts and materials.

5. CONCLUSIONS

5.1 Outputs and Evaluation of the Research

This research presents two important outputs. The first one is a comprehensive review of the related studies (presented in Chapter 3) which aim at developing Human-Computer Interaction (HCI) systems to be used in design development or fabrication. The second output is an applied project named TIM (Tactile Interaction for Making), which demonstrates a set-up of a hybrid design medium (presented in Chapter 4) that bridges the gap between the digital and physical environments in a new way and enables an act of design which integrates design development and fabrication towards an understanding of design as making.

The review focuses on the related projects which were held between 2000 and 2015. It lists 68 projects and categorizes them towards their fields of use, main objectives and the addressed audiences (Table 3.1). This categorization provides a comprehensive overview on HCI research which focus on design and fabrication. It transfers the fundamental know-how and the key concepts of HCI research to design fields from a designerly perspective. Among this list, 12 projects are chosen for having profound relationships with the objectives of this research. These projects are analysed within the modes of interaction which they demonstrate, the means of interaction which their users experience, the outputs which they provide and certain inherent features which they perform (Table 3.2). This unique method for analysing these projects illustrate the benefits and drawbacks of each technique which is used to develop HCI systems to be used in design and fabrication. Generally, these 12 projects are found successful and inspirational within the objectives of this research. Each of them points out a particular need and demonstrates solutions for solving it. Therefore, it is able to provide a roadmap to the designers who aim at developing better tools for interaction with the digital design media.

TIM is a demonstration of a potential approach which can be utilized for developing an interaction system that integrates design development and fabrication by making use of existing and simple tools. It is a proof of the concept that demonstrates the applicability of research objectives in the form of a prototype set-up. It illustrates how designing can be reframed as a form of creative crafting with the support of computer systems by enabling the designer to work with physical materials through bodily and intuitive means in order to process the acts of design and fabrication. Further, it is suggested that this approach can be developed further by using more expert and cutting edge tools in order to address a variety of real-world problems.

Both outputs are able to put forward and prove that digital design media is not only representative but also profoundly related with materiality. Particularly, the new developments in HCI technologies enable direct, organic and mutual interactions between the physical and digital environments; which is a key aspect to develop better design tools. By this means, it becomes possible to reframe design as a form of making. So that the qualities of traditional and typical craftsmanship are re-integrated into design thinking and the tacit dimensions of design knowledge are involved with the help of computer systems. Thus, it indicates a perspective for weaving the information technologies into the fabric of designerly practices.

5.2 Forms of Interaction through TIM

TIM enables reflective, synchronous and reciprocal interactions with the digital design environment through material artefacts during design development and fabrication. It is a medium which facilitates various acts of the designer. Thus, the form of the interaction through TIM is designated towards the needs and abilities of the designer and the properties of the particular task he/she is working on. One may think of several scenarios which are subject to performing different forms of interactions and producing different forms of outputs within the functionalities of this medium.

5.2.1 Scenario I: A linear workflow from the model to the object

The simplest form of interaction is through a linear workflow in which the designer builds a physical model manually, the software generates a digital representation of the model, and the robot fabricates the actual physical object or its scaled prototype (Figure 5.1). These three outputs can be produced synchronically or not, depending on the preferences. Moreover, the model and the object can be produced at the same place or not, depending on the preferences as well.

In this scenario, the most basic achievement is the affordance of the interaction as building the physical model is not much different than a freehand sketching process. Indeed, it is a freehand, physical and 3D sketching application. Therefore, the tacit dimensions of design knowledge and the intuitive skills of the designer are involved within the medium. Moreover, the actions and the perceptions of the designer are spatially and temporally synchronized on the model, which is a factor that makes it a better HCI system.

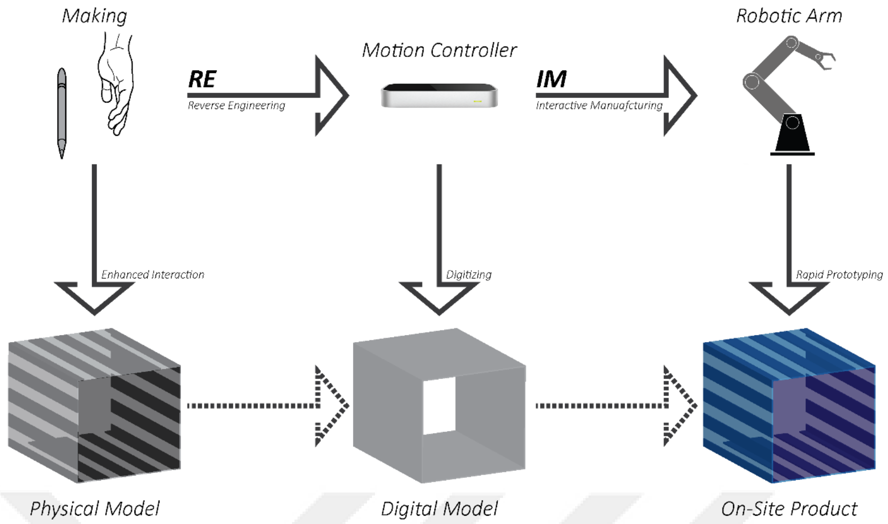

Figure 5.1 : A linear workflow from the model to the object.

Another achievement is that physical materials are used to build the model -therefore the digital representation, as well. So, quoting and extending Schön's (1984a) argument, designing becomes a reflective conversation with talking-backs between the designer and the material. While building the model, the designer needs to consider the material qualities such as; its ability to span, bend or rise, its structural performance, or its texture qualities. So, the material feedbacks the design by both integrating its qualities into the creative process and requiring the pre-rationalization of the design decisions. Also, using physical materials for modelling enables the designer to go beyond the limits of his/her sense of sight by allowing the sense of touch. Therefore, it is able to address Ponty's (1962) notion of embodied perception by enabling mutual engagements with things and providing the active involvement of the whole body.

The last important notion which is achieved by this simplest form of interaction is the capability to integrate design development and fabrication. This is achieved by integrating the robot into the interaction so that it can duplicate the model in order to produce the actual on-site object or its scaled prototypes. Within TIM, the robot duplicates the movements and gestures of the hands of the designer by rationalizing and optimizing them through a series of parameters which are predefined by the designer. This integration is the basis for the hypothetical statement of "design as making" of this research. The potential which is provided here is indicated by Gramazio and Kohler (2012) by arguing that design incorporates the idea and knowledge of its production already at its moment of conception. Moreover, this integration is key to embed the human notion of intuitiveness into robotic systems – so that they can better serve to a range of fields from music to healthcare which particularly need intuitiveness.

5.2.2 Scenario II: A reflective conversation between the designer and the computer

One of the potential forms of interaction through TIM provides an environment in which the designer and the computer collaborates on a design task. In this scenario, the model is built by incorporating the intuitive skills of the human and the computational capabilities of the software application. Basically, the designer starts the process by building a physical model manually. The software application understands the design by capturing the movements and gestures of his/her hands. Then, it provides an output by optimizing, rationalizing or developing the design. The output is applied onto the model through the robot. Thus, designing become a reflective conversation between the designer and the computer (Figure 5.2).

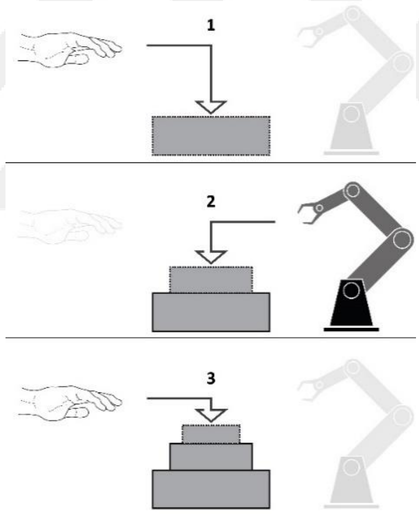

Figure 5.2 : Reflective conversation between the designer and the computer.

In this scenario, there are two outputs which are produced during the design process. The first one is a physical 3D model which is built by both the designer and the robot. The second one is the model's digital representation which is produced synchronically. Here, the designer is able to receive computational support during design development in addition to the functionalities which were described within the first scenario. The form of this support can be diverse; e.g. optimizing the structural performance by adding structural elements on the model, correcting the shape of the model by fixing the curve continuities, arraying the repetitive elements of the object, and so on.

In this set-up, the model is both the objectified design idea and the tactile interface for communication and collaboration between the human and the computer. Within the notions of HCI, the situation moves the interface out of the screen and moves it closer to the human world as addressed by Svanæs (2001). Moreover, what is being built in collaboration between the human and the computer can as well be the actual object itself. In this case, designing becomes collaborative making. This collaboration, both keeps the computational capabilities of the computer as support to design thinking, and sustains the initiative and flexibility of the person like indicated by Norman's (1993) notion of soft technology. Here, the computer becomes an instrument of thinking tied to the body just like argued by Latour and Yaneva (2008). And, designing becomes and activity of making, or a form of creative crafting, which is subject to the hybrid assemblage of brains, bodies and things like argued by Malafouris (2013).

5.2.3 Scenario III: A support for distant collaboration

The first and second scenarios can be merged and enhanced in order to support distant collaboration in design development and fabrication. So, more than one designer, each of which are located in distant locations, can work together in the same design process. Each designer needs to have access to the same equipment in order to be able to participate in the collaboration which is achieved simply by accessing the digital representation from several computers. This digital model which is shared online is the interface between the two designers and it both transfers and receives their inputs.

A sample collaboration between two designers is started by the first one who builds a physical 3D model manually. The software generates the model's digital representation simultaneously. The second robot duplicates the first model and produces an identical one for the use of the second designer. Then, the second designer develops this model by adding his/her inputs on it. These inputs are updated on the digital representation simultaneously. Then, they are transferred to the first robot so that it can duplicate them onto the first model (Figure 5.3). Therefore, this collaboration outputs identical physical models for each collaborator and a shared digital representation of the design.

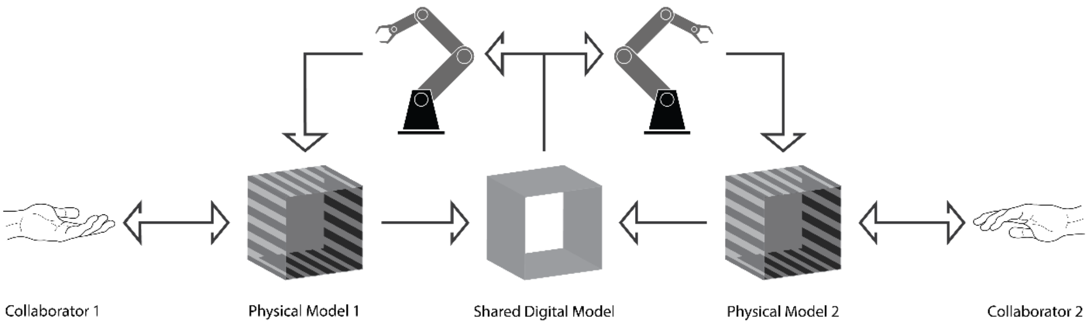

Figure 5.3 : Distant collaboration for design development.

The collaboration can as well output the actual object if an on-site actual scale robot is integrated into the system (Figure 5.4). This is simply achieved by transferring data from the shared digital model to the robot.

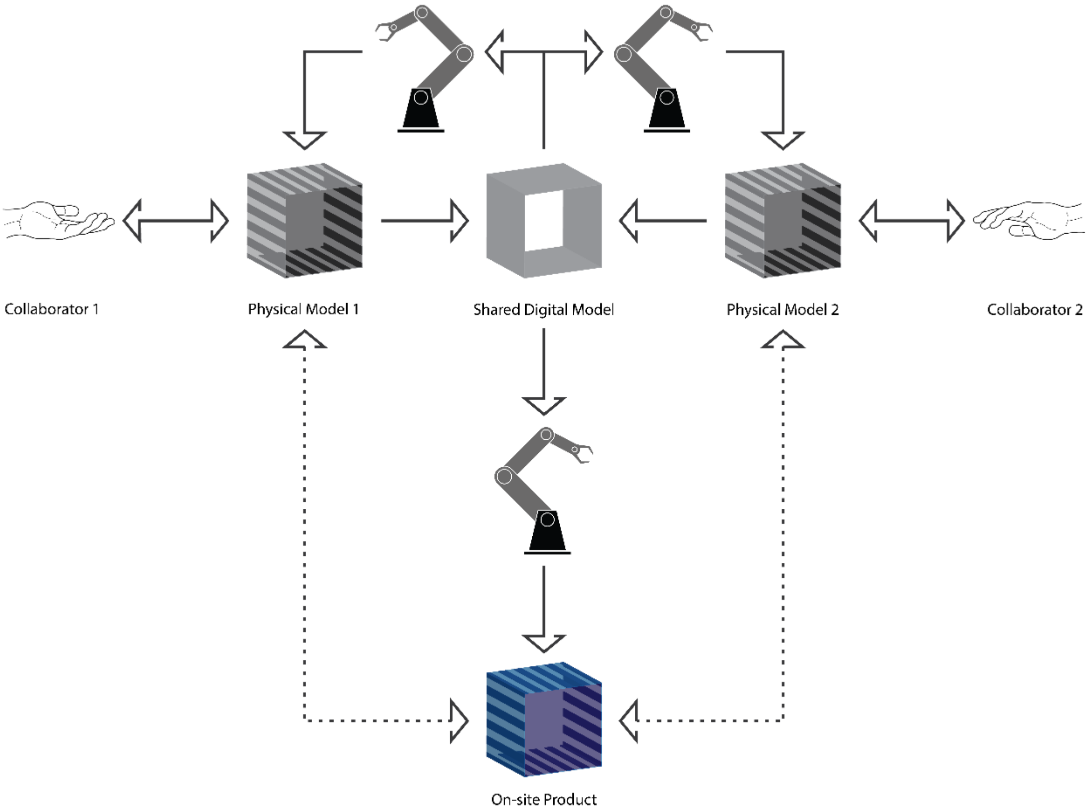

Figure 5.4 : Distant collaboration for design development and fabrication.

One of the challenges in distant collaboration in design and fabrication is the lack of tangible media which the collaborators can efficiently share. The achievement of this scenario is that it enables the parties to share tangible outputs which are produced collaboratively. Moreover, by doing so, it sustains the significant notions which are discussed in the previous sections in relation to design thinking within the collaboration.

5.3 TIM's Potential Fields of Use

TIM is a prototype set-up which demonstrates the applicability of the research objectives. As a proof of the concept, it principally points out the future directions towards developing hybrid media to be used in design development and fabrication. It is suggested that the scenarios which are described in the previous section can address several fields of use if the functionalities of the medium are improved by utilizing cutting edge tools.

Currently, TIM's most likely fields of use are creative practices which are subject to either the production of 3D objects such as architectural, product, interior and fashion design or artistic applications such as interactive installations and performing arts. The currently existing functionalities of the medium are able to support these kind of applications as it enables bodily interaction with digital tools and provides different forms of outputs. One may claim that any form of creative practice can benefit from such a medium as it integrates human's complex mechanism of perception and intuitive skills with the computational abilities of the computer systems and the physical functionalities of the robotic technologies.

One may suggest that it also has capabilities which can support education. This hybrid medium can potentially reinforce hands-on practices, collaboration and communication. Therefore, the learning environments in design education can benefit from such media and the learning methods which it can facilitate. First of all, it is able to encourage making and craftsmanship at the studio. By this means it supports the notions of learning by doing and experiential learning. On the other hand, it is able to provide interfaces which support communicating the implicit realms of design thinking between the students and the teachers. This aspect has been gaining importance with the increasing use of computer software at the studio. The input of the teacher on the student's work becomes fairly limited in certain situations in which the teacher is not familiar with the software that the student uses to develop his/her work. TIM reduces these limits by enabling the user to communicate his/her design thinking through more multimodal and natural modes of communication rather than pre-defined and inflexible operations which are required by the software. Hence, the input of the teacher in a learning environment which is equipped with such enabling media will not be limited to verbal critics on what the student presents. Moreover, he/she will have the chance to interfere with the student's making process more seamlessly and to provide concrete input on the methodological aspects as well. This form of a learning environment addresses the argument of Wood et al. (2009) who claim that involvement in a community of practice with peer support and critique is necessary to enable students to evaluate and improve on the quality of their work; traditionally working with a craft master has been the main way to achieve this. One the other hand, TIM is able to support distance learning in design, particularly through the qualities which are described in the third scenario in the previous chapter. E-learning technologies have already provided many benefits and have broad use in several fields. However, their use in design education is relatively rare especially for the applied courses because of the lack of tools. One may claim that tools like TIM, which enable tangible design media that can support distant collaboration, are useful towards developing efficient e-learning strategies.

Besides practice and teaching in creative fields like arts and design, tools like TIM are able to address a broader domain of real world tasks in various fields. Especially certain fields which are subject to hazardous work such as construction, mining, submarine, aviation or medical operations can highly benefit from the forms of interaction which are provided by such hybrid media. Because, these interactions enable the remote control of robotic systems (which can operate difficult, dangerous or precise tasks) which are equipped with computational support of the computer and the tacit and intuitive skills of the worker.

One may imagine; a construction worker who is operating a welding robot on top of a skyscraper through the scaled model on his/her desktop; a miner who is operating the drilling robot through its prototype in a safe work environment; or a surgeon who is working a risky operation on the patient’s body through a physical mockup in order to foresee the possible complications before they occur on the patient’s body; as examples of the potential fields of use of such interaction forms. To this end, the medium needs to be improved like discussed in Chapter 4.2.7 and tailored for the specific use.

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APPENDICES

APPENDIX A: Screen Image of the Algorithmic Definition in Grasshopper.

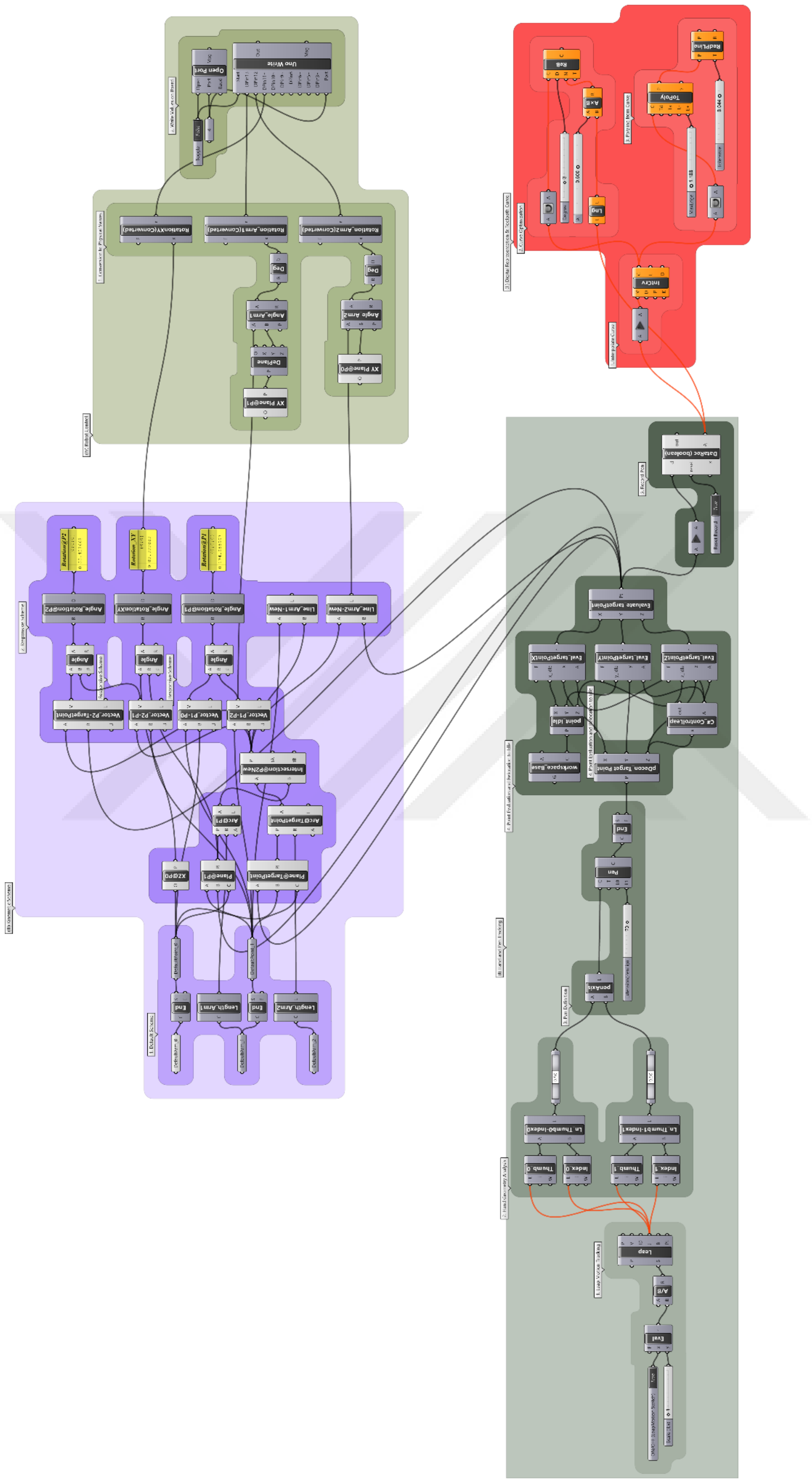

Figure A.1 : Screen Image of the Algorithmic Definition in Grasshopper.

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