Computational Gestural Making:

a framework for exploring the creative potential of gestures, materials, and computational tools

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Abstract

The emergence of digital computation in design reinforced the traditional view that 'to design' is 'to think,' 'to represent' is 'to plan,' and 'to make' is 'to fabricate.' Under this computational design trichotomy, the uniqueness of the gesturing hand to sense, communicate, grasp, shape, and interface in the world has been traditionally overlooked, relegating making as a peripherical stage of the creative process where no intellectual development -apparently- occurs. I argue that hand gestures have the power of blurring the limits imposed by the computational trichotomy reframing design as an integrated process in which representing, thinking, and making are intertwined and inseparable. In this dissertation, I start from the assumption that 'to make' equals 'to design,' and propose a 'computational gestural making' framework to capture the potential of the interaction between human gestures, intelligent machine behavior, and material context. I explore the creative power of the thinking hand through the development of fabrication tools embedded with machine learning algorithms focusing on the interactive, material, and performative aspects of the making process. The scope of this doctoral research centers on establishing a Computational Gestural Making framework that (1) establishes a model for Human, Machine, and Material interaction (2) outlines the development and assessment of a gesture-based framework for interactive design and fabrication as a method for computational gestural making. (3) applies the proposed framework in case studies to assess the means and the effectiveness by which computational gestural making emerges as an alternative way of designing embracing the uniqueness of the thinking hand as an agent for creating original and authored work.

Thesis supervisor: Terry Knight
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Finally I like to dedicate this thesis to my parents Fernando and Rosalía. This is for you. This was possible because of all your efforts and love. I love you.

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INTRODUCTION

1

The emergence of digital computation in design reinforced the traditional view that 'to design' is 'to think,' 'to represent' is 'to plan,' and 'to make' is 'to fabricate.' Under this computational design trichotomy, the uniqueness of the gesturing hand to sense, communicate, grasp, shape, and interface in the world has been traditionally overlooked, relegating making as a peripherical stage of the creative process where no intellectual development-apparently-occurs. The advent of a considerable number of computational techniques, methods, and tools comes accompanied by new types of interfaces to generate and develop design ideas. In that regard, we often see how the addition of new technologies has served as a conduit to translate the imagined into the realm of computers, increasing the distance between the uniqueness of a gesture and the physical execution of that gesture. In this research, I propose how hand gestures have the power to blur the limits imposed by the computational trichotomy reframing design as an integrated process in which thinking, representing, and making are intertwined and inseparable. I start from the assumption that 'to make' equals 'to design' and propose a 'computational gestural making' framework to capture the potential of the interaction between human gestures, intelligent machine behavior, and material context. I explore the creative power of the thinking hand by developing fabrication tools embedded with machine learning algorithms focusing on the interactive, material, and performative aspects of the making process.

This doctoral research seeks to establish a computational gestural-making framework with a threefold purpose. Firstly, it aims to create a model that elucidates the intricate interplay between humans, machines, and materials in the process of making. Secondly, it endeavors to develop and evaluate a gesture-based framework for interactive design and fabrication, using it as a means of realizing computational gestural making. Lastly, the proposed framework is applied in a series of case studies, assessing the efficacy and potential of this alternative approach to design, which embraces the creativity and individuality of the thinking hand as an agent for generating innovative, expressive, and original work.

1.1 The Computational Design trichotomy

The separation between designing – the ideation of an artifact– representing – the plan to build the artifact– and making – the physical execution of the artifact– has been present in western culture for centuries. Since the invention of architectural design the intellectual, imaginative, and creative were considered by-products of a creator's mental process that happened separately from any physical or material concern . It was Alberti's conception of architectural design that introduced new technological devices as vessels to translate the abstract into the physical, separating what a designer imagines, represents, and executes.

Design processes across different disciplines have inherited and deployed, either explicitly or implicitly, the Albertian dichotomy between designing and making up to the present day. However, if we consider representation separately from the domain of ideas, the dichotomy can be formulated and analyzed as a trichotomy in which ideas, and physical objects are mediated by representations. In this trichotomy, digital technology has served as a mediator between the stages of a 'design workflow,' and it has been the mechanism by which design information has been traditionally generated, processed, and communicated. This, in general terms, has been formalized and ingrained in the design field as a computational design trichotomy .

In the dawn of digital computation after World War II, the creativity and authorship domains inherited by the design trichotomy remained untouched as technological additions to the 'design workflow' evolved into several forms of representing 'better' and producing 'faster.' The creation of a 'computational design workflow' borrowed engineering concepts to organize the increasing complexity of projects in the light of new technologies adopted, especially since the early twentieth century. As a result, the development of design workflows transformed the creative process with a strong accent on the prospective (a plan) as well as the retrospective (the analysis of the execution of that plan) as the main drivers for producing 'better' things, as well as for formalizing the knowledge about how to make those things.

This resulted in a schism between the intellectual, technical, and scientific from the production areas, and the specialization according to skills and how complex work could be subdivided into simple tasks toward efficiency. Whereas the recurrent use of modern technology reinforced the computational design trichotomy by providing new means for cutting down laborious manufacturing-oriented tasks, it has increased –perhaps unwittingly– the gap between ideas and objects and, at the same time, the intellectual from the technical[1].

1.2 The problem with the computational design trichotomy

The design trichotomy was 'retooled' into various versions of a computational design trichotomy, with more or less attention to its three components. That is how the computation embedded in the trichotomy raised, from the start, questions of knowledge production, creativity, originality, authorship, and whether a personal style was possible for the ideas, designs, or objects produced. Consequently, and under the promise of bridging design and making using digital computers and numerically controlled machines, 'Computational Design' was framed as a new way of regaining control of the design process . A new computational design trichotomy shifted technological mediation toward the production areas of design to ultimately cope with the increasing complexity of designs, eliminating the burden of tedious production tasks that supposedly interfere with the development of creative ideas. Thus, the emergence of a computational design trichotomy encouraged the creation of 'computational design workflows' in which 'to design' is 'to think,' 'to represent' is 'to plan,' and 'to make' is 'to fabricate.' We became accustomed to the idea that when we design, we reflect, and know; when we represent, we rationalize, discretize, optimize, and freeze ideas; and when we make, we follow a recipe to shape things while taming materials according to that plan. Therefore, in the light of technological advancements, the developments and transformations of this trichotomy revealed over the years interesting areas of study and discussion for the creative disciplines in general and for the computational design field specifically.

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[1] In fields like architecture, engineering and also the arts as discussed in chapter 2.

1.3 Why is this a problem? What is problematic about it?

The addition of different technologies in design, has been traditionally aimed to make us more efficient, productive, and probably more empowered than before because of the possibility of manipulating information inside a computer to explore design spaces, simulate, and reduce the complexity of design problems. Nevertheless, the figure of a designer ideating something and engaging into a set of translations from idea to a sketchbook, to 3D model, to g-code, to 3D printed object, replicates the distance between something being thought and something being made. The use of design workflows[2] makes evident the separation between the object to be made and the object being made. While the latter considers the development of ideas in the making, prone to error, imprecision, ambiguity, and by exploration, the former-because of its unfolding in separate stages- seeks to represent and therefore, neglect imperfections, infidelities, and human 'clumsiness' from the process. The translations between the components of the computational design trichotomy, by being mediated by technological layers, have been oriented chiefly to represent, automate, (pre and post) rationalize, optimize, and encapsulate expert knowledge into precompiled black-boxes to be used on demand by the 'creative mind' and enacted by the 'obedient hand.'

1.4 What is missing in design processes based on the Computational Design trichotomy?

While the addition of computational design methods upheld the promise of creative freedom for designers, as part of the representational and analytic stages, it repositioned attention on how and where that creative freedom happened[3]. Under this computational design trichotomy, the deceptive supremacy of the eye-as the ultimate sensor- and the mind-as the ultimate creator- has cast a shadow over the creative power of the hand as a critical agent

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[2] The concept of ´design workflow' emerged from the need for organization due to the increasing complexity imposed by the industrial revolution, mechanization, and automation of different tasks Discussed in-depth in 2.1 A Design trichotomy: Idea,Representation and execution

[3] Vladimir Basnajac's article "The promises and disappointments of computer-aided design" illustrates the tone of the discussion about the use of computers for architectural design. Basnajac's was against the idea of using computers to liberate designers from the tedious tasks related to representing and elaborating budgets. To him, a fundamental problem with adding computers to the design process was in the processes and interfaces that resulted in too many distractions for the designer in detriment of the quality and relevance of the designed object.

of creation, innovation, and intellectual development in the design process. The uniqueness of the 'gesturing thinking hand' to sense, communicate, grasp, shape, and interface in the world, has been overlooked for centuries, relegating making as a peripherical stage of the creative process where apparently no intellectual development occurs. Thus, in the presence of a repertoire of computational gadgetry to make 'better' and 'faster,' old questions remain in terms of the disembodiment of the design, representation, and making stages of the trichotomy, where our designerly, tacit, and unique skillful ways of thinking through making, are lost. Pouring ourselves -as skilled designers- into a computational design trichotomy, forces us to input our unique intentions through generic actions (i.e: clicking and typing) to hopefully output meaningful outcomes from a computer screen or a 3D printer.

With the advent of 'novel tools' with artificial intelligence embedded operations, the old debate between augmented vs. automated design-which emerged in the dawn of computer aided design- is once again among the hottest topics in computational design and relates directly to the disembodiment of the creative process. Whereas the current discussion seems to replicate the old aspirations from the early days of CAD and AI, it unearths similar questions about the role of intelligent machines in creative processes and their impact on architecture and design in general . Nevertheless, when leaving aside the fascination of using a new type of intelligence capable of augmenting, helping, or replacing designers, we are left with the same uncertainties, bottlenecks, and questions when it comes to framing the role of technology in design as cognitive implementations, and the repercussions in the emergence of novel things and knowledge about how to make those things.

1.5 Who has worked on similar ideas before?

Over the last decade or so, there has been a proliferation of projects exploring real-time interaction with machines in various domains, including architecture, computer science, design, engineering, and art. These projects have focused on the performative, productive, and artistic aspects of creation, and have demonstrated a wide range of approaches to interactivity. For instance, Stephanie Mueller has been developing computational tools[456] to democratize personal fabrication, enabling anyone to create anything anywhere anytime[7], while Ryan Luke Johns[8] has been working on advanced workflows that integrate robotics, engineering, and manufacturing in architecture, with a particular emphasis on materiality[9], embodiment[10], and human-robot collaboration[11]. Similarly, Daniela Mittberger has been developing interactive applications for the construction industry that

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[4] Chan, Liwei, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. 2012. "CapStones and ZebraWidgets: Sensing Stacks of Building Blocks, Dials and Sliders on Capacitive Touch Screens." In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 2189–92. CHI '12. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/2207676.2208371.

[5] Mueller, Stefanie, Anna Seufert, Huaishu Peng, Robert Kovacs, Kevin Reuss, François Guimbretière, and Patrick Baudisch. 2019. "FormFab: Continuous Interactive Fabrication." In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction, 315–23. TEI '19. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3294109.3295620.

[6] Peng, Huaishu, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. "RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer." In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, 1–12. CHI '18. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3173574.3174153.

[7] https://meche.mit.edu/people/faculty/mueller_@mit.edu

[8] https://ryanlukejohns.com/

[9] Johns, Ryan Luke. "Augmented reality and the fabrication of gestural form." In Rob| Arch 2012: Robotic Fabrication in Architecture, Art, and Design, pp. 248-255. Springer Vienna, 2013.

[10] Johns, Ryan Luke. "Augmented materiality: modelling with material indeterminacy." Fabricate. gta Verlag, Zurich (2014): 216-223.

[11] Johns, Ryan Luke, Jeffrey Anderson, and Axel Kilian. "Robo-Stim: Modes of human robot collaboration for design exploration." In Impact: Design With All Senses: Proceedings of the Design Modelling Symposium, Berlin 2019, pp. 671-684. Springer International Publishing, 2020.

can be used on site[12], while Jose Luis García del Castillo has sought to democratize robotics among designers by providing a framework and tools that offer a low barrier to entry[13]. In the realm of art, Madeline Gannon[14] and Sougwen Chung[15] have explored the performative aspects of human and non-human collaboration. Although these are examples of a vast body of work related to Human-Machine interaction and design, my work presents a different apporach to interaction, focusing on the conversational aspects of design, as well as interface and the language necessary to implement a collaborative framework for design and fabrication.

1.6 What is my new approach?

Although the development of research around interactive fabrication technologies experienced a constant growth in the past decade, there are aspects that seem to be absent from the general discussion. Beyond the discussion about the implications of implementing interactive technologies in design that transcend making fabrication machines more accessible and easier to use, make robots more efficient to empower non-designers, or to make robots more inclusive, my approach focuses on the collaborative aspects of interactive technologies beyond mere control and that are aimed in the conversational aspects between machines and designers.

It seems that the focus of applying intelligent systems to design endeavors wanders around the ‘what’ (optimize designs, make faster and easier, ‘hallucinate’ new images, etc.), the ‘how’ (using AI, robotic fabrication, generative design, etc.) and the ‘why’ (to be more productive and ‘creative’) while neglecting the ‘So What’ (Why is this important? Why would anyone care as a designer?). Therefore, this dissertation focuses on aspects that seem to be absent from the

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[12] Mitterberger, Daniela, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. “Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-Site Robotic Plastering.” In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. CHI ’22. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3491102.3501842.

[13] http://nrs.harvard.edu/urn-3:HUL.InstRepos:41021631

[14] Gannon, Madeline. “Human-centered Interfaces for autonomous fabrication machines.” (2017).

[15] https://sougwen.com/

discussion around computational design and making, that relate to the interface between the components that interact within technology-mediated design processes, and the context in which that interaction happens. Therefore I ask:

- Can computation based on gestures provide the means to establish a framework for interaction between humans, machines, and materials, and at the same time reframe the way we design, make, and think through technology?

- What is the computation needed to establish methodologies that facilitate the interaction between a designer, tools, and materials so thinking and making are merged and inseparable?

Hunches, guesses, imaginings, errors, and all 'human things' that make a person experience insight, wonder, question, and act in the world, refer to 'making things' as a constant unfolding process in which nothing is fixed, and all is in nature interactive. Therefore, here I consider 'Design as Making' an active process, closely related to the definition of what constitutes an 'aesthetic experience .' In making, particular sensory aspects are synthesized with general intellectual concerns generating new meanings and -in the unfolding of life- new ways of making. In that regard, 'Computare'- the root word for 'computing' – means 'settling things together,' referring both to the act of 'putting things in order' and to the 'togetherness' of calculating as a collective endeavor.

I argue that reframing computational design as the enabler of novel and emergent interactions between humans, machines, and materials can deliver the answers to capture 'the unique' to generate 'the novel.' Hence, to establish design as a contingent collective endeavor within a design context, the way the agents involved in computational design processes interact must be reconsidered. In the presence of ambivalent postures between the use of technology as an enhancer through automation -to make faster- or augmentation- to think and make better-, it is possible to identify new possibilities for blurring the computational design trichotomy boundaries while engendering new modes of computational making as a contingent intelligent interaction.

The opportunities come hand in hand with challenges in defining the nature of the interactions that happen in making processes, and how those interactions become meaningful engagements in an intellectual exchange. Therefore, I assert that the development of systems that capture human gestures as intentions, as well as the methods for enabling meaningful machine action as a response to human gestures, are needed. I hypothesize that implementing different types of machine learning models and integrating them into the same pipeline opens novel opportunities for implementing human-machine interaction systems for design.

1.7 What is my proposed solution?

This dissertation proposes a Computational Gestural Making approach to design that seeks to establish a contemporary definition of making as a holistic creative process integrating two antithetical yet complementary modes of intelligence (Human and Artificial). The object of investigation in this dissertation is how interactive fabrication technologies – enabled by Gesture-based Human-Computer Interaction and Artificial Intelligence (AI)- can reformulate the interrelation between designing, representing, and making in the light of creative processes involving humans, machines, and materials.

If we consider design as an act of situated creation, oriented to find, solve, or even reformulate design problems, we must reorient how technology is formulated, thought, and applied. I argue that the situatedness of making within a 'design context' must account for the interaction between the agents involved to engender, develop, and capture new patterns and outputs that arise from the creative process. I propose a framework in which ideating, representing, and making are indistinguishable as they are part of the same enactive creative process. By focusing on the computation between two models of intelligence and cognition (human and artificial) mediating in a material context, new propositions about the designer's role in a technology-mediated world can emerge. Formulating a computational framework focused on unique human gestures, material context, and machine behavior can engender new ways of creation in which technology can surpass its mere efficient productive role and facilitate the creation of new designs and the knowledge about how to make those designs.

1.8 How do I validate my approach?

The proposition of a gesture-based computational making framework aims to integrate the components of the trichotomy into one. It does so by fostering the interactivity of making as a vessel for thinking through computational methods and tools. Moreover, using hand gestures to interact, control and communicate with machines, the methods proposed in this dissertation, aim to keep the designer as an active agent in the creative process. That is how, by being aware of the unfolding material processes that emerge from making with machines in real-time, the designer is no longer focused on representing but on making. Therefore, the uniqueness of the sensitive and creative thinking hand becomes the main driver of novelty and originality when paired with the processing power of machines. The Computational Gestural Making framework aims to integrate the qualitative (related to form, style, appearance, and so on) with the quantitative (related to performance) aspects of designs engaging exploration and fostering the emergence of new ways of making.

The scope of this doctoral research centers on establishing a computational gestural making framework that (1) establishes a model for human, machine, and material interaction (2) outlines the development and assessment of a gesture-based framework for interactive design and fabrication as a method for computational gestural making. (3) applies the proposed framework in case studies to assess the means and the effectiveness by which computational gestural making emerges as an alternative way of designing embracing the uniqueness of the thinking hand as an agent for creating novel and authorship work.

I answer to the questions proposed by the development of the Computational Gestural Making framework from a scientific and theoretical standpoint. This dissertation founds itself in a middle ground in which the theoretical discussion arises as a strong statement toward the definition of making as an embodied thinking process and the scientific approach as the technical application of a multimodal methodology to facilitate the integration of thinking and making through technology.

1.9 What are the expected contributions?

The main contributions of this dissertation relate directly to the field of computational design and digital fabrication. On the one hand, this dissertation aims to contribute to the field of computational design with the development of a theoretical stream of thought located at the intersection of technology and design, focused on the role and position of creativity in the making process. On the other hand, it aims to establish a technical framework for interactive computational processes that foster thinking with machines and materials in developing personal work. More specifically, this dissertation aims to expand the field of computational design and digital fabrication as research fields, through the proposition of body-centric interactive fabrication processes with the aid of artificial intelligence. It seeks to establish ‘computational gestural making’ as an alternative paradigm to explore the creative power of the thinking hand to impress the uniqueness of designers in a material context.

1.10 Dissertation structure and chapters description

This dissertation research presents a theoretical discussion as well as the technical implementations in the form of prototypes to discuss about the application of a Computational Gestural Making framework.

This dissertation is structured into three sections and six chapters. The first section includes the Introduction (chapter 1) and Literature review (chapter 2). The middle section includes three chapters divided into topics related to Ideas (chapter 3), Representation(chapter 4), and Making(chapter 5). The last section of this dissertation contains chapter 6 includes contributions and a conclusion.

Section 1

The first chapter introduces the research subject. I provide the problem statement, motivations and questions of this research.

Chapter 2, Literature review, addresses the theoretical concerns behind the emergence of what I denominated as the Computational Design Trichotomy. I delve into the historical relationship between design and technology and the transformation of design as a discipline in light of technological implementations from the Renaissance until the present time. I present the Computational Design Trichotomy in order to establish a theoretical foundation for the main concerns of this dissertation regarding technology and design tools as devices for cognitive and creative development.

Section 2

In this section I present three chapters dedicated to each component of the computational design trichotomy that include a theoretical discussion and reflection around ideas, representation and making, as well as one final technical prototype. Each prototype presented at the end of each chapter of this section aims to expand the discussion and apply the ideas derived from the theoretical discussion toward the establishment of a gesture-based computational making approach.

In *Chapter 3, Mediated Ideas*, I delve into the topic of ‘design ideas’ and ‘computational design workflows’. I build on the discussion from the previous chapter, where I explored the influence of technology in how ideas are generated, developed, and presented. Specifically, I elaborate on the technological implementations in the early days of CAD and their significance as ‘creative enhancers’ to the current-day implementations of machine learning in design.

I challenge the traditional computational design trichotomy view that limits creativity to the domain of the mind and views it as peripheral to the design process. Instead, and aligned with the views of authors such as Bohm, Merleau-Ponty, Ingold, among others, I propose that creativity is an active process that emerges from experience and enables innovation and originality[16]. I discuss the generation, transformation, and communication of ideas in design, along with the role of technology as an originator, supporter, or augmenter of creative ideas.

To exemplify the mediating role of technology in design workflows, I use contemporary implementations of machine learning[17] to build the argument that technology can extend creativity throughout the entire design process by actively enabling the unfolding and development of ideas and designs.

In the final part of the chapter, I present SkeXL, a machine learning implementation for interactive design in 3D environments. The project captures and interprets human gestures as design intentions for creating 3D models, reframing the concept of design workflows,

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[16] See a more in-depth discussion in 3.1 and 3.2

[17] Such as Image synthesis methods like generative adversarial networks (GANs) or diffusion models.

knowledge encapsulation, embodiment, and representation in 3D CAD processes. This project presents the hypothesis of gestures as the enablers of originality and innovation through an active process engaging with the object design beyond intermediate representations. This projects aims to answer the following questions:

a- Can the use of machine learning reframe the generation of 3D models in a more embodied way?- Is it possible to capture design intentions from sketches to generate 3D shapes using machine learning?
b- Can we design and explore ideas inside a computer without representing them?

I describe the technical implementation of a pipeline that translates human sketches into 3D models with the aid of Generative Adversarial Networks. I show a prototype that takes trace sequences from the user, to generate a 200 dimensional latent vector that can predict a 3D voxelized shape in real time.

Overall, this chapter emphasizes the importance of considering the role of technology in design processes and challenges the traditional views of creativity in design. By exploring contemporary implementations of machine learning, I highlight the potential for technology to augment and extend creativity in design workflows.

In *Chapter 4, Beyond Representation*, I delve into the complex and multifaceted discourse surrounding the role of representation in contemporary design. I examine the historical role of representation as a conduit for abstract concepts and plans while arguing that many technological advancements in design have prioritized facilitating the representation of designs over ideation and conceptualization. I expand on the various incarnations of representation and contrast the traditional role of representation in architecture with the role of sketching and model-making as unfolding mechanisms for exploration.

I posit the question of whether the use of technology in design can transform computers into active thinking tools that bridge the gap between ideas and construction. I discuss “design Intelligence” as a process of meaningful exchange among participants in a design, exploring the possibilities of interactive design systems through computational techniques, and provide a framework for understanding the interactive and collaborative aspects of mutual intelligibility.

I introduce NNN (Network of Neural Networks), a research project developed around human-machine interactive systems based on gestures. I explore the significance of gestures as a means of communication and thought and argue that gestures have the ability to generate unique outcomes through their ability to shape motion for creative purposes. In detail , NNN is a project that uses a custom-programmed node-based visual programming language to chain different machine learning models to interact with physical devices.

I then present “deep enactions,” a project that integrates different machine learning models into one integrated human-machine interaction system. Through the use of computer vision, gesture detection, and intelligent robotic motion, I developed a first iteration of the Computational Gestural making framework toward implementing a conversational system with a 7 degrees-of-freedom (DOF) robotic system. The goal of this project is to present the functioning of a framework for interactive design based on human-robotic interaction through the use of gestures as a language mechanism for generating unique and original designs. I present the implementation of a modular system integrating Inverse kinematics, path planning, reinforcement learning and computer vision to achieve an effective communication between designers and machines.

Overall, this chapter challenges the traditional view of representation in design and advocates for the incorporation of interactive design systems and gestures as tools for generating original and innovative designs.

In *Chapter 5, Making*, I explore the creative process of physical-making, focusing on the use of materials as design ingredients and plans for action as recipes. I argue that physical-making goes beyond mere representation and involves open-ended procedures that allow for free performance and the emergence of new things. Drawing upon Lucy Suchman’s approach to situated action , I highlight the role of language, interaction, communication, and tools in the making process.

I discuss the theoretical implications of computational making and making grammars as foundations for interactive making processes. I introduce two academic experiences, 'Discrete Heuristics' and 'Making Ingredients,' as practical applications of these theoretical concerns.

Finally, I implement the Computational Gestural Making Framework, adding a physical and material component to the developments presented in the previous chapter. I present a novel approach that leverages technology to produce new things, processes, and knowledge about the designs we create.

Using a custom robotic arm controlled by a multi-modal system that builds on top of the "deep enactions" project presented in chapter 4, I demonstrate different applications for interactive fabrication, constituting a seamless body-centric gesture-based approach to design. I implement the Computational Gestural making framework integrating different machine learning models categorized as sensors, processor, and effector modules that are integrated through a REST API deployed in a central server. The technical development of the computational design trichotomy allows a seamless integration between designers and tools while allowing a new re-imagined paradigm for thinking and making with machines.

Section 3

In *Chapter 6, Contributions and Conclusion*, I culminate with a concise overview and in-depth analysis of the contributions made by this research and their potential implications as well as limitations. Additionally, I suggest potential avenues for further exploration and investigation, to close with a concluding remark.

LITERATURE
REVIEW

2

2.1 A Design Trichotomy: Idea, Representation, and Execution

A division between designing – the representation of an artifact to be made – and making – the physical execution of the design – has been present in the western world for centuries. Alberti is the architect and theoretician most often identified with introducing this division into architecture. In his treatise On the Art of Building in Ten Books[1], Alberti proposed that the architect should not be a builder or maker but a designer. Moreover, his dualistic separation between designing and making included a third aspect related to the dimension of ideas. For Alberti, a design or "lineamenta" was the product of an intellectual activity – an idea - perfectly represented through drawings, which are then passed on to builders to execute with perfect fidelity. Alberti's "lineamenta" marked a clear separation with material and construction; it was a "product of thought," "a precise and correct outline, conceived in the mind, made up of lines and angles, and perfected in the learned intellect and imagination."[2]

Design processes across different disciplines and fields have inherited and deployed, either explicitly or implicitly, the Albertian trichotomy up to the present day. Design processes commonly include the development and use of procedures related to the ideation of something, its understanding and rationalization as a

Figure 1
The albertian dichotomybetween Design and Matter
source: author

representation, and the enaction of a physical process to achieve its construction in the real world. This trichotomy often underlies or serves as the basis for frameworks for creative or routine design processes, which are defined and shaped by the particular field of expertise in which they are applied.

The widespread adoption of digital computation in design-related fields has been scrutinized regarding the idea of a continuum digital 'workflow' that redefined the relationship between design and production. Along with the development of advanced Computer-Aided Design, the widespread adoption of Computer-Aided Manufacturing at a user level has made the idea of the digital continuum from conception to object a recurrent practice among design-related disciplines. As an example, 3D modeling and simulation tools, the use of algorithmic programming language environments, and the recent addition of powerful Machine Learning (ML) models -borrowed from the computer science field- have found a counterpart in the adoption and low-cost access to 3d printing machines, laser cutters, robotic arms and all types of numerically controlled devices to reproduce the digital in the physical world. Moreover, most of the contemporary design and production processes obey to well-defined procedures, often referred to as 'design and production workflow' that comprehend a discretized and structured set of stages ranging from ideation, representation, and fabrication.

Mostly borrowed from the engineering world, the concept of 'workflow' has been widely used in design processes and methodologies to illustrate the transition from what a designer designs and later produces by any physical means. The concept of 'workflow,' 'pipeline,' 'flow chart' and so on, when applied to design and building process, inherently suggests a globally integrated process composed of a series of discrete steps connected in a coherent successive way to achieve, for example, a predefined goal. Furthermore, originated in the late 18th century, the idea of 'Design Workflow' emerged from the need for organization due to the increasing complexity imposed by the industrial revolution, mechanization, and automation of different tasks in direct detriment of the role of the craft workers. These technological advancements resulted in a schism between the intellectual, technical, and scientific from the productive areas and the specialization according to skills and how complex work could be subdivided into simple tasks[18].

Deeply rooted in architecture and product design, the concept of Design Workflow has borrowed engineering concepts to organize the increasing complexity of projects in light of new technologies adopted, especially since the early twentieth century. Nevertheless, this separation between designing – the representation of an artifact to be made – and making – the physical execution of the design – has been present in western culture for centuries. The shift from a medieval way of designing and building in a more integrated way toward a complete separation between what is designed and what is built emerged with the invention of architectural design in the Renaissance[19]. Leon Batista Alberti is often designated as the one who coined architectural design into a distinct discipline by explicitly separating the intellectual act of creation from the construction processes (figure c2-1). In his treatise, *On the Art of Building in Ten*

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[18] Garber, Richard. Workflows : Expanding Architecture's Territory in the Design and Delivery of Buildings, John Wiley & Sons, Incorporated, 2017. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/mit/detail.action?docID=4834055.

[19] Carpo, Mario. 2011. *The alphabet and the algorithm*. Página 81. Cambridge, Mass: MIT Press.

The Mason/ Master Builder

Figure 2
The three builders (frontispiece to Viollet-le-Duc's Dictionnaire raisonnée de l'architecture française). Viollet-le-Duc, Eugène-Emmanuel. 1858. Dictionnaire Raisonné de l'architecture Française Du XIe Au XVIe Siècle. 10 v. Paris: B. Bance. //catalog.hathitrust.org/Record/005717447.

Books[20], Alberti proposed a dualistic separation between 'lineamenta' and 'matter' by remarking that design is inherently a 'product of thought,' wholly separated from matter. Alberti's theory, as noted by Terzoglou, was full of dualisms and based on a fundamental tension between the truth of reason (mathematical, ethical, and unified) and experience (ambiguous, differentiated, and concrete)[21]. This tension gave rise to Alberti's theory's fundamental dualities, often simplified and misconstrued by postmodern and digital discourse, primarily when the approach to 'lineamenta' focused on the 'technical, formalistic and algorithmic.'[22]

Nevertheless, strongly influenced by Neoplatonism[23], Alberti's theory was defined by metaphysical ideas -derived from the

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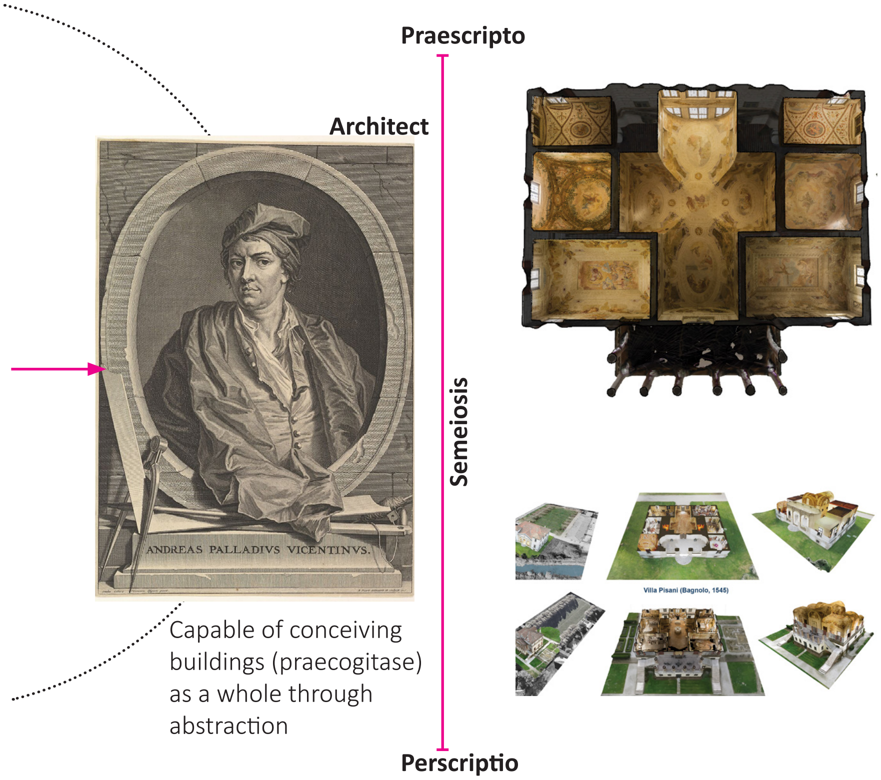
[20] Alberti, L. B. (1988). On the Art of Building in Ten Books. (J. Rykwert, N. Leach, & R. Tavernor, Trans.). Cambridge,Mass.: MIT Press.

[21] Terzoglou, Nikolaos-Ion. (2017). The Juridical Character of Alberti' s Mind. In Chora Seven. edited by Alberto Perez Gómez y Stephen Parcell.

[22] Ibid. pp-290.

[23] Hendrix, John S., "Leon Battista Alberti and the Concept of Lineament" (2011). School of Architecture, Art, and Historic Preservation Faculty Publications. P2



Capable of conceiving buildings (praecogitase) as a whole through abstraction

Figure 3
Andrea Palladio portrait. https://www.metmuseum.org/art/collection/search/399194
Villa Foscari 'la malcontenta'. Digital reconstruction by Diego Pinochet. Nagakura Takehiko, Tsai Daniel, Pinochet Diego Digital Heritage Visualizations of the Impossible Photogrammetric Models of Villa Foscari CHNT20, Austria 2015

Aristotelian thought- in which ideas project onto matter, known as hylomorphism. Moreover, often referred to as design and drawing, 'lineamenta' was concerned with the pure mental conception of 'the architectural world, before this process codifies into a graphic or digital representation.'[24] Hence, could a precise definition of 'lineamenta' introduce a third category to the design and matter dualism, redefining Alberti's theory into a trichotomy between idea, representation, and execution?

In Alberti's theory, there was a clear distinction between the architect as a designer -capable of envisioning and preconceiving ideas and constructing them in his mind- from the medieval architect (figure 2) -or workman, artisan- based on the ability of preconceiving ideas and space. Alberti's conception of a new Renaissance architect lay in the ability to produce-by process of semeiosis[25]- 'perscriptio,' which was defined as a notational registration device to write 'lineamentum' into

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[24] Terzoglou, Nikolaos-Ion. (2017). The Juridical Character of Alberti' s Mind. In Chora Seven. edited by Alberto Perez Gómez y Stephen Parcell. p. 291.
[25] Refers to the act of producing meaning from the interpretation of signs and symbols.

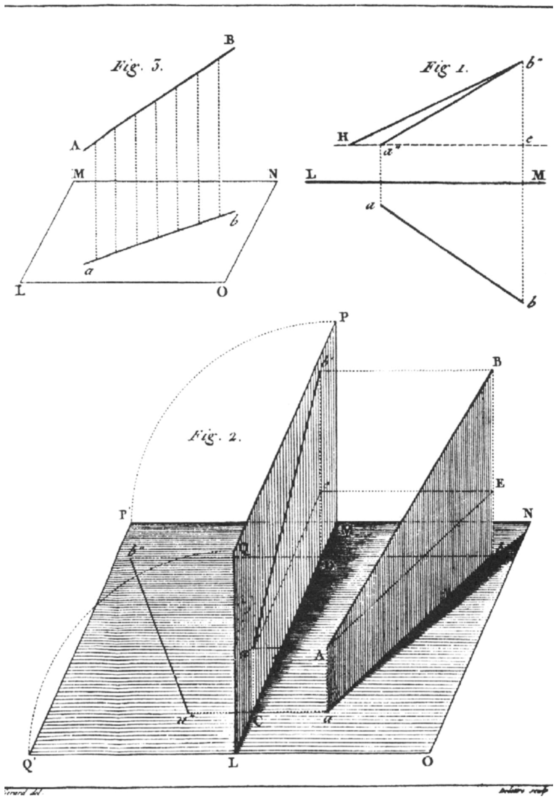

Figure 4
Diagram of projection in Monge's Géométrie Descriptive. Source: Gaspard Monge. Géométrie Descriptive. Paris: 1811, p. 13. "Monge Closing a Circle." 2007. In The Geometry of an Art: The History of the Mathematical Theory of Perspective from Alberti to Monge, 707–11. New York, NY: Springer New York. https://doi.org/10.1007/978-0-387-48946-9_13.

the material space[26] (figure 3). Simultaneously, 'lineamenta' relied upon another dualism between 'praescripto' - an intellectual, internal, and abstract process that produces concepts or precepts - and 'perscripto'- the external and sensible inscription as drawings or models[27]. The distinction suggests that Alberti considered the process of preconceiving a building ('praecogitase'[28]) also completely separated from its representation. As Carpo suggests, the invention of a notational system allowed Alberti to develop a way to completely represent designs by specifying measurements and instructions for constructing a building[29], detaching design from representation and construction. Also, creating a notational system allowed for the first time the comprehension of a building as a whole. It wasn't until the use of sections and elevations as part of a set of representations in the Renaissance that architectural drawings emerged as a crucial tool to represent and communicate designs, differentiating the new

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[26] Terzoglou, pp .

[27] Ibid.291

[28] The Latin word that refers to the act of 'thinking ahead.'

[29] Carpo, Mario. 2011. *The alphabet and the algorithm*. Page 71. Cambridge, Mass: MIT Press.

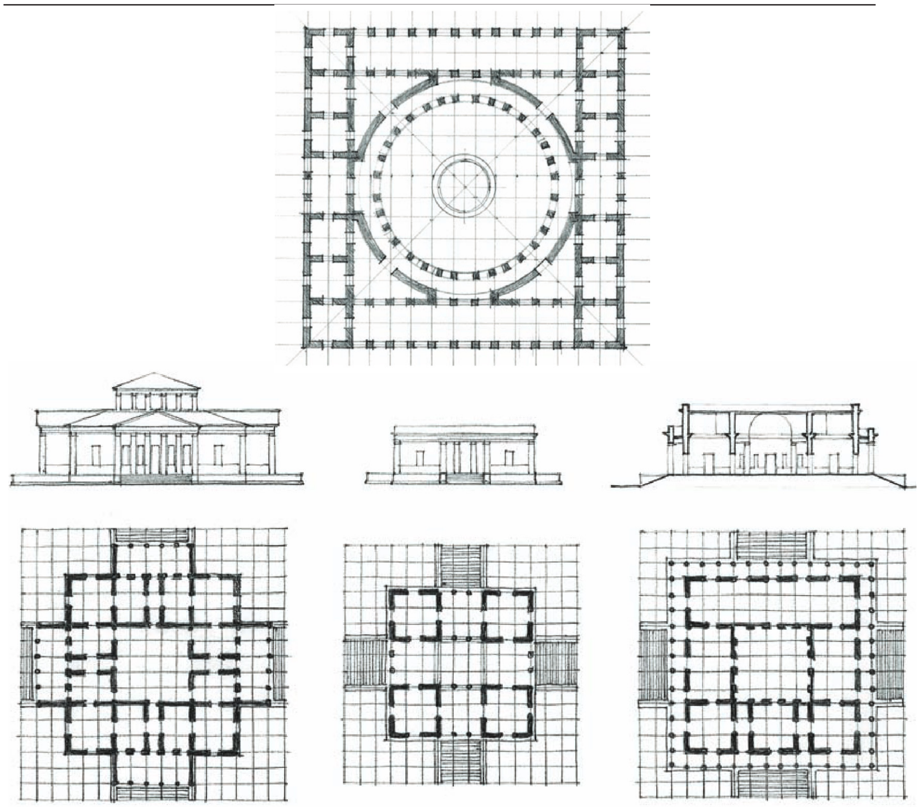

Figure 5
Jean-Nicolas-Louis Durand combinations from Précis. Durand's mechanism d' la composition was a reductive methodology devoided from any meaning towards efficent solutions through representation.
Drawn by Francis D.Ching, in Francis D. K. Ching, Mark M. Jarzombek, and Vikramaditya Prakash. 2017. A Global History of Architecture. Vol. Third edition. Hoboken, New Jersey: Wiley. https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=1492721&site=ehost-live&scope=site&authtype=shib&custid=s8978330.

Renaissance architect as a designer from the medieval architect as a master builder.

The dualism between the mental paradigm of 'praescriptio' and its material trace as 'perscriptio' was reinforced by defining other concepts such as 'aedificatio' (the fully developed concept of a building) and 'aedificium' (the construction). This specific distinction between the world of ideas and the material construction of buildings was recurrently tensioned by the fundamental difficulty that Alberti recognized in the act of ideating and translating those ideas to drawings for further construction[30]. The concept of 'lineamenta' encompassed a separation that was key to understanding how Aristotle's hylomorphic thought of 'form over matter' transcended its origin to a contemporary understanding of design and construction.

Alberti's theory suggested a modern concept of 'workflow' by separating the different design steps and disaggregating those steps into different actors such as the Architect, and the constructor. Moreover, with the advent of modernity, this trichotomy was

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[30] Ibid, p .295.

fundamental to understanding how design and production processes were formalized according to specific knowledge in the later centuries. The development of procedures for ideating something, understanding it, rationalizing it as a representation, and later building it reflected the modern trichotomy inheritance that emerged in the light of the Albertian theory. It is possible to argue that the design trichotomy often underlies creative frameworks or routine design processes, which are defined and shaped by the particular field of expertise in which they apply.

Albertian thought has remained until today, emerging and taking part in different disciplines and design-related fields. When examining the evolution of arts, crafts, architecture, and engineering, it is possible to observe how the trichotomy inherited from Alberti's thought shaped the way the arts and science suffered from a high specialization in the light of technological advancements. For example, Perez Gomez noted that the development of descriptive geometry generated a definitive systematization of drawing methods allowing, on the one hand, a transparent mathematical transition from drawing to building and, on the other, coping with the demand for precision and control by the industrial revolution[31] (figure 4). Moreover, descriptive geometry development emerged as a core discipline for architects and engineers[32] to codify intricate knowledge and information into a precise representational system. The development of descriptive geometry was the culmination of Alberti's quest for a perfect and accurate representation of ideas into a notational construction system (Figure 5).

Furthermore, the possibility of translating three-dimensional objects into accurate two-dimensional projections evolved into a science "capable of solving problems in a graphical way or by construction,"[33] reaching the degree of specificity needed to separate designing and making categorically. The inheritance of Alberti's design paradigm and the invention of new tools for representation and design knowledge encoding (descriptive geometry) allowed the disembodiment of the

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[31] Perez Gómez, Alberto in Questions of Representation: the poetic origin of architecture, en Holl, Steven, Juhani Pallasmaa, and Alberto Pérez Gómez. 2006. Questions of Perception: Phenomenology of Architecture. San Francisco, CA: William Stout, c2006.

[32] Ibid.

[33] J.C.L. Fish. Fish, J. C. L. (John Charles Lounsbury). Descriptive geometry /, 1870-1962.

process of making objects[34]. This change in design and making evolved further in the light of modern times, often criticized by authors such as Ruskin – and the transformation of workmen into slaves and the homogenization of the shapes from an evil industrialization[35],- to Marx -and the alienation of artisans into proletarians- to Heidegger -and the shift in the production from Dings to Gegestand[36].

2.2 Design across disciplines

The evident separation between science, art, and craft was one of the consequences of modernity. According to Perez Gomez, while scientific disciplines such as engineering used tools like descriptive geometry to attempt "a precise coincidence between the representation and an object,"[37] the arts remained fascinated with the distance between reality and its abstract projection. According to Williams, the divergence between science and the arts derived from the specialization of disciplines defined during the early nineteenth century[38]. Art suffered a separation from what was known as the 'fine arts' and the 'useful arts,' which eventually derived in the specialization of the term as 'technology.'[39]

This separation obeyed mostly the capitalization and commodity production in which every art production not determined by immediate exchange could be conceptually abstracted[40]. The practical arts specialization as 'technology' derived in the modern distinction between knowledge understood as science, and technology as the specific application of tools and methods according to a determined

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[34] Carpo, Mario. 2011. *The alphabet and the algorithm*. Page 71. Cambridge, Mass: MIT Press. pp- 77

[35] John Ruskin, The Stones of Venice (London: Smith, Elder, 1851– 1853), iii, iv, 35, pp-194.

[36] Carpo, Mario. 2011. *The alphabet and the algorithm*. Page 71. Cambridge, Mass: MIT Press. pp-78

[37] Perez Gómez, Alberto in Questions of Representation: the poetic origin of architecture, en Holl, Steven, Juhani Pallasmaa, and Alberto Pérez Gómez. 2006. Questions of Perception: Phenomenology of Architecture. San Francisco, CA: William Stout, c2006. p. 224

[38] Williams, Raymond. Keywords : a Vocabulary of Culture and Society. New York :Oxford University Press, 1985.

[39] Ibid.

[40] Ibid. pp-10.

field. Furthermore, modern culture[41] made a "sharp separation between the world of arts and that of technology and machines," deriving from the schism between the scientific and quantifiable "hard sciences" from the aesthetic, evaluative "soft arts."[42] This division of the arts relates in many ways to how design processes are conceived in present times, understood as a discretized 'workflow' in which the trichotomy obeys to different stages associated with specific domains of expertise. However, according to Flusser, in contemporary life, the separation between the technological and artistic worlds is bridged by design, making a new form of culture possible[43]. Hence, it is valid to question the differences and similarities in how design processes across fields such as architecture, engineering and the arts -including crafts- make this trichotomy as a framework evident.

The most noticeable differences between the arts, engineering, and architecture can be traced to the advent of the Industrial Revolution. Because of the high degree of specialization in labor that emerged from industry mechanization, mass production, and the standardization of materials, it was possible to find similarities and differences in design processes in architecture, engineering, and crafts related to the trichotomy. To name a few, aspects such as the distance between idea and execution in terms of time and discretization of the whole process; the form of and methods of representation; the project's scale and complexity; and the approach in terms of utility versus aesthetics. These differences defined how design as a concept evolved in different disciplines making more or less evident the separation between what a designer thinks and makes. As an example, architecture experienced a radical and definitive change from a craft to a profession in the light of elitist academic training -with places such as the Ecole d' Beaux-Arts and

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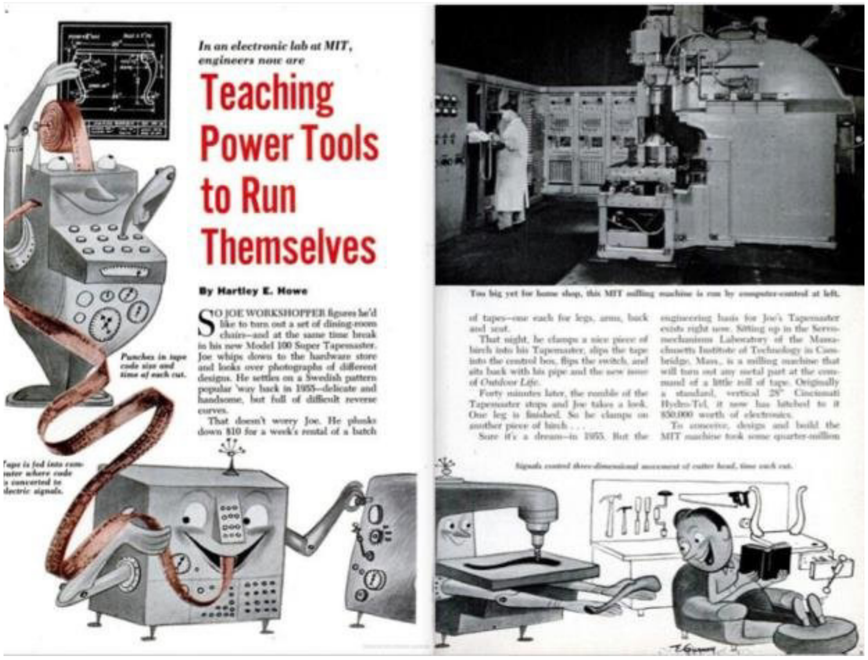
[41] Modern culture as a period of time closely associated since the 18th "century with the notions of ''progress'' and ''development'' attributed to the West, the attribute ''modern'' describes a wide range of historical phenomena characterized by continuous growth and change: in particular, science, technology, industry, secular government, bureaucracy, social mobility, city life, and an ''experimental'' or modernist approach in culture and the arts." see Bennett, Tony, Lawrence. Grossberg, Meaghan. Morris, and Raymond. Williams. New Keywords : a Revised Vocabulary of Culture and Society. Malden, MA: Blackwell Pub., 2005. pp 219.

[42] Flusser, Vilém, and John Cullars. "On the Word Design: An Etymological Essay." Design Issues 11, no. 3 (1995) pp- 50-53.

[43] Ibid pp- 51.



In an electronic lab at MIT, engineers now are

Teaching Power Tools to Run Themselves

By Hartley E. Howe

SO JOE WORKSHOPPER figures he'd like to turn out a set of dining-room chairs—and at the same time break in his new Model 100 Super Tapemaster. Joe whips down to the hardware store and looks over photographs of different designs. He settles on a Swedish pattern popular 'way back in 1955—delicate and handsome, but full of difficult reverse curves.

That doesn't worry Joe. He plunks down $10 for a week's rental of a batch

Too big yet for home shop, this MIT milling machine is run by computer-control at left.

of tapes—one each for legs, arms, back and seat.

That night, he clamps a nice piece of birch into his Tapemaster, slips the tape into the control box, flips the switch, and sits back with his pipe and the new issue of *Outdoor Life*.

Forty minutes later, the rumble of the Tapemaster stops and Joe takes a look. One leg is finished. So he clamps on another piece of birch . . .

Sure it's a dream—in 1955. But the engineering basis for Joe's Tapemaster exists right now. Sitting up in the Servomechanisms Laboratory of the Massachusetts Institute of Technology in Cambridge, Mass., is a milling machine that will turn out any metal part at the command of a little roll of tape. Originally a standard, vertical 28" Cincinnati Hydro-Tel, it now has hitched to it $50,000 worth of electronics.

To conceive, design and build the MIT machine took some quarter-million

Signals control three-dimensional movement of cutter head, time each cut.

Figure 6
"Too big yet for home shop, this MIT milling machine is run by computer-control at left." Popular Science, volume 167, August 1955.
Image from Howe (1955).

the Ecole Polytechnique d' Paris- which instilled Albertian ideas concerning the architect as an individual mastermind dedicated to creating an ideal building[44]. The architect's concept as an "author" and mastermind behind the design of a building detached from any execution endeavor was facilitated further by the increasing complexity of buildings. Because of the aggregation of mechanical systems and new materials such as steel or glass, a building's technical aspects demanded the project's segmentation in different steps incrementally managed by models borrowed from the engineering world[45]. The technical aspects of designs post-industrial revolution changed how buildings were designed, represented, and thought. In the case of technical systems, these demanded expert knowledge that often lay outside the architectural discipline, making evident the Albertian paradigm as a trichotomy that gave origin to the field of 'design engineering.'

Design engineering -developed in the late 1950s- is considered a system of knowledge that aims to integrate what are considered

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[44] Woods, Mary N. 1999. *From craft to profession: the practice of architecture in nineteenth-century America*. Berkeley: Univ. of California Press.
[45] Johnston, George Barnett. 2008. *Drafting culture: a social history of Architectural graphic standards*. Cambridge, Mass: MIT.

"islands of object information"[46] into a well-defined process to go from abstract to concrete in the most optimal way. In design engineering, the distinction between 'designing' and a 'design process' establishes a fundamental difference in terms of design and how it is applied to go from idea to produced object. Whereas in architecture, design is mainly driven by the interplay between aesthetic and formal elements (such as mass, space, volume, texture, light, shadows, materials, program) with realistic elements (such as cost, structural compliance, and technologies implemented), engineering design is focused primarily by the creative application of scientific and mathematical principles toward a well-defined goal. In design engineering, the degree of complexity and the technical requirements necessary for producing something demands a systematic application of procedures -reducing global complexity into more straightforward steps- and technical solutions-oriented to generate a transformation that satisfies or solves the initial need. According to Eder and Hosnedl[47], in the engineering field, 'designing' is dedicated chiefly to emphasizing a design's artistic elements. Moreover, in the distinction between 'designing' and a 'design process,' 'designing' is categorized as a subset of the design process in which designers, bricoleurs, or tinkerers conceptualize possible future artifacts by the use of intuition with an emphasis on 'creativity.'[48] Furthermore, designing is considered a non-deterministic process dedicated to establishing a preferred solution based on the characteristics mentioned above, such as intuition or aesthetic value, not necessarily considering analytical metrics or based on knowledge[49]. In the case of design engineers, a design process is considered a transformation system comprised of well-established discrete steps derived from the implementation of a Technical Process (Ts) for the creation of a Technical System (Ts) capable of solving or eliminating a given or recognized problem in the most optimized way[50].

In the case of the crafts, its definition in qualitative terms has provoked its association with the realm of practical and repetitive tasks. By definition, crafts have been relegated -because of a

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[46] Eder, W. and S. Hosnedl. "Design Engineering: A Manual for Enhanced Creativity." (2007) pp-6
[47] Ibid. pp 10
[48] Ibid pp- 5
[49] Ibid.pp-46
[50] Ibid.pp-287

deeply rooted modern prejudice- as lower category labor, usually conceived as making functional objects by executing preconceived plans. Authors such as Collingwood[51] misconstrued craft by placing the object indistinguishable from the process in his craft definition. Collingwood's situates craft as execution based on preconceptions and as something opposed-or at least different – to art as a creative activity not based on preconceptions. However, Collingwood's incorrect approach to the difference between arts and crafts[52] serves its purpose of examining how craft is wrongly placed in the realm of pure execution – in terms of the trichotomy – and can be considered as an activity that combines and integrates ideation, representation, and execution in particular ways. As an example, terms like 'woodworking' or 'glassblowing' imply, at the same time, the interplay of action, technique, and material. Even though it is possible to categorize action, technique, and material in craft, the way these happen and intertwine in the making process are indistinguishable and hard to separate.

Since the invention of architectural design in the Renaissance, the increasing complexity of projects pushed a technological development of designs that resulted in a trichotomy between idea, representation, and execution. The need to cope with complexity pushed significant changes in design processes toward representation and production to the detriment of the artistic and aesthetic side of design. Simultaneously, academic training exacerbated the architect's status as a creator, artist, and mastermind behind the project[53], often clashing with a reality in which the designer's duties were reduced to a mere representation of others' designs. Such technological changes post-industrial revolution and later post-World War II resulted in

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[51] Collingwood, R. G. 1938. *The principles of art*. Oxford: Clarendon Press. Bottom of Form
p15-16

[52] As noted by authors such as Risatti in "a theory of craft: function and aesthetic expression" the fact that artists use sketches, diagrams, test color palletes and recur to preconceived concepts as portraits, landscape, still life and so on, debunks one of the main reasons to differentiate art from craft. Risatti, Howard. 2007. *A theory of craft: function and aesthetic expression*. Chapel Hill: University of North Carolina Press. http://qut.eblib.com.au/patron/FullRecord.aspx?p=880380.

[53] As expressed and remarked by Daniel Cardoso in Daniel Cardoso Llach. 2015. Builders of the Vision: Software and the Imagination of Design. Routledge, USA.

new opportunities to redefine Design in the light of new theories from different fields. For example, mathematics, computation, cybernetics, artificial intelligence, were fields that through the use of digital computers were used under the hope and aspirations of bridging the gap imposed by the Albertian Trichotomy.

2.3 The emergence of a computational design trichotomy

The introduction of computation and computers into architecture and design in the decades following WWII led to new considerations and manifestations of the idea/representation/execution trichotomy. Pioneering researchers and projects – from the MIT Computer-Aided Design initiative[54] to Steven Coons' computer "slave"[55] to Ivan Sutherland's Sketchpad[56] to Chuck Eastman's Building Description System[57] to March-Steadman configurational engineering[58] to Stiny and Gips's shape grammar theory of design[59] – reimagined these three aspects of design, separately and conjointly, and in relation to people and machines. Early theorizing was followed by technological breakthroughs and advances in digital technologies, allowing for the implementation and testing of ideas. Work on automating the design process, including ambitions such as file-to-factory production and, more recently, interactive fabrication, have come with promises for a return to pre-Alberti times when designing and building were one. Simultaneously, computational, but non-digital, research, and applications advanced alternative scenarios for conceiving (perceiving), representing, and making designs. One question that emerges is: How does the design trichotomy relate to computation

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[54] See Ross, Douglas T. Computer-Aided Design: A Statement of Objectives. Cambridge, MA: MIT ESL, 1960.

[55] Coons, Steven A. An Outline of the Requirements for a Computer-Aided Design

[56] Sutherland, Ivan Edward. "Sketchpad, a Man-Machine Graphical Communication System". Thesis (Ph. D.)--Massachusetts Institute of Technology, 1963., 1985.

[57] Eastman, C. 1976. "General Purpose Building Description Systems." Computer-Aided Design 8 (1): 17–26. https://doi.org/10.1016/0010-4485(76)90005-1.

[58] March, Lionel, and Philip Steadman. The Geometry of Environment : an Introduction to Spatial Organization in Design. 1st U.S. ed. Cambridge, Mass: M.I.T. Press, 1974.

[59] G. Stiny and J. Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture," in C. V. Freiman, ed., Information Processing 71 (North Holland, Amsterdam, 1972), pp. 1460-1465.

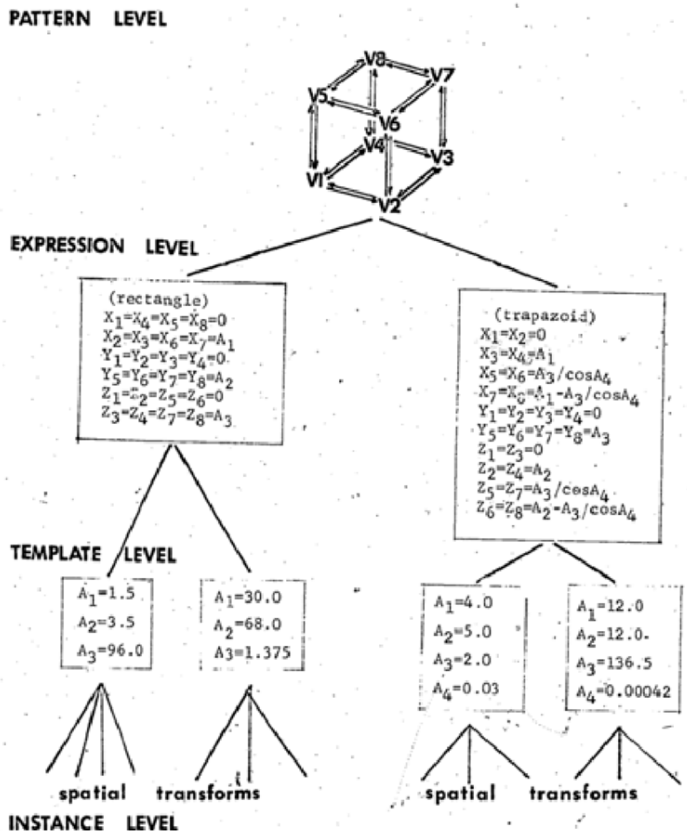

Figure 7
The four hierachylevel of the Building Description System database
Source: Eastman, Charles: An Outline of the Building Description System, Carnegie-Mellon Univ., Pittsburgh, US, 1974.

theories, models, methods, and tools, and how are the roles of the human and the machine considered in computational approaches to idea, representation, and execution?

After WWII, there was an urgent need for more efficient industrial production methods. The need for documentation standards, more efficient ways of reproducing and checking technical drawings, and the need for faster ways of calculating complex equations derived in computers' development to automate the design and production process. In that regard, MIT became a hotspot of research and development in partnership with the US military[60]. Initiatives such as the Whirlwind computer, the work on CRT displays, and modern input devices such as light pens were crucial for the later development of Computer-Aided Design due to the possibility of performing real-time computations interacting with a machine (figure 6). Also, and funded mainly by the US military, several initiatives sought a close collaboration between academic research, military, and industry to

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[60] David E. Weisberg .http://www.cadhistory.net/03%20MIT%20CAD%20Roots%201945-1965.pdf Chapter 3, pp1

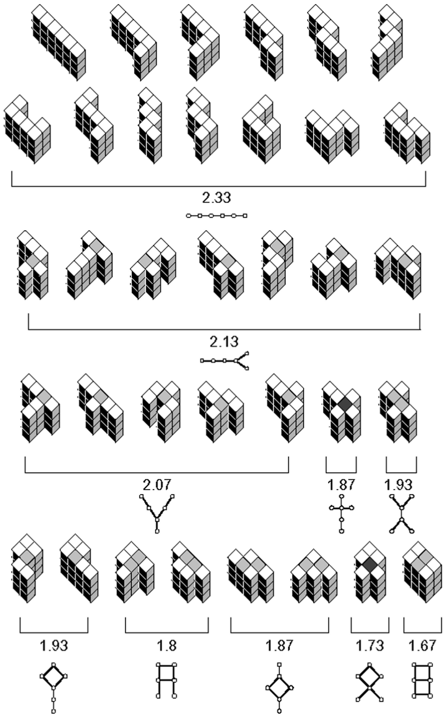

Figure 8
Lionel March, "Architecture and Mathematics Since 1960", pp. 7-33 Source: Nexus IV: Architecture and Mathematics, eds. Kim Williams and Jose Francisco Rodrigues, Fucecchio (Florence): Kim Williams Books, 2002.

develop automated Engineering Design and Manufacturing systems[61] bridging Design and Manufacture into one integrated platform. The vision of integrated platforms for designing and manufacturing was envisioned by people like Douglas T. Ross and Steve Coons. They sought to create systems where the human would work back and forth with a (general purpose) computer in a conversation-like mode[62]. Ross's 'Man-Machine' vision was crucial in developing CAD systems, emphasizing the importance of understanding design as a mental endeavor that can be aided by computers instead of the process's full automation[63]. Even though the primary focus of

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[61] As an example, the Servomechanics Lab at MIT introduced with the collaboration of the US airforce, the first NC machine in 1952 along with the development of the automated programming tool (APT) by the Computer applications group inside the Servo Lab.

[62] Reintjes, J. Francis – Numerical Control: Making a New Technology – Oxford University Press, 1991. P81.

[63] According to Ross: "if we are to have computer- aided design rather than 'automatic' or 'computed' design, or 'computer aids to' design, we must make the computer a partner to the scheming process. This requires blending the man and computer into a problem-solving team". AED stands for "Automated Engineering Design." See Douglas T. Ross, "The AED Approach to Generalized Computer-aided Design," in *Proceedings of the 1967 22nd National Conference,* ACM '67 (New York, NY, USA: ACM, 1967), 367-385, http://doi.acm.org/10.1145/800196.806006.

computer implementations for design was militaristic and oriented to improve the US industry, the team behind the CAD project sought a more general approach to design. However, to Ross and his team, there was no distinction between computer-aided design and general man-machine problem-solving. In that regard, as Cardoso clearly noted, the origins of Computer Aided Design saw light under the opposite views of two groups (Ross and Coons) inside the CAD project. To Ross and his team at Electronic Systems Laboratory (ESL), 'Design' was a *"special term for some ill-defined type of problem-solving, but no distinctive features are reflected in a system for design versus a system for general problem-solving."*[64]. Under this belief, the vision of Ross and the Electronic System Laboratory engineers "sought to use computers to automate what they understood as the design stage: the preparation of the paper tape containing the information for automated manufacturing."[65] Conversely, Coons and his team at the Department of Mechanical Engineering at MIT, considered that the CAD project's technological developments were the foundation to theorize and speculate about the future of Design in terms of creative enhancement and representation.

The main visions and ambitions of the early implementations of computers for design purposes relate to the Albertian trichotomy in several ways. As stated previously, each technological implementation that transformed the design process since the Renaissance implied an additional layer of complexity that increased the distance between idea and execution, focusing mostly on a design's representation or a design's physical execution. The invention of architectural drawing, the creation of descriptive geometry, and the advent of the industrial revolution -which derived in the increasing complexity of buildings- derived from the need for new layers of information and separation between what is ideated, represented, and executed. Moreover, it disaggregated the design process as well as the actors involved in the process. In the case of design and especially architecture, the addition of digital computers in design had a particular effect on how creating things was conceived. On the one hand, it reaffirmed the Albertian trichotomy by establishing a clear separation from idea to execution based on the representation of shapes and their inherent structure inside a computer through the concept of 'design

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[64] Ibid. p1

[65] Daniel Cardoso Llach. 2015. Builders of the Vision: Software and the Imagination of Design. Routledge, USA. P54.

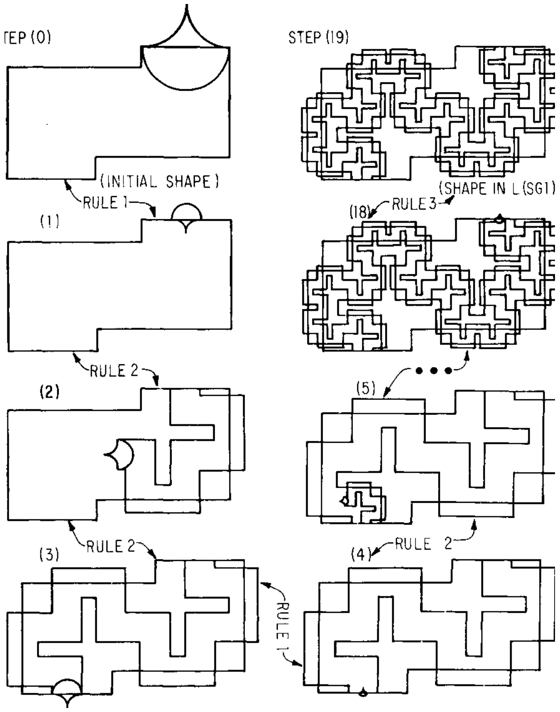

Figure 9
Source: Stiny, George and James Gips. "Shape Grammars and the Generative Specification of Painting and Sculpture." IFIP Congress (1971).

workflow.' On the other hand, the introduction of computers and theories of computation to the design process allowed the addition of theories and knowledge from other fields into architecture and design, enabling new design paradigms.

Although the origins of CAD are related to productive purposes, the opposite visions about design between Ross and Coons, opened the door to imagining new ways of enhancing architects' and engineers' labor through new technologies. The development of theories like Ross's plex[66] as a general theory of representation capable of describing and computing any problem-including design- emerged as a provocative path to enhance and broaden computer programming and was crucial to implement digital computation in design[67] in the form of software. In the case of Coons, the development not only of important techniques and tools for CAD, but also the theory behind it was crucial to push a more experimental side of the design process. In that regard, the use of computers by designers came accompanied

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[66] https://groups.csail.mit.edu/mac/projects/studentaut/The%20Plex%20Tract.htm

[67] The development of the APT and the AED were the foundation for the future development of many important CAD software packages.

by new theories associated with new forms of intelligence and ways of thinking, imagining, and building our surrounding environment like never before. By proposingnew platforms in which the computer acted as a support system for designers, the emergence of computational theories for design, beyond the promise of producing faster, better, and more optimized ways, started populating the minds of other disciplines, such as architecture. Coons and his students, such as Ivan Sutherland and later Nicholas Negroponte, proposed not only tools but alternative futures for the design discipline in which computers could enable augmented possibilities for design.

In the case of architecture, the addition of digital technology -originating with the need to cope with the increasing complexity of architectural problems concerning actors, systems, and general information involved in projects- enabled a change in how architecture was designed, reasoned, and finally produced. Moreover, to achieve such workflows, technological implementations in design were based upon the beliefs and aspirations of those who conceived computers as cognitive machines, which with the implementation of artificial intelligence, could augment the design process in terms of automation versus creative enhancement. The addition of computation (digital and non-digital) to design was framed under the positions between design as a discretizable combinatorial system capable of being automated and computation as support for designers to enhance the design process.

The automation versus augmentation debate[68] inside the CAD project reflects the design's trichotomy inheritance of idea, representation, and execution. The debate and "bargain" inside the CAD project – as noted by Cardoso [69]- resulted in a project shaped by computer aids' short-term goals to design and the long-term goals of a fully automated design system. As a result, the division of humans and machines and the reframing of the design and manufacturing process emerged as a cybernetic feedback loop. Moreover, with creativity as the frontier between humans and machines, a new form of Albertian paradigm emerged. The division between design as a mental activity and manufacturing as an automatic activity performed by a machine was established and framed under the

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[68] As noted by Cardoso in Daniel Cardoso Llach. 2015. Builders of the Vision: Software and the Imagination of Design. Routledge, USA. pp 60.

[69] Ibid, pp 63.

notion of a modern 'Computational Design Workflow.' The design process responded to a procedural and iterative process of ideation, representation, analysis, and materialization framed as a 'new design theory.'[70] The symbiosis between the human-designer and the machine-slave was framed under a well-discretized workflow as a set of well-suited stages for the most relevant actor to perform them. Coons' vision of a designer sketching in front of a computer -the creative stage- getting feedback from a computer in the form of a refined design according to quantitative criteria- a mechanical stage- and the eventual fabrication of the design by numerically controlled machines -the materialization stage- responded to a computerized version of the Albertian Paradigm.

The CAD project influenced a new conception of design in both the engineering and the architecture fields. On the one hand, most of the projects based on using computers for design emerged from the engineering field with specific goals oriented toward enabling a technological revolution in the manufacturing industry, facilitating the development of a billion-dollar industry providing computational tools in the form of hardware and software packages[71]. On the other hand, it enabled a new conception of design based on a new understanding of the creative process as systematized descriptions. In the case of engineering-related disciplines, the understanding of design as a workflow, in which the symbolic manipulation of parts containing data that could be structured, queried, and modified via computational systems, was key to developing a revolution in the manufacturing industry. Furthermore, we see this paradigm applied to architecture in the form of 'Building information modeling' (BIM) and parametric software packages for product design[72]. Also, the development of complex systems that comprised the imagination, representation, and manufacture of a design and the complete lifecycle management of the produced artifact reinforced CAD's conception under the trichotomy paradigm. Conversely, in the case of architecture, the use of computers beyond its drafting capabilities and the conception of computation (both analog and digital) as a new stream of thought enabled the emergence of new theories

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[70] Ibid, pp 64.

[71] David E. Weisberg .http://www.cadhistory.net/03%20MIT%20CAD%20Roots%201945-1965.pdf Chapter 3, pp1

[72] Such aRevit, Solidworks, CATIA, Pro engineer.

of design influenced by other fields such as cybernetics, artificial intelligence, mathematics, graph theory, and cognitive sciences. In that regard, most architects adopted computation in a problem-solving fashion and with different goals that either focused on the creative, representational and-or execution stages. As noted by Cardoso, the emergence of CAD was possible thanks to the initial goal of using digital computers for design and manufacturing in the form of Computer Aided Manufacturing[73]. It was the effort of describing and physically reproducing engineered designs that pushed forward the development of all sorts of algorithms, theories, and systems for design.

Architecture experienced disciplinary transformations after the introduction of digital computers, generating a shift in how architecture was produced and thought. While the world of engineering design experienced a final turn during the 1970s and 1980s toward computers as the main platform for development, many architects still considered computers just as a production tool entrenching themselves in the belief that design and creativity happen in a pre-digital stage. However, a group of more experimental practitioners saw the possibility of designing through computation (digital and non-digital) by describing the underlying structure of shapes instead of a final image (as a perspective drawing or a floor plan). In the case of Ivan Sutherland, the development of new algorithms for the topological description of shapes and the development of new interfaces for man-machine interaction founded the development of future software and hardware platforms[74]. Sutherland's work influenced the stream of thought that gave origin to new theories and methods such as Charles Eastman's Building Description System (BDS). Eastman's BDS focused on the description of buildings by assembling symbolic objects linked to the object's attributes as data (figure 7). The idea of design as a sort of digital construction system through a general but detailed description of topologies focuses on the efficient production of buildings. BDS's goal was to provide a model for general building's description dealing with "industrial

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[73] Cardoso, pp 37.

[74] "Ivan Sutherland's initial graphics work at Lincoln Laboratory soon led to a much broader series of research projects, attracting some of the best talent associated with the development of computer graphics." David E. Weisberg .http://www.cadhistory.net/03%20MIT%20CAD%20Roots%201945-1965.pdf Chapter 4, pp 16.

systems as well as the most custom designed architecture"[75] instead of representing a drawing, narrowing the Albertian schism between design and construction.

However, the description and computation of shapes through an inherent structure allowed the emergence of other types of computational theories that were not necessarily focused on neither the representation nor the execution of designs. As Vardouli[76] argues, the shift from the "old geometry" of metric shape to the "new geometry" of patterns and structure propelled the development of computation with symbols and discrete descriptions as "skeletons." That is the case of March and Steadman -who made similar claims as Eastman- proposing the idea of transcending from pictorial architectural representation toward a more analytical description of shapes (figure 8). This shift from representation to the description of shapes was possible by bridging geometrical descriptions to geometrical constructions using modern[77] mathematical ideas. By developing a 'purely structural'[78] geometrical approach called under the name 'configurational engineering,' March and Steadman were able to generate a system for the combinatorial generation, search, selection, and optimization of design possibilities within a representation space. The use of topological descriptions toward a dimensionless approach to design based on topological descriptions and relations led in March and Steadman's case, not only to a separation between the creation of forms from their representation but also in a system highly analog to parametric design. To describe topological relations and properties, exploring the range of designs one can produce by using graphs is today at the core of most parametric software packages. Even though different in their aspirations, Eastman's BDS and March-Steadman's configurational geometry developed systems in which the design process derived into using alternative vessels for the generation of architecture.

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[75] Eastman. pp25

[76] Vardouli, T. Skeletons, Shapes, and the Shift from Surface to Structure in Architectural Geometry. Nexus Netw J 22 (2020), p490

[77] Mostly mathematical theories developed in the Nineteenth- and twentieth-century toward the description of an object's structure.

[78] Vardouli, T. Skeletons, Shapes, and the Shift from Surface to Structure in Architectural Geometry. Nexus Netw J 22 (2020), p492

Those systems were suitable for their application under the digital computation paradigm due to their symbolic processing nature.

Other computational theories were developed around the same time, addressing different issues related to the design process. As an example, developed as a computational design theory, shape grammars (figure 9) were introduced in 1971 by George Stiny and Jim Gips[79]. The theory behind shape grammars addressed areas commonly obviated by contemporary computational design theories concerning aesthetics, delight, style, and-reading between the lines- authorship and original work. Deeply rooted in the Albertian paradigm, Shape Grammars presented a non-digital computational theory to make 'good art' and understand 'what makes it good,'[80] introducing right from the start a clear division between designing from making and designing from representing. Claiming that the definition and solution of design problems can be based on a representation of an art object instead of the object itself through the use of generative schemas was an alternative approach to design that has been further developed throughout the following decades influencing architecture and design beyond art. An example is the Design and Computation group at MIT. Described as a group that '*inquires into the varied nature and practice of computation in architectural design, and the ways in which design meaning, intentions, and knowledge are constructed through computational thinking, representing, sensing, and making*'[81] most of the work developed by students at Master and Ph.D levels has been influenced by the theory behind Shape grammars and the underlying theory between design and computation. Although establishing a clear depart from making, the distance between design and object in shape grammars, could also extrapolate to the distance between idea and representation as it proposes the development of shape's

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[79] G. Stiny and J. Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture," in C. V. Freiman, ed., Information Processing 71 (North Holland, Amsterdam, 1972), pp. 1460-1465.

[80] "Our underlying aim is to use formal, generative techniques to produce good art objects and to develop understanding of what makes good art objects" in Stiny, G. and Gips, J. Shape Grammars and the Generative Specification of Painting and Sculpture, in Proceedings of IFIP Congress 1971, 1972, North Holland Publishing Co.

[81] See https://architecture.mit.edu/computation

specification instead of representing them classically (as sections, floorplans, or general technical drawings) based on visual aspects that respond to the designer – and critic – way of seeing things.

The importance of theories like shape grammars for design relies on precisely what Stiny's claim is missing from the computational design field: the ability to compute while remaining human. Shape grammar theory exposes one missing part of design in the application of both digital and non-digital new theories of design that emerged after WWII, which is the possibility of computing and exploring design spaces but also computing the ambiguities that appear in the process related to shapes.

The introduction of digital computation to design, as well as new mathematical frameworks and methods, not only originated the emergence of new tools and paradigms for the physical production of designs but also originated a new conception of the creative process in which computation could be understood as a mechanism for thought. The design trichotomy evolved into a computational design trichotomy from which different computational theories populated the mind of architects and designers in general, changing in the following decades how designs are not only produced but imagined and thought. However, the incorporation of computation to design processes has struggled with the same questions from the beginning regarding automation and augmentation of design. Beyond questions of what is automatable or what is augmentable, the main question about the computational design trichotomy is how it affects original and autographical work. Moreover, what is the place of originality style, and authorship in the light of the trichotomy in this new conception of design through technology.?

2.4 Personal Style, Authorship, and Originality in a Computational Design Trichotomy.

As noted previously, the introduction and development of computational design theories and tools led to new approaches to design ideation, representation, and execution. The traditional design trichotomy was "retooled" into various versions of a computational design trichotomy, with more or less attention to its three components. The automation or computation embedded in the trichotomy raised, from the start, questions of originality and authorship, and whether a personal style was possible for the ideas, designs, or objects produced. These questions were raised regardless of whether the computing was done by a person or by a machine. However, they were not new and recall Ada Lovelace's reservations about computation around 100 years earlier of the introduction of the first digital computers. On Babbage's Analytical Engine, she wrote: "The Analytical Engine has no pretensions whatever to originate anything. It can do whatever we know how to order it to perform... Its province is to assist us in making available what we are already acquainted with."[82] Although computation in design is now ubiquitous, questions like Lovelace's remain. They are compounded with conflicting views of computation as disembodied and immaterial on the one hand and as enabling seamless ties between design and physical fabrication on the other hand.

Picon has claimed, for example, that "the digital era has extricated information from matter. … But it regrets this state of affairs and is longing to once again fuse information and matter. Digital designers and makers dream of restoring their lost unity."[83] At the same time, he observes that today there is "a strong attachment to authorship" since "he [the architect] can now both design and fabricate."[84] While most attention is focused on the digital in design, non-digital computational approaches have also elicited important questions

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[82] Countess of Lovelace, Ada Augusta, (1842), Note G in translation of Menabrea, L. F., "Sketch of The Analytical
Engine invented by Charles Babbage".

[83] Picon, A. (2019) "Digital Fabrication, Between Disruption and Nostalgia" in Chandler Ahrens, Aaron Sprecher (eds.),
Instabilities and Potentialities: Notes on the Nature of Knowledge in Digital Architecture, New York, Routledge, 2019,
pp 226.

[84] Ibid. pp 229

about originality and authorship. It is valid to ask, in what ways does computation impede, facilitate, or transform notions of authorship and originality, given the computational design trichotomy[85]?

As expressed previously, the introduction of computation – digital and non-digital- into the design field led to a significant change in how Design was conceived. The addition of computers boosted technological breakthroughs in the manufacturing industry and how design was produced. New Design theories appeared to cope with technological transformations derived from the increasing CAM and CAD applications inside the design engineering and Architectural field while at the same time captivated the attention of designers to apply other disciplines into the design field, such as AI, cognitive Sciences, and others. Furthermore, in the origins of CAD in the early 60s, the changes could be thought of, on the one hand, about computation improving and optimizing design through automation and, on the other hand, augmenting, aiding, and enhancing designers' intelligence and creativity. The augmentation versus automation debate derived from the implementation of new conceptions of design that, in one way or the other, established new ways of thinking, representing, and making. Consequently, in the following decades, while the use of digital computers and digital tools replaced drafting boards for digital models and databases, the emergence of computation in the form of graphs, symbols, parameters, schemas, rules, and so on derived from the emergence of fertile fields of exploration engaged in by more experimental practitioners. Nevertheless, even though the design trichotomy's separations and boundaries remained present after methodological and theoretical changes in the design domain, the addition of computation led to concerns related to authorship, originality, and style that are related to how from a personal perspective, new things come into being.

While architecture wandered between artistic aspirations and technical revolutions after the industrial revolution, it continued focusing on draftsmanship and theory to the detriment of building practice[86]. In that regard, the constant tension between the 'artistical'

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[85] This question is framed under the notion of the trichotomy involving someone that thinks, someone that represents and someone that makes that might be different either the same person or different individuals.

[86] Cuff, Dana. Architecture: The Story of Practice. Cambridge, MA: The MIT Press, 1991.

and 'technical' sides of the design was evident in the post-World War II changes in design through computation. While the addition of computational design methods upheld the promise of creative freedom for designers by eliminating the 'tedious' through computers as partners and slaves-as proposed by Steve Coons- gave rise to the attention to how and where that creative freedom happened.

The antithesis between Design as 'discretizable' and 'optimizable' versus Design as something uncertain, free, ambiguous, and abstract determined the clear distinction between the development of an idea, its representation, and, finally, its execution. The computational trichotomy was reinforced even more with the further development of CAD systems where, as Forrest mentions: "the D (in CAD) became not design but drafting…"[87]. In the following decades, CAD's development was reoriented toward production and industry urgencies and to respond to users' pragmatic needs[88]. During the 1980s and 1990s, advancements in software led to increased information processing capabilities, which sparked a continuing debate about whether technology empowers creativity or if project management and information processing are more important. This debate continued as designs became more complex, mirroring the experience of architecture in the 1960s. Whereas technology was ubiquitous in the professional practice of design and architecture, primarily for representation and the physical execution of designs, the ideation part of it remained entrenched under the limits imposed by the Albertian paradigm. The creativity and authorship domain inherited by the Albertian Paradigm remained untouched as the trichotomy was "retooled" into various versions of a computational design trichotomy, with more or less attention to its three components. The automation or computation embedded in the trichotomy raised, from the start, questions of originality and authorship, and whether a personal style was possible for the ideas, designs, or objects produced. That's how under the promise of bridging design and making through the use of computers and numerically controlled machines, computational Design was framed as a new way of regaining control of the design "lost when designers began to make drawings."[89]

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[87] As cited in Daniel Cardoso Llach. 2015. Builders of the Vision: Software and the Imagination of Design. Routledge, USA pp 85.

[88] Ibid. pp 86.

[89] Mitchelll, William J., and Malcom McCullough. 1995. Digital design media. New York: Van Nostrand Reinhold.

Populating the academic curriculum in design and architecture schools and the practice of more experimental architects, the figure of a 'digital master builder'[90] and the idea of a 'digital design continuum' boosted the ethos around bridging the gap between designing and producing[91]. Nevertheless, the discourse about regaining complete control of the design process confronted the contradictions found in the ones upholding a fully automated translation process from design to object through computers and robots. The motto "new tools and new thinking go together"[92] points in a different direction with the claim that "with the computer comes to a further disengagement of ideas from matter,"[93] reinforcing the idea of how the use of a technological layer gave birth to a new computational design trichotomy.

It is no surprise to anyone that the use of technology transformed Design as it did with the advent of new technologies and personal computation. What remains is the question of whether the way design is thought of through these new technologies changed. Technology made us more efficient, productive, and more empowered than before because of the opportunity to manipulate information inside a computer to explore design spaces, simulate and reduce the complexity of problems. Nevertheless, the figure of a designer ideating something and engaging in a set of translations from idea to a sketchbook, to 3d model, to g-code, to 3d printed object replicates the distance between something being thought and something being made. Fragmented design practices make evident the separation between the object being made and the object to be made. While the former considers the development of ideas in the making, prone to error, imprecision, ambiguity, and exploration, the latter-because of its unfolding in separate stages- seeks to represent and, therefore, neglect imperfections, infidelities, and so on from the process. One might question how both approaches deal with the production of original creative work and, therefore, new knowledge about the produced object's designs and the retrospective process that gave its origin to it. Whereas the "object being made" considers a free

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[90] Kolarevic, Branko. 2003. Architecture in the digital age: design and manufacturing. New York, NY: Spon Press.

[91] Mitchelll, William J., and Malcom McCullough. 1995. Digital design media. New York: Van Nostrand Reinhold.

[92] Ibid pp 422

[93] Ibid.

exploration of "ways of making," the "object to be made" focuses on the representation of fixed structures to produce an optimum error-free result.

Although computation is ubiquitous in contemporary design practice, the question evolves toward using computation -both digital and non-digital- integrating thought, representation, and execution into a more intertwined process to produce new things and knowledge about how to design through technology. The way to achieve such integration may be at the core of computational theories aforementioned in 2.2, such as shape grammars theory. Although it explicitly separates design from a physical object, the theory behind shape grammars proposes an "embed-fusion cycle" in which creativity melds recursion and embedding to calculate in a visual way generating new designs as we see new things. With shape grammars, design is about seeing and doing; nevertheless, as Knight asserted, they "have promoted design as an activity that demands perceptual, active engagements with materials."[94] Suppose design is a kind of making, as asserted by Knight[95]. In that case, the discussion's focus gets closer to the differences that Pye[96] establishes between the workmanship of certainty versus the workmanship of risk. While the former could be framed as analogous to what digital design is today, the latter could be framed as what design should become again to put humans back into the equation. As Pye describes, in the workmanship of risk, the result is continually at risk during the process of making in which judgment, dexterity, and care count as essential characteristics in the process[97]. Whether referencing a drawing, a cardboard model, or a 3d printed object, the claim here is that the design's material aspect of the process has much to say to the whole enterprise of creating new original things. Furthermore, by stressing the concept of authorship not as an authoritarian position of the designer as the harbinger of the ultimate truth but one that advocates for personal style development toward the original, it can "retool" the design process through technology to overcome the schisms imposed by the computational design trichotomy.

If design is considered a process of creating new things by being in

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[94] Knight, T. (2015). Shapes and Other Things. In Nexus Network Journal, 17(3), 963– 980. P..978https://doi.org/10.1007/s00004-015-0267-3

[95] Ibid. pp 965.

[96] Pye,D.(1968).The nature and art of workmanship.

[97] Ibid pp 22.

the world, it can be asserted that being is in the presence of material things beyond a cognitivist perspective, where things can be reduced to pure mental representations enacted in the posterior stages of the process. Therefore, considering beyond its symbolic nature, it is possible to assert that design relates to a concept of indexicality where things happen by "bundling." Moreover, the co-presence of qualities is one of the essential effects of materiality. One can assert that qualities bundled in any object vary according to their salience, value, utility, and relevance across contexts. Also, objects -with qualities- can resemble something every time anybody attends to them. It seems the idea of using technology in design can relate to the distinction between icon vs. index. Whereas an icon refers to an object's qualities (passive, inert), an index affirms that objects exist - although not what that thing is. Hence, original things and knowledge about them are elicited by being active in the world in the presence of objects, by generating the assemblage, gathering, and bundling that we find in Keane's semiotic ideology. Keane stresses that "the semiotic character of material things means that outcome is not settled, not that meanings are undetermined but that their semiotic orientation is in part toward unrealized-future- potential."[98] Although not directly, the concept of bundling refers to an inherent characteristic of every creative endeavor. In that regard, in the case of architecture, Semper's late ideas related to style as the "artistical treatment of the fundamental idea in a work of art" modified by internal factors - materials and techniques – and external factors – such as local and personal influences, and climate comes into the discussion. Semper's functional approach refers to style as contingent and derives from matter and techniques.

As designers, we rely on technology because of its multiple ways of representing and bringing to life Design ideas in myriad ways. However, the conflict arises in light of problems originated from digital Design practice, such as the 'creative gap' from idea to object, the use of tools as 'black boxes,' and the use of 'generic' structures that enforce the emergence of the computational design trichotomy. Hence, the Computational Design Trichotomy promotes the designer's engagement into a constant translation from idea to physical prototype, facilitating the creation of plans

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[98] Keane,Webb,"Signs are not the garb of meaning : On the social analysis of material things" in Miller, Daniel. (2005). Materiality. Durham, N.C : Duke University Press. pp-188

for representation that lead to a disembodied process where the performative act of improvisation and discovery in design disappears. As mentioned before, the computational design trichotomy involves questions about the creative act of design related to design skills development is redefined, and therefore, authorship and originality are affected. Under the trichotomy framework, a designer enforces the emergence of the creative and original in the ideation stage, while the representation and production of that idea happen detached from it. In that case, there is a missing discovery opportunity. Hence, the question remains: How may new computational design strategies and methods enable designers to transcend the modern distinction between ideas, representation, and execution, and to generate original and autographic work? Ada Lovelace's reservations about Babbage's analytical engine re-emerged reconfigured as a discussion about a machine's agency and the place of creativity in using technology in design. As Lovelace argued, the machine has no pretensions to originate anything; however, we design things because it means something to us. It is in that 'meaning something' that the discussion about design and technology has relevance. The argument that "… when it comes to perform demanding tasks, whether with the brain or the body, computers can replicate our ends without replicating our means"[99] addresses precisely the argument introduced here. It is valid to argue that the production of the creative is related to questions about originality and personal knowledge as consequences of meaning, where that meaning is located inside the domain of the humans instead of the machine.

As asserted by physicist David Bohm, there is an inseparable relationship between meaning and action, as meaning not only indicates the significance of something but also an intention towards it[100]. Meaning emerges from being, but at the same time, that being according to meaning is ambiguous as every content is dependent on a context[101]. Meaning is a constantly expanding structure, according to the "disharmonies between our intentions, as based on these meaning(s), and the actual consequences that flow out of

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[99] Nicholas Carr. 2014. The Glass Cage: Automation and Us (1st ed.). W. W. Norton & Company.

[100] Bohm, David. "Meaning and information" in Paavo Pylkkanen "The Search for Meaning"- "The New Spirit in Science and Philosophy". Published by Crucible1989.

[101] Ibid p52.

these intentions."[102] The claim here is that design has an inexorable connection to meaning, and its constant unfolding as new structures of understanding of our reality emerge. New meanings come with a new awareness of how to act in the world according to mental -as virtual activities - and material -according to operations - sides not separated but interwoven by meaning. Being implies that we develop new skills to act in the world as new meanings emerge from our actions. In that regard, the concept of skill understood as the learned ability to do a process well[103] plays a fundamental role in creating original things. As McCullough denoted, skill – represented mainly by the manual- involves sentience, personal worth, and the development of an intimate relationship with, for example, tools[104].

Furthermore, skill holds a direct relationship with what Polanyi referred to as 'personal knowledge.' With personal knowledge informed guesses, hunches, and imaginings are part of exploratory acts motivated by what he describes as 'passions,' whioch cannot necessarily be stated in formal terms as he asserts "we know more than we can tell."[105] To Polanyi, a discovery component is contained in this type of knowledge. As a designer engages in the process of discovering and acquiring knowledge, they must exercise personal judgment to connect evidence to an external reality that they are trying to understand.. The development of personal knowledge through practical activity refers to manual engagement with the world where gestures' enaction plays a crucial role in discovering new things. Hence, it is possible to relate the act of design to contextual awareness and the idea of feeling the actions instead of thinking about actions. Paxson defines an example of material engagement through skillful practice as synesthetic reasoning[106] , which is the capacity to feel the material in conjunction with sensory apprehension and reasoned analysis. The feeling of doing something

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[102] Ibid.

[103] Malcolm McCullough. 1996. Abstracting Craft: The Practiced Digital Hand. MIT Press, Cambridge, MA, USA. P.3.

[104] Ibid p.7

[105] Polanyi,M.(1967).The tacit dimension. GardenCity,N.Y:AnchorBooks.

[106] Paxson, Heather. (2011). The 'art' and 'science' of handcrafting cheese in the United States. Endeavour. 35. 116-24. 10.1016/j.endeavour.2011.05.004. p.118.

emerges as an integral process of producing knowledge through all the senses. More questions arise from the answers to these three questions in relation to how computation impedes or facilitates creativity, originality, and personal style in the light of the trichotomy. How to move forward? If the current design practice relies on the inherited trichotomy, Is there a way to think and make through digital technology to grasp the full potential of design as contingent? Can we design and make without representation? If the answer is yes, why is this relevant for design in the present time?

Whereas modern technology reinforced the digital design trichotomy by providing new means for cutting down laborious manufacturing-oriented tasks, it has increased -perhaps unwittingly - the gap between ideas and objects and, at the same time, the intellectual from the technical. As discussed previously, the antithetical views of using technology in design toward automation versus augmentation of design derived from the consideration of making as a peripherical stage of the creative process where no intellectual process occurs. If we are to consider making through technology as a transformational process (of things, materials, people, etc.) that deals with design knowledge production using design intelligence[107], the study of interactive and collaborative systems that capture real-time contingencies of humans, tools, and the world becomes a necessity.

To do so, we must understand the differences between using technology as a mere tool for representation and detached production of objects and the possibilities of technology as a mediator between us and the world to capture, amplify and use skills as active components of the making process. Let's examine the history of tool development in architecture. We can hypothesize that the quest for technological domination of reality by its description through geometry had a strong impact on design in which the syntactic dimension of meaning was privileged over the semantic dimension of meaning[108] It is possible to argue that representation fills the gap between idea and

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[107] Which is the ability to acquire, generate and apply design knowledge.

[108] As stated by Perez Gomez in Perez-Gomez, Alberto "The historical context of contemporary architectural representation" in Ayres, Phil. Persistent Modelling : Extending the Role of Architectural Representation. Abingdon, Oxon ;: Routledge, 2012. pp20

object by adding technological layers to the design process, allowing the mathematization of reality, and deriving knowledge about reality from representations (static knowledge). Nowadays, it seems that the gap filled by representation has privileged technology for technique and made us think that mere prescription and instrumentality[109] suffice when it comes to design and creative endeavors. The more technology takes over and mediates between idea and matter, the less we focus on the importance of technique, skill, expertise, and the knowledge involved. By considering technique as something that lies encapsulated in specific technologies (black-boxed knowledge), the use of computers (software and hardware) is justified to the extent that they allow access to a structure- in the form of commands and combinatorial rules- to obtain meaning and the recipe to tame matter. Moreover, by replacing technique as a consecutive use of technological layers, we black-boxed skills, expertise, and dexterity into automatic commands and steps. By doing so, we miss discovery, awe, the chance of experiencing insight, and therefore, components necessary for learning in the interplay between object, subject, and environment. Therefore, we miss the opportunity of using design intelligence to produce new design knowledge.

2.5 Design and Making

Objects, with their inherent qualities, have the capacity to resemble

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[109] As stated by Perez-Gomez in his criticism of representation in architecture: "...the prevailing and popular contemporary desire to circumscribe the epistemological foundations of the design disciplines primarily concerns the appropriateness of language to modulate our actions, and yet it can never pretend to "reduce" or "control" their meaning. For more of Pérez Gomez criticism in the role of representations, instrumentalizations and systematizations of design see Perez-Gomez Pérez-Gómez, Alberto. "Hermeneutics as Discourse in Design." Design Issues 15, no. 2 (1999): 71–79, Alberto Pérez-Gómez, Architecture and the Crisis of the Modern Sciences(Cambridge, Mass.: MIT Press, 1984) and Alberto Pérez-Gomez, The historical context of contemporary representation in Ayres, P. (2012). Persistent Modelling : Extending the Role of Architectural Representation. pp 13-25

something whenever they are perceived[110]. Therefore, the use of technology in design is often reduced to the dichotomy between icons and indices. Whereas icons represent the qualities of an object, which are passive and inert, indices affirm the object's existence but not necessarily its identity. Knowledge elicitation is achieved through active engagement with the world and objects, resulting in the assemblage, collection, and bundling of qualities, as posited by Keane's semiotic ideology or Maturana's definition of intelligence[111]. Hence, it can be argued that the act of designing encompasses not only the creation of a visual representation of an idea but also the elicitation of knowledge through interaction with the world. Although not explicitly stated, and going back to Keane's materiality, the concept of bundling refers to a fundamental attribute of every creative pursuit. Design can be understood as an expression of our unique human condition as creative individuals. By viewing design as making, we can appreciate how we imbue our surroundings with our individual uniqueness and understand that it is always perceived as something distinct. The act of design is a manifestation of our distinctive perspective and a way of looking at and attending to things.

The indexical nature of design empowers creators to generate novel objects and attain an understanding of the manner in which things come into being in the world. As emphasized by Bohm, knowledge is created and transformed through the act of thinking[112]. Furthermore, thought, in its continuous state of becoming, gives rise to the concrete existence of knowledge, making it an intrinsic material process[113]. Consequently, it can be posited that design as a mode of making is an instance of knowledge production that is situated,

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[110] Here I assume the perspective in which the act of designing is informed by the its indexicality in which the concurrent manifestation of qualities, a crucial aspect of materiality, are bundled together. This "bundling" refers to the different material qualities integrated in an object that are subject to variation based on factors such as salience, value, utility, and relevance across diverse contexts.

[111] See Maturana, Humberto R., and Gloria D. Guiloff. 1980. "The Quest for the Intelligence of Intelligence." Journal of Social and Biological Structures 3 (2): 135–48.

[112] Bohm, D. (1980). Wholeness and the Implicate Order (Vol. 32). Routledge. pp 49

[113] Ibid pp50

interactive, intrinsically material, uncertain, vague, and, therefore, inherently imprecise. The way in which it takes form is through the act of designing, where we impart a distinct perspective on the object based on our continued learning and interpretation of how it resembles other things. This is consonant with Heidegger's concept of "begegnen"[114], in which objects confront and reveal themselves to us as we engage with the world, which ultimately relates to his rejection of the explicitness of thought as every decision is rooted in something that remains unknown[115].

2.6 Discovering through material engagement.

The acquisition and refinement of skill, which can be defined as the learned capability to execute a task proficiently[116], is deemed to be a crucial factor in the production of innovative works of art. As noted by McCullough, skill - largely embodied through manual techniques - encompasses sentience, personal worth, and the cultivation of a close relationship with, for instance, tools[117]. Additionally, skill holds a direct correlation with what Polanyi referred to as personal knowledge[118], where informed assumptions, intuition, and imagination are integral components of exploratory actions driven by what he defines as "passions". For Polanyi, a vital aspect of discovery lies within this type of knowledge, which necessitates a personal evaluation of the relationship between evidence and external reality. This process of discovery and knowing is embodied through hands-on engagement with the world, where the execution of physical gestures plays a crucial role in the revelation of new things. Thus, design can be seen as related to contextual awareness and the idea of physically experiencing actions rather than purely thinking about them. A prime example of material engagement through skilled practice is the concept of 'synesthetic reasoning,' described

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[114] Dreyfus, H. L. (1990). Being-in-the-World: A Commentary on Heidegger's Being in Time, Division I (Vol. 102). Bradford. pp 4.

[115] As cited in Ibid, pp 4.

[116] Malcolm McCullough. 1996. Abstracting Craft: The Practiced Digital Hand. MIT Press, Cambridge, MA, USA.pp 3.

[117] Ibid, pp 7.

[118] Polanyi, M. (1967). The tacit dimension. Garden City, N.Y: Anchor Books. pp 4

by Paxson[119], which is the ability to sense the material through a combination of sensory perception and rational analysis, with the physical experience of doing something emerging as an integral part of producing knowledge through all the senses. In that regard, hands play a crucial role in sensing and understanding the world. That said, gestures become a mechanism by which humans interact with the surrounding environment by manipulating and developing new ways of handling objects and learning new skills based on a constant loop between seeing, thinking, and acting.

2.7 From making gestures, to making mistakes, to making new original things

Gestures, through their movements, have the power to encapsulate not only mental and intermediary representations, but also the moment of perceiving and performing. As Flusser[120]puts it, a gesture can be described as "A movement of the body or a tool attached to the body, for which there is no satisfactory causal explanation". He also notes that a gesture is considered as such because "it represents something, because it is concerned with a meaning"[121]. This definition highlights how gestures are defined in relation to motion, not just as an intention, which is an understanding process that deciphers the movement based on its results and cause, but also with meaning, which is related to a forward understanding of the processes that are continuously unfolding, as Ingold describes it, always in the making[122].

In the field of cognitive science, gestures are considered to be the manifestation of the interplay between the action, perception, and anticipation cycle. According to Maldonato, body movements or gestures are the results of the interplay between anticipatory (feed-

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[119] Paxson, Heather. (2011). The 'art' and 'science' of handcrafting cheese in the United States. Endeavour. 35. 116-24. 10.1016/j.endeavour.2011.05.004. pp 128.

[120] Flusser, V. (2014). Gestures. (N. A. Roth, Trans.). Minneapolis: Univ Of Minnesota Press. pp 3.

[121] Ibid pp 4.

[122] Hallam, E., & Ingold, T. (Eds.). (2008). Creativity and Cultural Improvisation. New York, NY: Bloomsbury Academic. pp 3.

forward) and compensatory (feedback) mechanisms, which enable humans to respond to certain situations[123] not just through reaction but also through anticipation. The body uses feed-forward to prepare for action and feedback to adjust the movement based on the sensory information from multiple receptors[124]. Furthermore, the efficiency of these mechanisms as an active motor schema improves with experience through what Maldonato calls "Embodied action," which is "a set of sensory and motor schemas and habits acting as a system capable of recalling bodily perceptions"[125]. Therefore, gestures, with their unique manifestation of the self, can be seen as the result of the constant relationship between action, perception, and memory (which emerges from experience and learning).

The distinctiveness of each gesture can be accounted for by Schmidt's schema theory[126], which is grounded in two key concepts: the Generalized Motor Program (GMP) and the Motor Schema. The GMP provides a motor pattern stored in memory that enables certain characteristics that remain constant in the intended gesture, while the Motor Schema modulates specific parameters of that motor response to accommodate situational demands. As Maldonato asserts, due to the interplay of these internal mechanisms, the repetition of a movement or gesture will never be precisely the same[127]. Thus, the originality of a gesture is intertwined with its uniqueness.

Bohm explains that the definition of "originality" is elusive and encompasses an element of indefinability as it involves defining

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[123] Maldonato, Mauro. "The Predictive Brain: Consciousness, Decision and Embodied Action. Sussex Academic Press. 2014. 112 Pp. ISBN: 9781845196394." The British Journal of Psychiatry 206, no 6 (2015), 524–24. doi:10.1192/bjp.bp.114.161554. pp 59.

[124] Ibid pp 60.

[125] Ibid pp 60.

[126] Schmidt, R.A (1975) A Schema theory of discrete motor skill learning. in Psychological Review, vol 82. American Psychological Association.

[127] Maldonato, pp 61.

something within a fixed structure, which in turn, takes away its originality[128]. However, Bohm suggests that our ability to learn new things through trial and error from a young age is what gives rise to originality. As we grow older, our acquisition of knowledge and the tendency to stick to established conventions tend to suppress our ability to see new things, as Bohm asserts that knowledge and the capacity to see new things are inversely proportional. To truly learn about something new, Bohm believes that it is necessary to take risks, try new things, and make mistakes[129]. This highlights that mistakes can be the harbinger of future novel work and the capacity for experiencing insight through the interplay of action and perception. Therefore, the ability to see and make things in a new and unique way can be seen as developing a personal style or autographic practice.

The ability to learn through experience in the world and uncover new discoveries through making mistakes could be the foundation for creating more mutually beneficial models of computational creation. This doctoral research places significance on the role of error as a means for humans to progress towards new frontiers. The use of digital technologies in design often limits the opportunity for making mistakes and reflecting on them in real-time. It is important to note that the concept of making mistakes should not be conflated with technical failures or glitches in a computer program. While these technical issues may lead to interesting and unexpected outcomes, mistakes made during the creative process reflect a synesthetic reasoning and are integral to the generation of new and original work.

The integration of thought, representation, and execution through computation, both digital and non-digital, is a growing concern in

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[128] Bohm, David, and Lee Nichol. On Creativity. London; Routledge, 1998. pp5

[129] Ibid pp 6

contemporary design practice[130]. It presents the potential to create new knowledge and objects by fusing these elements into a more cohesive process. The way to achieve such integration may be at the core of computational theories like the shape grammars theory. Although explicitly separates design from a physical object, the theory behind Shape Grammars proposes an "embed-fusion cycle" in which creativity melds recursion and embedding to calculate in a visual way generating new designs as we see new things. To Shape Grammars, Design is about seeing and doing; nevertheless, as Knight asserted, they "have promoted design as an activity that demands perceptual, active engagements with materials."[131] Suppose design is a kind of making, as asserted by Knight[132]. In that case, the discussion's focus gets closer to the differences that Pye[133] establishes between the workmanship of certainty versus the workmanship of risk. While the former could be framed as analogous to what digital design is today, the latter could be framed as what design should become again to put humans back into the equation. As Pye describes, in the workmanship of risk, the result is continually at risk during the process of making, in which judgment, dexterity, and care count as essential

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[130] For example, and as discussed throughout this chapter, the addition of different technological implementations for design processes, involved the production of vast bodies of work around their implications at a disciplinary level. One example of this is the Design and Computation group at MIT, which in its description: "inquires into methods of architectural design, and challenges the limits of current technology, as well as conventional design teaching and practice. It focuses on the development of innovative computational tools, design processes and theories, and applying these in creative, socially meaningful responses to challenging design problems ". see http:// https://descomp.scripts.mit.edu/www/about.php?layout_index=0

[131] Knight, T. (2015). Shapes and Other Things. In Nexus Network Journal, 17(3), 963– 980. P..978https://doi.org/10.1007/s00004-015-0267-3

[132] Ibid. p.965.

[133] Pye,D.(1968).The nature and art of workmanship.

characteristics in the process[134]. Being a drawing, a cardboard model, or a 3d printed object, the claim here is that the design's material aspect of the process has much to say to the whole enterprise of creating new original things. Furthermore, by stressing the concept of authorship not as an authoritarian position of the designer as the harbinger of the ultimate truth but one that advocates for personal style development toward the original, it can "retool" the design process through technology to overcome the schisms imposed by the computational design trichotomy.

The need for a gestural computational-making framework in light of the discussion presented is the object and foundation of my work. I argue that the essence of design is rooted in a series of interactions that demands focusing on the manual and the visual. The development and application of technologies for such purposes is a challenge but more possible than ever before in light of advances in robotics and artificial intelligence. I argue that the uniqueness of the 'skillful gesturing hand' sensing, communicating, grasping, shaping, and interfacing in the world becomes the ultimate harbinger of novelty and new design knowledge in the presence of technology.

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[134] Ibid p.22.

3

Mediated IDEAS

3.1 Mediated ideation

In this chapter, I discuss "design ideas" and "computational design workflows." Specifically, I expand the discussion from the previous chapter about the mediating role of technology in how ideas are generated, developed, and externalized. I elaborate and reflect around the technological implementations in the early days of CAD and their connotation as 'creative enhancers' up to the contemporary implementations of machine learning in design as 'prosthetic imagination.'[135]

I present SkeXL, a prototype that implements machine learning for interactive design in 3D environments. As a practical implementation of the theoretical discussion developed in this chapter, this project seeks to implement a computational design system that captures and interprets human gestures as design intentions for creating 3D models. I describe the technical implementation of a pipeline that translates human sketches into 3D models with the aid of generative adversarial networks. This implementation aims to explore the unfolding of design ideas while reframing the concept of design workflows, knowledge encapsulation, embodiment, and representation in 3D CAD processes. Developing alternative approaches to 3D modeling, this prototype presents the hypothesis of gestures as the enablers of originality and innovation through an active process engaging with the design of an object beyond intermediate representations .

Through the chapter, I challenge the computational design trichotomy view in which ideas and creativity are developed solely in the domain of the mind and emerge in the peripherical stages of the design process. Regarding creativity, two essential aspects of the discussion and questions proposed by this chapter relate first; to the generation, transformation, and communication of ideas in design; and second to the role of technology as an originator, supporter, or augmenter of creative ideas. Moreover, and acknowledging that creativity is a somewhat elusive concept that varies depending on the field of application, I elaborate a discussion focused on its place in the design process. In that sense, I reflect on the view of creativity as

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[135] Leach, pp 5.

an active process that emerges from experience, enabling innovation and originality.

I take contemporary implementations of machine learning in design as a paradigm to discuss the mediating role of technology in design workflows. I argue that gestures can extend creativity throughout the entire design process, actively allowing a constant unfolding and development of ideas and designs.

3.2. Mediated creativity

Digital computation and its ubiquity in everyday life make us focus on its inexorable use in contemporary design practice, raising questions and concerns about how creativity is affected either in a good or a bad way. As general as this assertion might sound, the use of digital design technologies to enhance and support creative processes has been a constant topic of discussion since the invention of Computer-Aided Design (CAD) in the early 60s. In addition, denoted as the harbinger of 'better,' 'smarter,' and 'faster' ways of 'doing what designers do,' digital technologies have undergone a constant transformation in the way they have been applied, considered, and taught over the years. Nevertheless, the questions that are relevant for this dissertation wander not only around what designers 'do' but also around how and when we 'do what we do.' These questions are more relevant than ever in present times as the advent of more capable software and hardware is having an unprecedented impact on how we design and make.

For example, in the last four to five years, questions such as How can machines think creatively? have revived some of the old aspirations and promises of early CAD implementations from the early 1960s. In addition, with the advent and widespread use of machine and deep learning techniques in everyday life, design today is facing- at least in theory- the addition of another layer of technology and information on top of its inherent complexity as a creative endeavor. Therefore, if Minsky's prediction[136] that machines finally become smarter and being capable of outperforming humans becomes true, the discussion about the place of creativity, novelty, originality, and delight in the emergence of new things is more relevant than ever. Moreover, this

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[136] Steenson, M. W. (2017). Architectural Intelligence: How Designers and Architects Created the Digital Landscape. The MIT Press. (2017, ch1,p13)

discussion often confronts two positions between one that considers using technology for “creative augmentation by automation” versus a more traditional position that defends creativity as a uniquely human characteristic.

In the previous chapter, the Albertian paradigm, in its proposition of a clear distinction between the world of ideas and matter, installed a figure of the architect as a designer capable of envisioning, preconceiving, and constructing ideas in his mind based on the ability to imagine space. This ability, determined as ‘lineamenta,’ was an inherently mental process prone to a further codification to externalize what was envisioned, developed, and ‘created’ inside the architect’s mind. Albertian thought established a paradigm in which the translation from the mental to the physical demanded the generation of several technological devices as vessels to externalize designs. Moreover, technological developments have played a crucial role in the conception of methods by which ideas are generated, developed, and realized in the physical world, a process often determined as ideation.

The discussion about the origin of the computational design trichotomy and its repercussions in current design can be explained by the historical relationship between design and technology. More specifically, the trichotomy can be discussed around the premises (mainly since the invention of CAD) concerning the use of digital computers, on the one hand, as enhancers of productivity and, on the other, as enhancers of creativity.

Regarding productivity, the development of new technologies has been regarded as a liberating agent for the creative work of artists, architects, and design-related disciplines, eliminating tedious tasks that interrupt the generation of creative ideas. Supposedly, the mediating role of technologies in art and design-related areas has been liberating through skills encapsulation, tool generation, systems, and methods to expedite production in favor of freeing thought. Technology’s use as a shortcut to externalize, represent and produce ideas allowed designers to think freely and ‘do what they do.’ Authors such as Andrew Witt have argued that the development of technologies (machines) in design is inevitably linked to epistemological challenges as the “abstract systems detach the user from operative logic” in favor of more instrumental knowledge to detriment of design knowledge[137].

Regarding creativity, two essential aspects of the discussion and questions proposed by this chapter relate first; to the generation, transformation, and communication of ideas in design; and second to the role of technology as an originator, supporter, or augmenter of creative ideas. Concerning the former, it is essential to understand and define what we refer to in this chapter when discussing creativity and its relationship with the generation of ideas, innovation, and originality in design. Concerning the latter, and based on the previous definitions, it is possible to comprehend how, within the trichotomy, the ideation process generates and transforms ideas in the light of technology. It is not the purpose of this dissertation to engage in a historical, philosophical, psychological, or anthropological discussion about the generation of ideas, its relation to consciousness, or to define creativity. Instead, the discussion focuses on how design ideas are originated, transformed, represented, and subsequently executed. Furthermore, given the ubiquity of technology in design workflows shaped by the trichotomy, it is valid to discuss not only how but when and where ideas are transformed, enhanced, and externalized.

Alberti's thought, inherited by modernism up to our times, emphasizes the generation of ideas in the mind, the image, and the representation of these ideas as plans for action (discussed further in the next chapter.) In Albertian theory, the conception of ideas and their generation resonates with the new Renaissance perspective of the artist as a genius, giving value to concepts such as individual originality and spontaneity[138]. The conception of a new humanism as an alternative to the divine order engendered new worldviews that

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[137] Witt, Andrew. "A machine epistemology in architecture." Translated By Annette Wiethuchter. Candide-Journal For Architectural (2010).

[138] The conceptual change from art as utilitarian towards a conception of it as a commodity resulted in a change in the artist's status as an individual character capable of producing new ideas given their familiarity with a new 'knowledge' in perspective, anatomy, optics, classical arts, and theory. Virtue as a personal endeavor was installed by a new humanism resulting in the artist's concept as a genius. See more in Watson, Peter. Chapter 18th, "The arrival of the Secular: Capitalism, Humanism, Individualism" in "Ideas: A History of Thought and Invention, from Fire to Freud." United States: HarperCollins, 2009. p388

stimulated intellectual innovation[139]. For Alberti, the potential for awareness and creation of beauty and harmony was innate to the mind and separated from any actions related to construction[140]. In accord with Platonic thought[141], although Alberti pointed out that 'Man' has qualities of mind analogous to divine qualities, such as the 'capacity to recognize' and the 'capacity to make,' installed the rigid boundaries of the domain of ideas generation as an activity of pure thought. Truthful to a Platonic view of the world, the emergence of creation resulted from reconciling 'thoughts of inspiration' and the 'thoughts of beauty' that a virtuous artist brings down to earth[142]. Moreover, the place of the mind as the generating and transforming medium of ideas is inevitably associated with an ocular-centric perspective in which the visual has a privileged place among other ways of sensing and experiencing the world. One of the main consequences of this belief-as discussed in the previous chapter- was the origin of a design trichotomy and, more importantly, the establishment of the belief that all intelligence, creativity, and knowledge are developed solely in the domain of the Mind.

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[139] For example, Dürer's humanistic view of the artist as an innate genius whose creative imagination departed from the Platonic-Religious perspective of divine inspiration responding more to a capacity to the mind developed by training. His famous quote: 'What Beauty is I know not, though it depends upon many things,' reflected his thoughts about the act of creation having a component of uncertainty that originates new things. To Dürer, the creative capacity relied upon the 'power of imagination' originating from the link between what a man gathers and what he puts forth. See more on Beardsley, Monroe C. Aesthetics from Classical Greece to the Present; a Short History. [1st ed.]. New York: Macmillan, 1966. Chapter SIX, Renaissance, p.129-p.130.

[140] Consonant with Neoplatonism ideas such as the ones found in Ficino. Based on Plato's Phaedo, Ficino developed a theory of contemplation that consisted of the withdrawal or disassociation of the soul from the body as the engender of all creative activity and quality essential for producing art. As a way to envision what does not yet exist.
See more on Ibid, p. 119.

[141] According to Plato, the artist, the production of art (like architecture, painting, or even poetry) was an endeavor that required a personal 'insight' about the nature of ideal beauty in which the effort to 'bring it to earth' required a state of inspiration derived from creative forces-the Muses-. Ibid. Chapter two "Plato", Page 45

[142] This is also related to Plotinus' concept of the three 'Hypostasis' as the source of reality in which the Intellect or 'Mind' (ideas or Platonic forms) interplays with the one of the 'All-Soul' (or 'psyche') that is the principle of creativity. Ibid, Chapter Four, "The later classical philosophers," page 79.

3.3. The place of creativity

Developing technologies associated with art and design have demonstrated the creation paradigm as an act that belongs purely to the mind. Generally, the development of technologies, systems, and devices for design have been developed directly to make explicit and represent an idea that originates in our minds. These representations go hand in hand with developing technologies oriented to expedite the process of 'freezing' ideas, usually as images containing descriptive information about that idea (for example, a floor plan). Either to be communicated, explained, or faithfully executed by another person or machine, the translation of ideas to designs has been subordinated to a prospective (preparing an action plan) and retrospective (analyzing the result of that plan) process of seeing and reflecting. This process of externalization, enables a convergent process of rationalization from the abstract to the concrete. Therefore, the discussion is directed to how design processes keep the development of creative ideas entrenched in the early stages of the creative process. In this regard, Ideation, often regarded as a cognitive and creative endeavor that implies a process of emergence, expansion, and exteriorization of new ideas. Under the hypothesis of the trichotomy, this view of design assumes that what it is imagined must be represented, and what is executed physically must be evaluated post-facto. What is essential for the discussion in this section is not the definition per se of what creativity is but its 'location' or place in the process of making things. In that regard, locating creativity solely in the mind has been challenged by views of creativity in which experience is the matter of all creative endeavors beyond paradigmatic or axiomatic worldviews[143]. Although creativity is a word or concept whose definition remains elusive, it is constantly used in design-related areas as one of its main associations concerns the generation of novelty, originality, and innovation. As expressed by Lindauer[144], even though there are similar characteristics common to

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[143] In this dissertation, the concept of creativity as an ongoing process that emerges from experience can be found in the work of authors such as physicist David Bohm and anthropologist Tim Ingold. See Bohm, David, and Lee Nichol. On Creativity. London; Routledge, 1998. Also see Hallam, Elizabeth, and Tim Ingold. Creativity and Cultural Improvisation. Oxford; Berg, 2007.

[144] Lindauer, Martin S. "Art, Artists, and Arts Audiences: Their Implications for the Psychology of Creativity." (2011). In Runco, Mark A., and Steven R. Pritzker. Encyclopedia of Creativity. 2nd ed. Amsterdam ; Academic Press/Elsevier, 2011.

creative individuals and their capacity to be creative across different disciplines, it is precisely the myriad of areas and domains in which creativity is expressed that make a unified definition of it as a concept complex and problematic.

Bohm expresses the difficulty of defining not only what creativity is but also the defining the concept of originality itself as a quality inherent to the mind of specific individuals[145]. His perspective brings crucial definitions that open doors to challenge the role and location of creativity inside the design process. Bohm provides an indirect perspective of creativity and the production of novel things -that he calls a 'newness'- which is a learning process that implies the perception of new orders and sensitivity to difference and similarity. Bohm's theory of creativity comprises the perception of novelty as new 'orders of structure' not only in the 'Mind' but also in the objective physical world. In a similar fashion as Ingold[146], Bohm advocates for a perspective in which originality and creativity emerge not from the effort to achieve a pre-formulated goal but rather from a process of personal experience[147]. Thus, by adhering to this definition of creativity as an ongoing process that unfolds from experience, it is possible to enter into a discussion that challenges creativity and the production of new ideas in design as peripherical stages of the creative process either as exclusively prospective or retrospective. While the introduction of computational design methods and tools held the promise of creative freedom for designers as part of the representational and analytic stages, it repositioned attention on how and where that creative freedom happened. Under this computational design trichotomy, the deceptive supremacy of the eye -as the ultimate sensor- and the mind -as the ultimate creator- overlooked aspects related to experience and concentrated the efforts on how to "extract" the knowledge from the mind, to see, evaluate and consequently 'to act.'

3.4. Artificial Intelligence and Design

The use of digital technology was not new in the field of architectural

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[145] Bohm, David, and Lee Nichol. On Creativity. London ; Routledge, 1998. Chapter 1, Page 1.

[146] Ingold Tim, in Introduction to Hallam, Elizabeth, and Tim Ingold. Creativity and Cultural Improvisation. Oxford; Berg, 2007.

[147] Bohm, David, and Lee Nichol. On Creativity. London ; Routledge, 1998. Chapter 1, Page 1.

design, with a few examples of successful use during the 1950s[148]. Slowly, computers attracted the attention of architects as the practice of the discipline became more complex with the addition of new layers of information, systems, and actors to projects. As Wright-Steenson writes, “For architects, this meant changes in both the nature of their practice and what they designed. They needed to interface with more systems and handle problems of greater complexity,”[149] meaning that building’s designs and architects were a part of a more extensive network among different actors and fields. As a consequence, not only was the designed artifact a topic of concern inside the field, but the new dynamics of how the designed artifact was produced was a concern as well. It wasn’t until the invention of Computer-Aided Design (CAD) that architects turned to computers as systems that could help to cope with the aforementioned complexity of new architectural projects. As Wright-Steenson[150] writes, “just as architects turned to computers, engineers and programmers also turned to architecture … computation, cybernetics and AI researchers reached toward architecture”[151]. She explains how through the symbiotic collaboration among these disciplines, architects sought the possibility of creating new ‘workflows’ for the demanding complexity of designs. Also, this allowed researchers to apply their emergent work to obtain tangible results. As a result, at the beginning of the CAD era, Human-Computer Interaction (HCI) became a central topic for architectural and engineering researchers, who, under the paradigm of cybernetics and Artificial Intelligence (AI), sought the development of new intelligent systems and interfaces to complement or augment their design workflows. Moreover, Douglas Engelbart’s vision of a ‘clerk’ system considered that because of its information processing capacity, computers could handle anything from mathematical to symbolic problems that require using symbolized concepts in direct favor of architects[152]. In addition, according to

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148 Buildings such as Utzon’s Opera house in Sidney is one of the first examples of the use of computers in the construction of complex shapes.

149 Steenson, M. W. (2017). Architectural Intelligence: How Designers and Architects Created the Digital Landscape. The MIT Press.(2017, ch1,p9)

150 Ibid

151 Ibid (ch1, p10)

152 Engelbart, D. C. (1962). Augmenting Human Intellect: A Conceptual Framework. Air Force Office of Scientific Research, AFOSR-3233, (Engelbart, 1962, p.5)

Baznajac[153], the use of computers as a tool for design was taken into consideration by many architects mainly because of the 'sweet promises' made by the upholders of Computer-Aided Design, which claimed that computers would 'free' designers from distracting and tedious activities to allow them to spend more time in the design itself. Baznajak addressed precisely the vision of intelligent systems ro not only process large amounts of information and deal with great complexity, but also the vision that systems could understand, learn, and could embed the designer's knowledge into the system. In addition, this promise was supported by lead researchers in the field of AI, such as Marvin Minsky. He predicted by the end of the century the emergence of computers embedded with an intelligence superior to humans.

For Minsky, by adding sensors and mechanical capacities, computers could not only create but assemble things- in this case, buildings- faster and cheaper than humans. In Minsky's words, "Contractors will have to face automation in construction just as architects will have to face automation of design. Eventually, computers will evolve formidable creative capacity"[154]. Minsky's prediction became, in part, a reality establishing the rendering of architects and designers in general obsolete as one of the main concerts about the use of computers[155]. That's how questions about computers developing creative capacities were established in the agenda of various researchers during the 1960s in places like MIT. Nevertheless, the promise made during the 1960s turned into disappointment and skepticism from early adopters of these technologies after some years, mainly because of the realization that this type of 'creative intelligence' was based on assumptions and hypothetical models translated from engineering to the architectural world. This implies that the common belief at the time was that intelligence and creativity were related to problems with information and symbolic processing instead of more embodied, abstract, or even obscured human endeavors. Nevertheless, Minsky's predictions of computers as machines that in the future would surpass human limits of intelligence

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[153] Bazjanac, Valdimir. "The Promises and the Disappointments of Computer-aided Design."In Reflections on Computer Aids to Design and Architecture, ed. Nicholas Negroponte.17-26. New York: Petrocelli/Charter, 1975. (1975)

[154] As cited in Steenson, M. W. (2017). Architectural Intelligence: How Designers and Architects Created the Digital Landscape. The MIT Press.(2017, ch1,p13).

[155] More on this in (Wright Steenson, 2016, ch1, p14), Leach, Neil 'the dead of the architect'

Toggle display of multitude of design and contextual data such as terrain, neighbouring program, regulations and structure.

Figure 10
Tools loke Digital Blue Foam, use machine learning for urban analysis based on contextual information. source: https://www.digitalbluefoam.com/

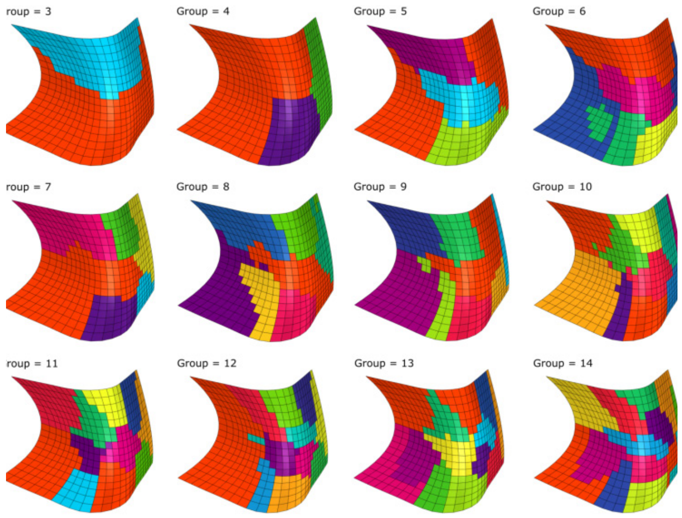

Figure 11
Panel clustering based on attributes using Gaussian mixture models in LunchBox-ML. source: https://provingground.io/2018/03/12/new-machine-learning-examples-with-lunchboxml/

and creativity were rapidly replaced by the mere hope that in the future, artificial intelligence would make the enterprise of augmented creativity for design through computers possible.

3.5. Augmenting Intelligence

In the last 10 years, the field of AI has grown exponentially with the emergence of powerful techniques in the area of machine learning. Permeating every aspect of human life, design-related areas are experiencing an explosive interest in adding these techniques and methods to traditional design practices. In academic environments and more experimental areas affine to digital art, the emergence of new machine learning methods for generative creation gained considerable attention from the design field as, for the first time, a computer could produce new content that, in appearance, rivals human capacities.

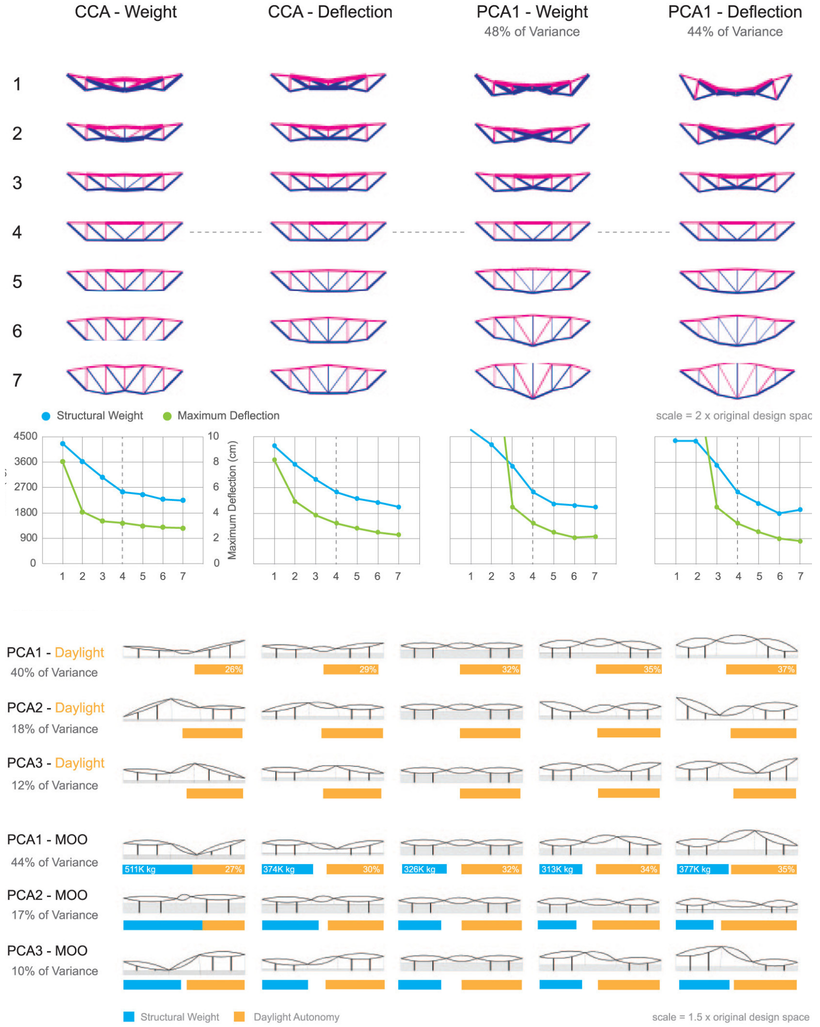

Figure 12
Analysis of variable importance in initial structural and Daylight workflows using Machine learning.
source: Brown, N. C., & Mueller, C. T. (in press). Design variable analysis and generation for performance-based parametric modelling in architecture. International Journal of Architectural Computing.

Facilitated by the availability of two of the main ingredients of machine learning techniques (computational processing power and data[156]) for novel content creation, a newfound interest in older discussions on design, computation, and creativity emerged.

Although the use of machine learning for design-related disciplines is an area under constant development and growth, the primary uses of advanced ML techniques have been oriented toward simulations (figure

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[156] The availability of powerful graphic processing units (GPU) capable of parallelization of matrix calculations and the emergence of frameworks for the creation and training of deep neural networks efficiently, such as Tensorflow or PyTorch. Along with the availability of vast amounts of data derived from the explosion ubiquity of the internet and especially user content generation in the forms of text, audio, images, and so on, advanced models are capable not only of predicting or analyzing complex problems but also generating new unseen content.

10) or analysis (figure 11). It was only when the generative power of novel ML algorithms established the generation of new, unseen content that new applications seeking to augment, support, or even replace functions that lie often in the human domain began to emerge. For example, in fields like structural design, we see how ML's generative capacities inform processes to generate, curate, and navigate design spaces or to generate novel design solutions using performance-driven iterations at early design stages (figure 12) . Although the generative capacities of machine learning models and techniques present opportunities to designers and engineers to handle complexity in unprecedented ways -for example, by processing enormous quantities of data to generate design spaces and shape iterations- there are still concerns related to the discretized nature of their implementation inside design workflows. In that regard, the "at early design stages" that usually ornament the titles of much of the research in AI and creativity sheds light on the challenge to extend creativity from the inception of ideas to further stages of making. At what point does creativity begin or end in a design process? Does creativity end after ideas are "extracted" and represented as images or "data?" Are there alternatives to overcome the computational design trichotomy in developing ideas through computational technologies that could expand beyond the production of an image? In the case of the emergence of generative ML methods, image synthesis is probably the most paradigmatic case of technology adoption from the art and design community that illustrates the persistence of the trichotomy in design and its relation to creativity and novel ideas.

The invention of Generative Adversarial Networks (GANs) in 2014[157], paved the road for an explosive amount of research about content generation, including audio, text, or images. Image generation has been the most popular and in-demand technique in art and design-related areas. The possibility to generate novel and unseen content generated by a trained model without human intervention opened the door for a myriad of AI-related projects, academic papers, books, and even academic programs looking to explore the intersection between computational design and artificial intelligence. The exponential growth of GANs use in art and design -especially architecture- comes from

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[157] Goodfellow, Ian, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, and Yoshua Bengio. "Generative Adversarial Nets." In Advances in Neural Information Processing Systems, edited by Z. Ghahramani, M. Welling, C. Cortes, N. Lawrence, and K. Q. Weinberger, Vol. 27. Curran Associates, Inc., 2014. https://proceedings.neurips.cc/paper/2014/file/5ca3e9b122f61f8f06494c-97b1afccf3-Paper.pdf.

the fascination of generating an infinite number of 'inspirational' images (designs?) by a process often referred to as 'hallucination.' As a form of 'prosthetic imagination'[158] capable of 'augmenting our intelligence,' the avalanche of image synthesis techniques available to end users[159] has been bestowed with the capacity to extend our creative intelligence to become a part of ourselves[160]. However, most of the theory generated around the use of AI as a means to generate Intelligence Augmentation (IA) is somewhat contradictory. In the case of AI for design purposes, designers usually wander between the instrumental knowledge necessary to operate an AI model and the lack of knowledge to modify, create or develop new algorithms to push ML techniques beyond what's delivered by the computer science community.

3.6. Generative Design Machines

Let's analyze image synthesis techniques from the computational trichotomy perspective. Their popularity arises from the 'oracle-like' capacity to generate realistic images 'on demand.' However, the way these techniques are produced, trained, and deployed leave ample space for skepticism concerning first, the cognitive aspects of their use in design, second, the outcomes from their implementation as designs, and finally, how they enhance or extend our intelligence. In the case of GANs, two models (a generator and a discriminator)

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[158] Leach, Neil. Architecture in the Age of Artificial Intelligence: An Introduction to AI for Architects. United Kingdom: Bloomsbury Publishing, 2021. Page 6.

[159] Since the creation of the first GAN for image generation, new architectures and techniques emerged to improve the performance, stability, and quality of the models in terms of content and resolution. For example, Deep convolutional GANs, WGANs, Conditional GANs, or StyleGAN, among others, are models that pushed significant improvements to the original GAN architecture. See Radford, Alec, Metz, Luke, and Soumith Chintala. "Unsupervised Representation Learning with Deep Convolutional Generative Adversarial Networks." arXiv, (2015). https://doi.org/10.48550/arXiv.1511.06434. Mirza, Mehdi, and Simon Osindero. "Conditional Generative Adversarial Nets." arXiv, (2014). https://doi.org/10.48550/arXiv.1411.1784. Arjovsky, Martin, Soumith Chintala, and Léon Bottou. "Wasserstein generative adversarial networks." ***International conference on machine learning***. PMLR, 2017. Karras, Tero, Laine, Samuli, and Timo Aila. "A Style-Based Generator Architecture for Generative Adversarial Networks." arXiv, (2018). https://doi.org/10.48550/arXiv.1812.04948.

[160] Leach proposes an integrated view of Human and artificial intelligence as a form of Intelligence Augmentation that puts humans in control while leveraging computational power to leverage our capabilities. Leach, Neil. Architecture in the Age of Artificial Intelligence: An Introduction to AI for Architects. United Kingdom: Bloomsbury Publishing, 2021. Page 9.

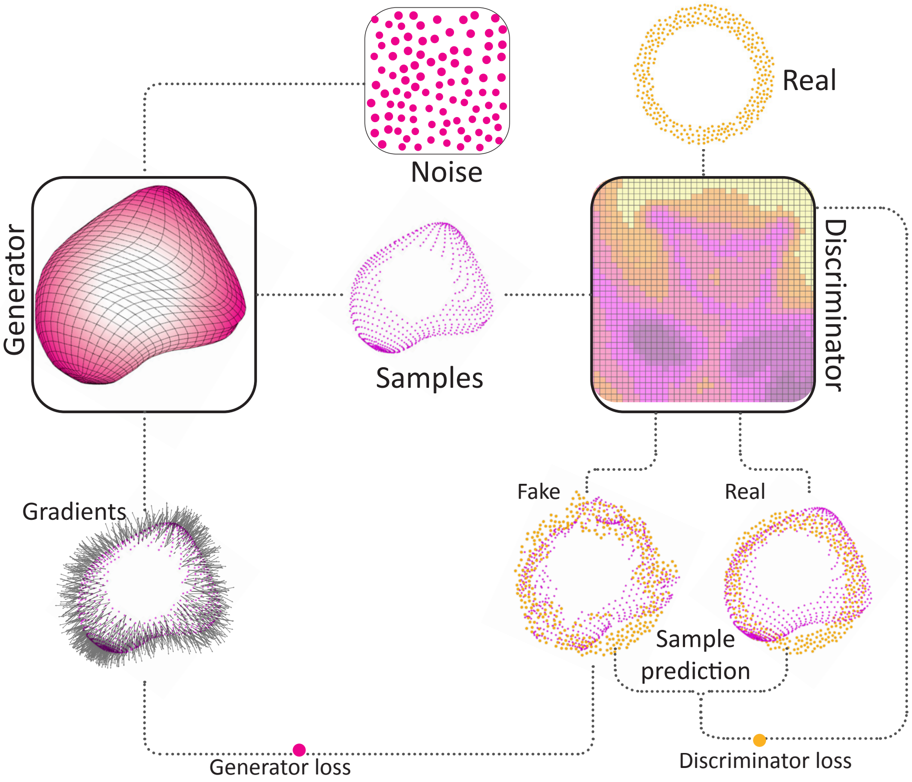

Figure 13
Generative adversarial network pipeline.
Source: author

interact in a 'game-like' process to generate new content. In other words, GANs learn the underlying distribution behind a dataset, usually constituted by thousands of image samples. In the process, a 'generator' transforms random inputs into plausible samples that resemble the original data. This is achieved by training the generator to map some latent space (k) into a sample space (p) (figure 13). The learning process of a GAN is based on the ability of the two networks to retrofit each other in a sort of competition. The 'generator' presents new samples to a 'discriminator' that evaluates if the sample is either 'fake' or 'real' according to how close it is to the original data. This interaction allows for both networks to, in time (or epochs),eventually improve their efficiency to either generate new samples (generator) or also to distinguish which ones are 'real' (the discriminator). The desired outcome of the GAN training process is a generator network capable of producing 'realistic' outputs as close as possible to the original dataset. After training, the process of producing new images involves a process of 'feeding' the network with a latent vector to retrieve new images. This process, often called inference, is one capable of 'creating' unlimited content or powerful image manipulations (figure 14). However, GANs' power

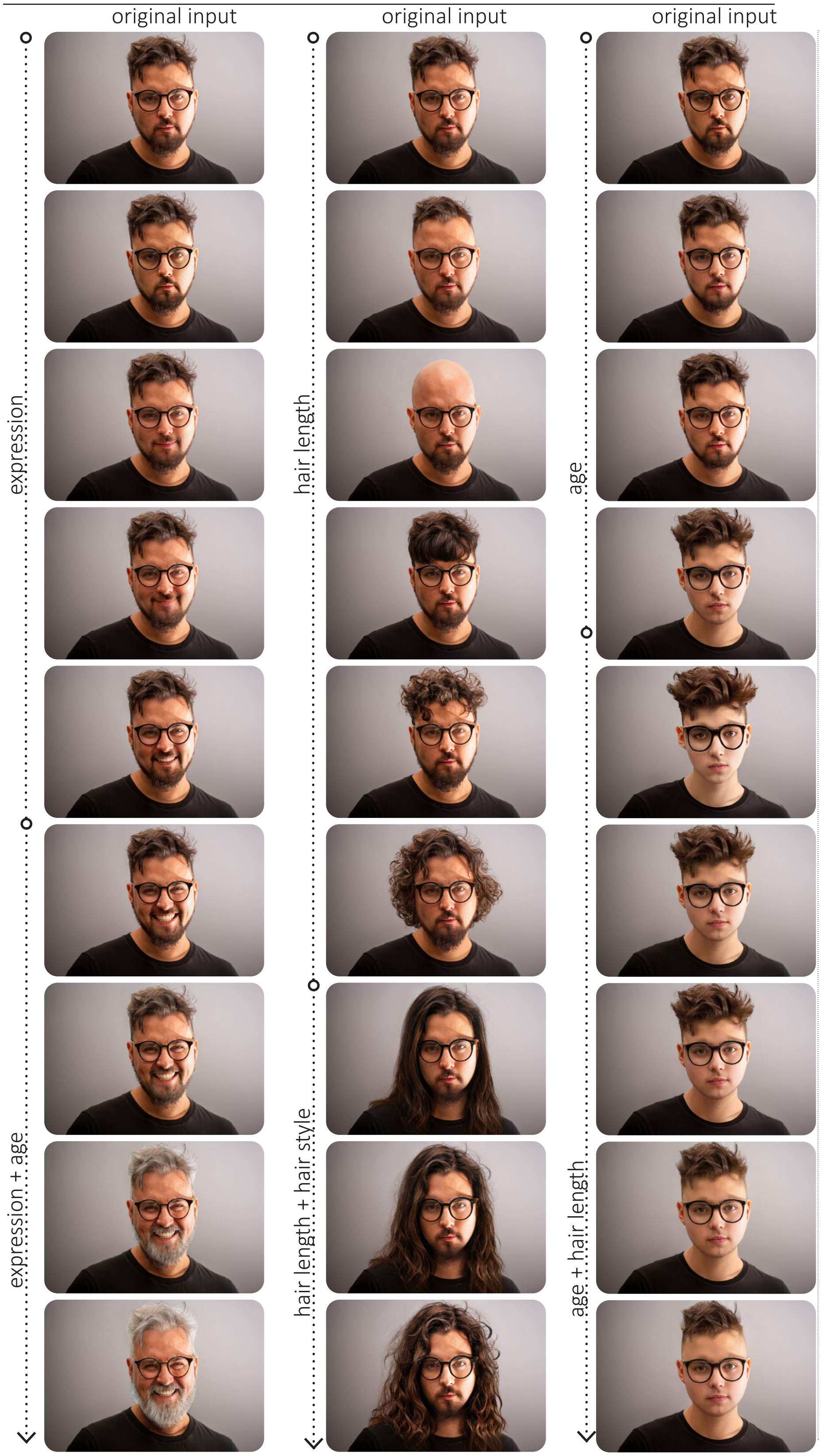

Figure 14
GANs have the power of generating realistic images while at the same time performing arithmetic operations to explore latent space to generate image modifications. In this example, a trained StyleGAN 3 model is capable-from an original image- to perform modifications by interpolating between different vectors that detemrine some characteristics such as age, expression, hair, etc.
source: author

to generate unlimited novel outputs in design fields shows some typical characteristics also present in parametric design tools.

As expressed in previous research[161], I claimed that current intersections between design and AI inherited the computational design trichotomy and the idea of design workflows in which the generation of ideas occurs at the early stages of the creation process. In the development of ideas and in the transition from mind to-mo del to-code to-machine to-material, it is possible to identify three fundamental problems with using technology in the digital design process. The first one is the problem of black-boxed processes embedded into software and machines that might bias the design processes into more representational efforts instead of the creative/cognitive aspects of the design process. From this black box concept, it is possible to identify the other two problems. One is related to the inability of generic operations -embedded into software and hardware- to impress a specific and non-generic design idea. The final one is related to the 'creative gap' that occurs due to the use of black-boxed generic operations in the mentioned transition from the design idea to the fabrication of the prototype. Different tool, same old problems.

3.7. Obscure technology and methods to extend our creativity

The translations between the components of the computational design trichotomy, by being mediated by technological layers -in this case, AI- have been oriented chiefly to represent, automate, (pre and post) rationalize, optimize, and encapsulate expert knowledge into precompiled black boxes to be used on demand by the 'creative mind' and enacted by the 'obedient hand.' Moreover, the widespread adoption of image synthesis generation-primarily through GANS- works mainly as precompiled tools that are difficult to put together, modify, and for most people in the design field, difficult to understand. Due to knowledge and technical barriers that are inexorable when pairing Design and AI, most of the implementations adopt these techniques as black boxes with little room to modify or expand their use. So, why or how is this problematic.?

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[161] Pinochet, D. (2016), "Making- Gestures: Continuous design through real time Human Machine interaction",
Proceedings of CAADRIA '16 / Living Systems and Micro-Utopias: Towards Continuous Designing, the 21st
International Conference on Computer-Aided Architectural Design Research in Asia, Melbourne, Australia,
March 30- April 2, 2016, CAADRIA, Hong-Kong, pp. 281-290.

If the claim is that ML tools work as a prosthetic imagination, as some oracle capable of imagining a myriad of designs for us, we are in trouble as this claim situates the intelligence and idea generation in the same place as the trichotomy. However, with the exponential availability of machine learning models and a strong support from the open source community, the work of practitioners interested in topics akin to interaction and real-time content generation are appearing. That is the case of the work of Rebecca Fiebrink[162] with projects such as InteractML[163], a project to use interactive machine learning inside VR environments.

In this case, the computer model gives me ideas in the form of inspirational representations, so I -a designer- can either be inspired to do something new with it or take the image as is and execute it physically. In both situations, using imagination to generate creative ideas responds to a traditional pure contemplative and reflecting practice. My process as a designer is limited to clicking, waiting, and reflecting; nothing is much different from getting inspiration from experiencing a sunset or by throwing a sponge full of color to a wall[164]. Using image synthesis methods in design processes reaffirms the trichotomy view of creativity's role and idea development as discrete steps in the overall design workflow.

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[162] https://researchers.arts.ac.uk/1594-rebecca-fiebrink/

[163] Hilton, Clarice and Plant, Nicola and Gonzalez Diaz, Carlos and Perry, Phoenix and Gibson, Ruth and Martelli, Bruno and Zbyszynski, Michael and Fiebrink, Rebecca and Gillies, Marco (2021) InteractML: Making machine learning accessible for creative practitioners working with movement interaction in immersive media. In: VRST 2021: ACM Symposium on Virtual Reality Software and Technology, 8-10 December 2021, Osaka, Japan.

[164] As commented multiple times by professor George Stiny in his Ph.D. seminar classes of computation at MIT, Leonardo uses the example of the sponge to disparage Boticelli's methods for depicting landscape: 'A painter cannot be said to aim at universality in the art, unless he love equally every species of that art. For instance, if he delight only in landscape, his can be esteemed only as a simple investigation; and, as our friend Botticelli remarks, is but a vain study ; since, by throwing a sponge impregnated with various colours against a wall, it leaves some spots upon it, which may appear like a landscape. It is true also, that a variety of compositions may be seen in such spots, according to the disposition of mind with which they are considered; such as heads of men, various animals, battles, rocky scenes, seas, clouds, woods, and the like. It may be compared to the sound of bells, which may seem to say whatever we choose to imagine. In the same manner also, those spots may furnish hints for compositions, though they do not teach us how to finish any particular part; and the imitators of them are but sorry landscape-painters.' Leonardo. and Brown, John William. and Rigaud, John Francis. A treatise on painting / by Leonardo da Vinci; translated from the Italian by John Francis Rigaud; with a life of Leonardo and an account of his works by John William Brown George Bell & Sons London 1877

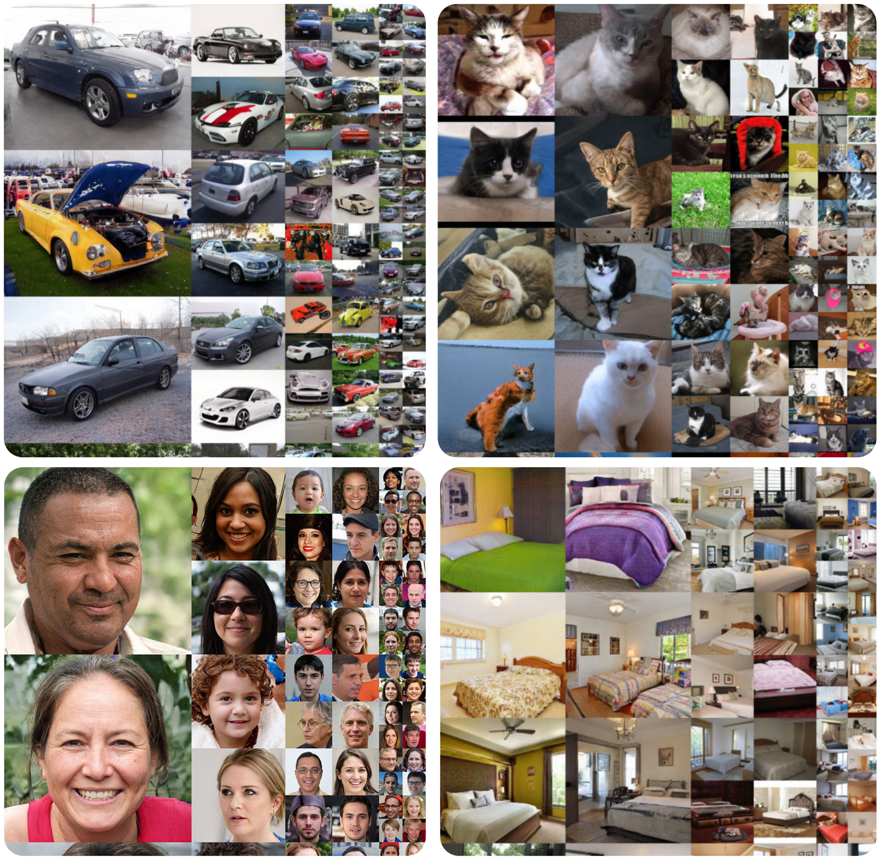

Figure 15
Different examples of images generated using specific LSUN datasets of cars, cats, faces and rooms from the original StyleGan paper from NVidia .

Source: Karras, Tero, Samuli Laine, and Timo Aila. “A style-based generator architecture for generative adversarial networks.” In Proceedings of the IEEE/CVF conference on computer vision and pattern recognition, pp. 4401-4410. 2019.

Nevertheless, in this dissertation, an important premise is that the creation of novel and creative ideas goes beyond a contemplative practice into a more active one. Furthermore, when leaving aside the hype of a new type of intelligence capable of supporting your creative process by augmenting your intelligence as a designer, we are left with the same uncertainties, bottlenecks, and questions when it comes to framing the creative role of technology in design, and the emergence of novel things and knowledge about how to make those things. It is fair to ask, what does a designer learn, internalize, and add to the design process by using these AI techniques?

3.8. Getting creative as the size of your data… or the number of nodes in your grasshopper definition

In the case of GANs, the complexity of creating or customizing ML models to make what we ‘want them to do for us’ is paired with their training difficulty both in terms of control and time expenditure. Most research around GANs presents similarities with parametric design workflows in which the capacity to generate unlimited ‘designs’ inside a computer is subordinated to an inherent predetermined structure. This structure serves as an unlimited generator of designs as long as we don’t get too creative and discover new things that could render the whole parametric model obsolete. This means that in the case of parametric design, the development of ideas inherently requires a constant modification of the structure that generates designs as soon as we discover new patterns or ways to cope with the contingency of the process. A similar claim can be made about image synthesis methods as they will generate newness and variations in direct proportion to the size of the dataset used to train the network. The larger and more heterogeneous the dataset’s content, the better the inference that the model will make to generate new content. Nonetheless, GAN’s "Achilles heel" is quite similar to other ML techniques – for example, object detection algorithms- as their capacity to generate new content-or predict and classify objects in a picture- will be limited by the data size and variability.

The development of GANs has shown this a reality since, for many years, training a model with new data that can generate new ‘designs’ -for example, a new picture of a house- required specific hardware, time, and the necessary knowledge to expand the capabilities of the network to produce something beyond than faces, cars, or cats (figure 15) while at the same time avoiding typical GANs problems such as modal collapse[165]. The belief that image synthesis methods such as GANs could work as a universal idea generator fell short as the amount of data and time needed to make it work that way is beyond current hardware capacities[166].

3.9. Maslow’s hammer redux: how to ‘imagine’ almost anything

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[165] Modal collapse refers to a situation where the generating part of the model generates-regardless of the input- only a limited amount of variety of samples. The result is that the generator learns how to ‘fool’ the discriminator by generating limited new data that is ‘good enough’ to pass the discriminator’s evaluation of the image as fake or real. Although more recent GAN models addressed this issue in remarkable ways, it was not until the emergence of these new models that the few designers using ML had the chance to avoid or work around this issue, meaning that the solutions and answers needed to generate more content came from other disciplines such as CS.

[166] Although the performance of GANs has improved tremendously since their invention in 2014 in terms of resolution, fidelity, and training speed, they still show problems that make their training unstable or efficient enough to generate almost any type of image.

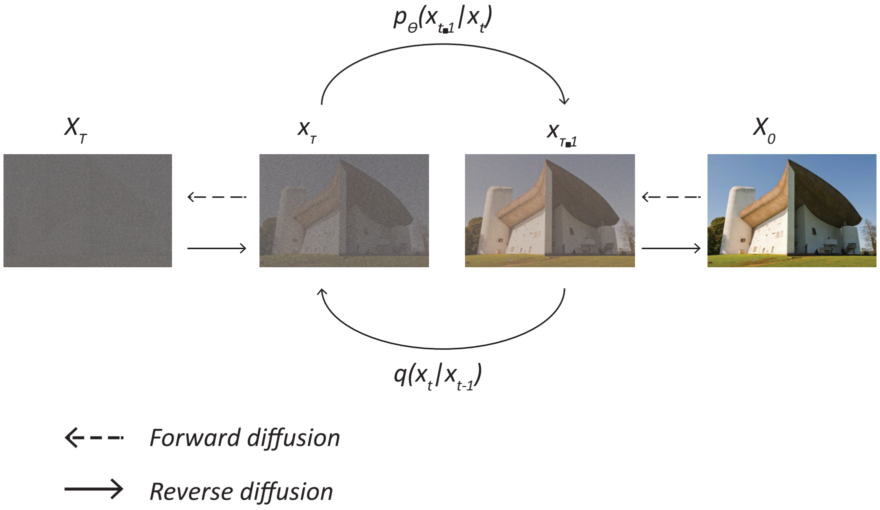

Figure 16
Graphical representation of a parameterized Markov chain used in diffusion models. the transitions of this chain are learned to reverse a diffusion process that consists in adding noise to data in the opposite direction of the sampling until signal is destroyed.
Source: Redrawn from original source. Ho, Jonathan, Ajay Jain, and Pieter Abbeel. "Denoising diffusion probabilistic models." Advances in Neural Information Processing Systems 33 (2020): 6840-6851.

Over the past two years, a revolution in image synthesis emerged as new techniques such as diffusion models[167] and autoregressive transformers[168] led to the emergence of robust text-to-image generation architectures, rapidly relegating GANs as the weapon of choice when it comes to 'hallucinating' new images. Moreover, the emergence of tools such as DALL-E solved the main GANs problem of trading off diversity for fidelity resulting in high-quality results but limited coverage of the whole distribution[169]. In other words, unlike GANs, which learn to map random noisy data to a point in the distribution, diffusion models take noisy data -an image- and, by a sequence of de-noising operations, continuously reveal an image that is part of the training distribution.

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[167] Diffusion models were introduced by Sohl-Dickstein. In this paper he introduced the idea of sampling from a distribution by reversing a gradual noising process. Sohl-Dickstein, Jascha, Eric Weiss, Niru Maheswaranathan, and Surya Ganguli. "Deep unsupervised learning using nonequilibrium thermodynamics." In International Conference on Machine Learning, pp. 2256-2265. PMLR, 2015.

[168] Brown, Tom, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared D. Kaplan, Prafulla Dhariwal, Arvind Neelakantan et al. "Language models are few-shot learners." Advances in neural information processing systems 33 (2020): 1877-1901.

[169] Dhariwal, Prafulla, and Alexander Nichol. "Diffusion models beat GANs on image synthesis." Advances in Neural Information Processing Systems 34 (2021): 8780-8794.

Diffusion models (DM) are good at both generating high quality and sampling because of their architecture which consists of two processes: adding noise and denoising. The central concept underlying DMs is that if we could build an architecture that can learn the progressive decay of information due to noise, the model should be able to reverse the process and reconstruct the information back. In a very similar way to Variational Auto Encoders (VAE), DMs optimize an objective function by projecting the data onto the latent space (encoding) and then recovering it back (decoding). Nonetheless, DMs do not learn the data distribution; instead, they learn how to model a series of noise distributions in a Markov chain to decode the data by a hierarchical denoising process (figure 16). Essentially, diffusion models work as a Markov chain trained to produce samples matching the original data after a finite time t. At each step of the process, the model works as a function $\varepsilon(x_t,t)$ which predicts the noise component of x_t. By this process, the model learns how to reverse (denoise) a diffusion process (adding noise) by generating a slightly more denoise x_{t-1} from x_t. During the training process, the models generate a random image of a data sample x_0, at a time step t and a noise ε, that eventually will result in a noised sample x_t. That's how diffusion models improve their results through the objective function that calculates the simple mean-squared error (MSE) loss between the 'true' noise and the predicted noise.

Through a series of additions[170] oriented to improve performance in both image quality, speed, and accuracy, the development of image synthesis models based on diffusion models is experiencing exponential growth (figure 17). That is the case with the most popular tools developed by companies such as OpenAI's Dall-E 2[171],

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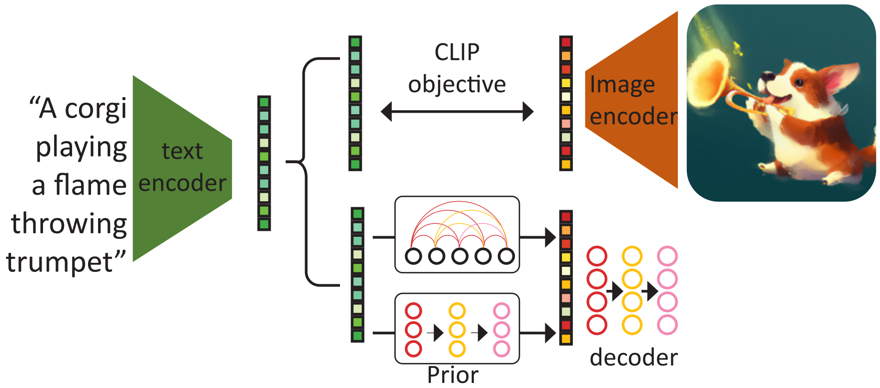
[170] Dhariwal and Nichols, introduced ablations and guided classification to improve image quality. Ablation is a technique in which specific components of an AI system are removed dynamically to understand their contribution to the overall system. Also, different classification techniques were introduced to guide the sampling process toward arbitrary class labels. For more information see Meyes, Richard, Melanie Lu, Constantin Waubert de Puiseau, and Tobias Meisen. "Ablation studies in artificial neural networks." arXiv preprint arXiv:1901.08644 (2019) and Dhariwal, Prafulla, and Alexander Nichol. «Diffusion models beat GANs on image synthesis.» Advances in Neural Information Processing Systems 34 (2021): 8780-8794.

[171] Ramesh, Aditya, Prafulla Dhariwal, Alex Nichol, Casey Chu, and Mark Chen. "Hierarchical text-conditional image generation with clip latents." arXiv preprint arXiv:2204.06125 (2022).




an espresso machine that makes coffee from human souls, artstation

panda mad scientist mixing sparkling chemicals, artstation

a corgi's head depicted as an explosion of a nebula

Figure 17
OpenAI's DALL-E (2021) and DALL-E 2 (2022), were one of the first implementations of text-to-image models. Although the code or model were not released publicly, these models inspired a new revolution in image synthesis using different variations of guided image generation using diffusion models.

Above: Low level diagram from original paper (redrawn by the author). Below: Sample images from the original paper. Source: Ramesh, Aditya, Prafulla Dhariwal, Alex Nichol, Casey Chu, and Mark Chen. "Hierarchical text-conditional image generation with clip latents." arXiv preprint arXiv:2204.06125 (2022).

Google's Imagen[172], MIDJOURNEY,[173] or Stable Ai's Stable Diffusion[174]. While DALL-E 2 and MIDJOURNEY are accessible as freemium[175] services, their architectures remain private. In the case of IMAGEN[176] and STABLE DIFFUSION[177] both code and research papers are publicly

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[172] Saharia, Chitwan, William Chan, Saurabh Saxena, Lala Li, Jay Whang, Emily Denton, Seyed Kamyar Seyed Ghasemipour et al. "Photorealistic Text-to-Image Diffusion Models with Deep Language Understanding." arXiv preprint arXiv:2205.11487 (2022).

[173] MIDJOURNEY is an independent research lab that produces a proprietary artificial intelligence program that creates images from textual descriptions. Released in 2022, it is a tool that works over the social platform DISCORD using bot commands. https://www.midjourney.com/home/

[174] Rombach, Robin, Andreas Blattmann, Dominik Lorenz, Patrick Esser, and Björn Ommer. "High-resolution image synthesis with latent diffusion models." In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pp. 10684-10695. 2022.

[175] A pricing strategy in which a product is provided free of charge for basic use, while premium features are offered under subscription methods. In the case of both DALL-E and MIDJOURNEY, additional features such as faster computation, unlimited generation, and improved resolution are part of the premium paid subscriptions.

[176] https://github.com/lucidrains/imagen-pytorch/tree/main/imagen_pytorch

[177] https://github.com/CompVis/stable-diffusion

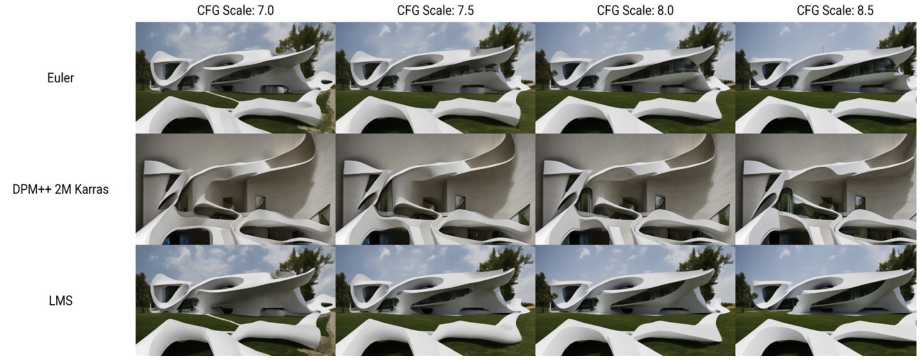

Figure 18
Images generated from the prompt “ a house designed by Zaha Hadid’ using different guidance parameters , and samplers using Stable Diffusion Model v1.5
Source: author

Figure19
“A house designed by Zaha Hadid“, using LMS sampler and A guidance scale of 8.5.
Source: author

available.

The availability of State of the Art (STOA) Image generation tools, either as services or open-source repositories, are responsible for an unprecedented explosion in the use of AI-based methods for creative purposes given the possibility to ‘drive’ image generation through the use of text. While improving the efficiency and results of GANs, text-to-image models present none of their drawbacks, allowing designers, artists, and mostly everyone to ‘create almost anything’ you can write and the machine can 'imagine.' Of course, this remains true as long as you put it into "the right words." This calls to mind the phrase "When the only tool you have is a hammer, everything will look like a nail." Are we finally in front of the definitive form of "prosthetic imagination" capable of unleashing our creative potential as designers or is this another form of Maslow’s hammer[178]?

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[178] Abraham Maslow wrote in 1966, «If the only tool you have is a hammer, it is tempting to treat everything as if it were a nail» Referring to a cognitive bias that involves an exaggerated reliance on a familiar tool. Maslow, Abraham Harold. The Psychology of Science: A Reconnaissance. United Kingdom: Harper & Row, 1966.

3.10. A new conduit metaphor

Text-to-image models, although very powerful in content creation due to their capacity to sample images very efficiently from the sample data, present new drawbacks about their function as cognitive (dealing with knowledge and intelligence) and creative tools (dealing with the intelligent use of knowledge to produce something new). One of the problems is related to the interface used to generate new content. Text-to-image models present specific characteristics concerning how 'ideas' are generated and developed. For example, mediated by Natural Language Processing (NLP) models, text-to-image tools rely on an interface in which design intentions are generated using text prompts describing a 'design idea' as the primary input form[179]. The process considers translating something from the designer's mind into a logical sequence of words that a computer will 'interpret' as a design intention and 'imagine' an image that the designer gets as the output. Images, as works of 'art' or 'designs' (figure 18 and 19) emerge as novel outputs from a prompt that can be ornamented with specific keywords that will steer the inference according to desired graphic styles, level of detail, type of illumination and so on (figure20). Although the results might be viewed as impressive, the ways each of the different models allow the exploration of variations of those outcomes is still a challenging task. Furthermore, exploring the model's latent space via text is a convoluted task for most designers as these explorations do not always result in smooth and controlled results (figure 21). Although this situation will likely improve in the short term[180], using these models still presents the problem of unusual interfaces for designers. Moreover, using text as a mediator between a human and a machine opens the door to many concerns about how language is understood and processed inside a machine. Furthermore, the fascination

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[179] Although tools like stable diffusion, midjourney or dall-e are expanding the way users can generate image allowing to upload images as starting points, most of the users prefer using texts as the main generator.

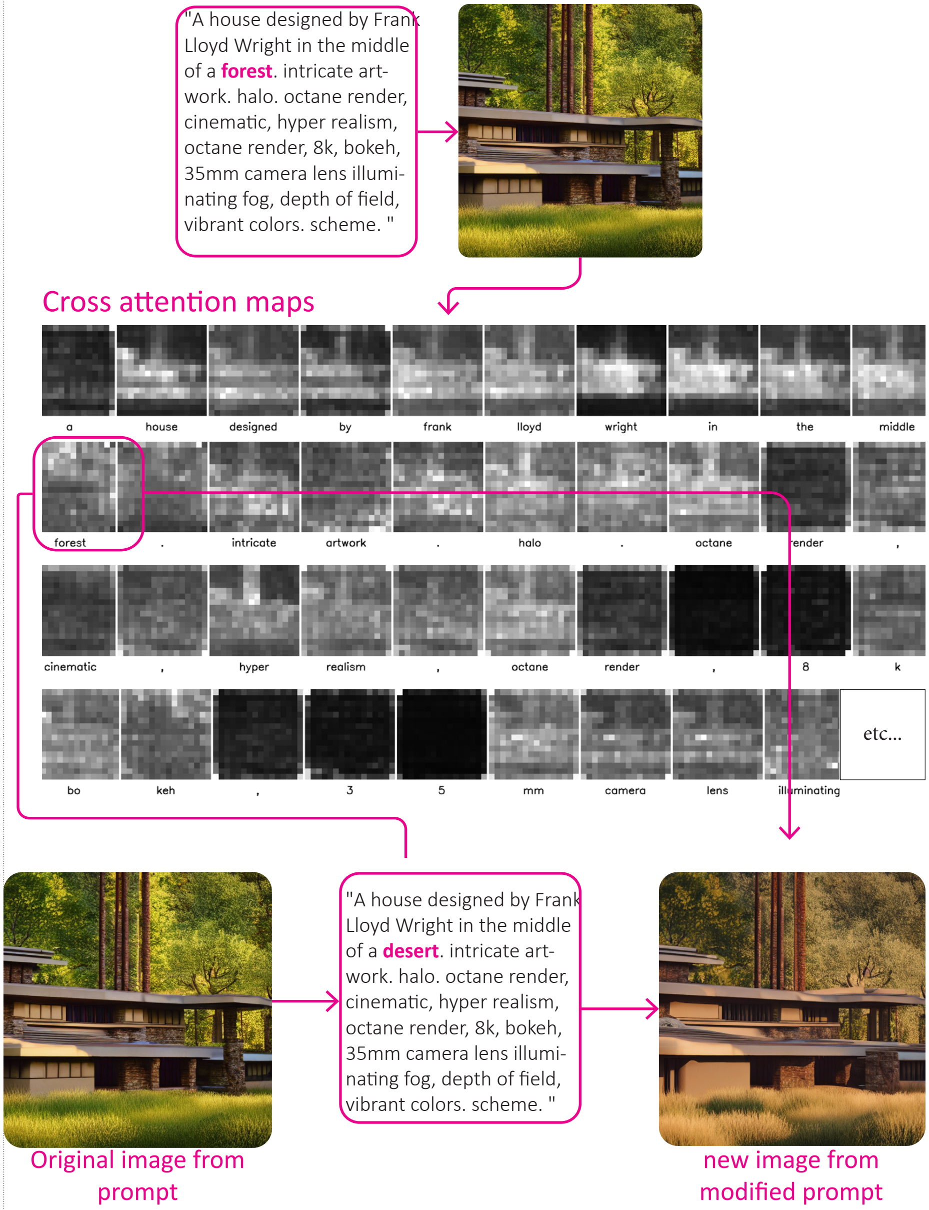
[180] According to the Artificial Index 2022 report, the amount of publications in the Artificial Intelligence topic doubled, growing from 162,444 in 2010 to 334,497 in 2022. Zhang, Daniel, Saurabh Mishra, Erik Brynjolfsson, John Etchemendy, Deep Ganguli, Barbara Grosz, Terah Lyons et al. "The AI index 2021 annual report." arXiv preprint arXiv:2103.06312 (2021). The Field of Machine learning, for example , doubled the amount of publications in the same period. These numbers indicate the interest and fast rate of development of new techniques that go hand in hand with incrementes in data and computing power available. The explosive development of transformers and diffusion models and their various combinations for content generation is an example of a trend that eventually will lead to faster, and more accurate models over the next years.

Figure 20
A: “A house designed by Frank Lloyd Wright in the middle of a forest, spring, 8k , DSLR, bloom, high resolution , artstation”

B: “A house designed by Frank Lloyd Wright in the middle of a forest, Autum, 8k , DSLR, bloom, high resolution , artstation “

C: “A house designed by Frank Lloyd Wright in the middle of a forest, Autum, 8k , DSLR, bloom, high resolution , artstation “

D: “A house designed by Frank Lloyd Wright in the middle of a forest, summer, 8k , DSLR, bloom, high resolution , artstation “



"A house designed by Frank Lloyd Wright in the middle of a **forest**. intricate artwork. halo. octane render, cinematic, hyper realism, octane render, 8k, bokeh, 35mm camera lens illuminating fog, depth of field, vibrant colors. scheme. "

"A house designed by Frank Lloyd Wright in the middle of a **desert**. intricate artwork. halo. octane render, cinematic, hyper realism, octane render, 8k, bokeh, 35mm camera lens illuminating fog, depth of field, vibrant colors. scheme. "

Figure 21

Using prompts for image modification remains a challenging task. techniques like prompt-to-prompt focusing on operations at specific cross-attention layers shows a promising path for improving image generation exploration.

The example shows the manipulation of an image generated from the text prompt “A house designed by Frank Lloyd Wright in the middle of a forest“ Source: Hertz, Amir, Ron Mokady, Jay Tenenbaum, Kfir Aberman, Yael Pritch, and Daniel Cohen-Or. “Prompt-to-prompt image editing with cross attention control.” arXiv preprint arXiv:2208.01626 (2022).

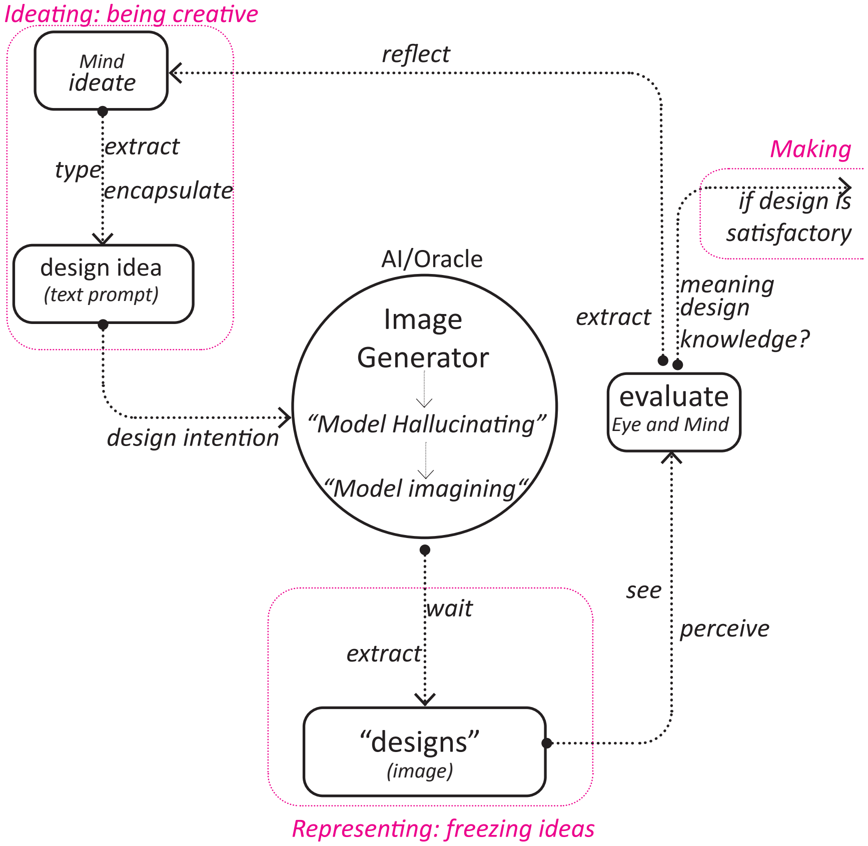


Figure 22
Translations of ideas into sentences and images using AI.
Design ideas generate in the mind, extracted, encapsulated, interpreted by a ‘prosthetic imagination‘ and evaluated evaluated by the user/designer.

with text-to-image tools as ‘pandora’s boxes’ reminds us of the main ideas presented by Reddy about what he called the conduit metaphor framework[181]. Using text as a medium to ‘pour’ ideas into a computer comes with the same biases and miscommunication problems when using language as a conduit for ideas communication and development. Using tools such as MIDJOURNEY, DALL-E or STABLE DIFFUSION implies that ideas are encapsulated into words in the same ways as ideas -and supposedly new designs- are extracted from the generated images. The unidirectionality imposed by these models established them as a computational oracle in which ideas can be introduced, modified, and extracted from a model (figure 22). Expressing design intentions through fixed sentences -instead of actions- as carriers of ideas, makes the use of AI and the creative augmentation enterprise objectify creativity[182]

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[181] Reddy, M.J. (1979). The conduit metaphor-- a case of frame conflict in our language about language. In A. Ortony (Ed.), _Metaphor and thought_ (p. 284-297 only). Cambridge: Cambridge University Press.

[182] See Hirsch, Eric & Macdonald, Sharon (2007). Introduction, creativity and the passage of time: History, tradition and the life-course. In Elizabeth Hallam & Tim Ingold (eds.), ***Creativity and Cultural Improvisation***. Berg. pp. 185--192.

Figure 23
Andy Warhol and Deborah Harry in a tech demo of the AMIGA WORLD magazine dedicated to computer art and creativity. In this issue Warhol expresses computer's potential for art while at the same time recognizing the interface problems and limitations. In the interview, Warhol expresses the dificulties of producing art through the use of a mouse and a key in replacement of a brush or pen. source: https://archive.org/details/amiga-world-1986-01/mode/2up

and neglect the cognitive aspects involved in the unfolding process of creation.

3.11 Beyond Images: unfolding ideas through technology

The availability of robust and powerful models for image creation holds the potential to impact creative processes in unprecedented ways. The incremental interest in image synthesis techniques such as generative adversarial networks and generative diffusion models suggests these potential impacts in architecture and art[183]. Whereas new generative tools based on ML allow the generation of a catalog of images as design options on demand, the aspect of how ideas evolve and transform into knowledge is under scrutiny. Reducing the process of design ideas generation to the production of an image neglects the very aspects of design that relate to knowledge elicitation. Conversely, as Perez-Gomez claims, the insufficient capacity of images (representations) to convey meaning from design ideas, emerges from its disconnection to the phenomenological

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[183] An interesting overview of these exponential adoption on AI in design is discussed in Zwierzycki, Mateusz. "On AI Adoption Issues in Architectural Design Identifying the issues based on an extensive literature review." (2020).

aspects of design as a contingent process[184]. Along the same lines, the notion of creativity as the bi-product of a contingent process that challenges the polarity between novelty and convention situates the generative power of creative improvisation as one of the crucial aspects of creation[185]. In this sense, Ingold and Hallam introduced the discussion that shifts the notion of creativity as innovation (retrospective) towards creativity as improvisation (performative). Whereas innovation implies a backward reading from the products it produces, improvisation characterizes creativity by its processes[186]. Understanding the relationship between creativity and the production of new things not as products but as processes, it is possible to assert that the creative in the digital must account for a component of interactivity to cope with the contingency in the evolution of ideas as new patterns of reality start to emerge. Wherever the intention of creative augmentation goes hand in hand with the production of novelty in terms of unseen, novel things as final objects, current technological solutions, and their upcoming iterations will suffice. However, the understanding of creation as a forward process of discovery and learning that tightly relates to ever-changing contexts must entail alternative paradigms to account for the performative nature of creating something new. The challenge of this dissertation is to push the current trend that privileges image, end products, and a discretized view of design, toward a focus on the aspects that can truly make a difference when it comes to the creative use of technology.

Whereas the use of digital tools is ubiquitous in design-related areas, how designers use them presents challenges in terms of the interface and the experience of developing design ideas. In the first place, as discussed previously, clicking and typing use generic operations to express design intentions (figure 23). The actions implied to generate and develop a design inside a software are constrained to discrete movements and sequences that relate more to the operations needed to generate a design representation rather than the design itself. The interface problem becomes more evident in most 3D

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[184] See Pérez, Gómez. “The Historical Context of Contemporary Architectural Representation,” in Persistent Modelling: Extending the Role of Architectural Representation edited by Phil Ayres (London and New York: Routledge, 2012).

[185] Tim, Ingold & Elizabeth, Hallam (2007). Creativity and Cultural Improvisation. An Introduction [w:] ciż, eds. In Elizabeth Hallam & Tim Ingold (eds.), _Creativity and Cultural Improvisation_. Berg. pp. 1--24.

[186] Ibid. p11.

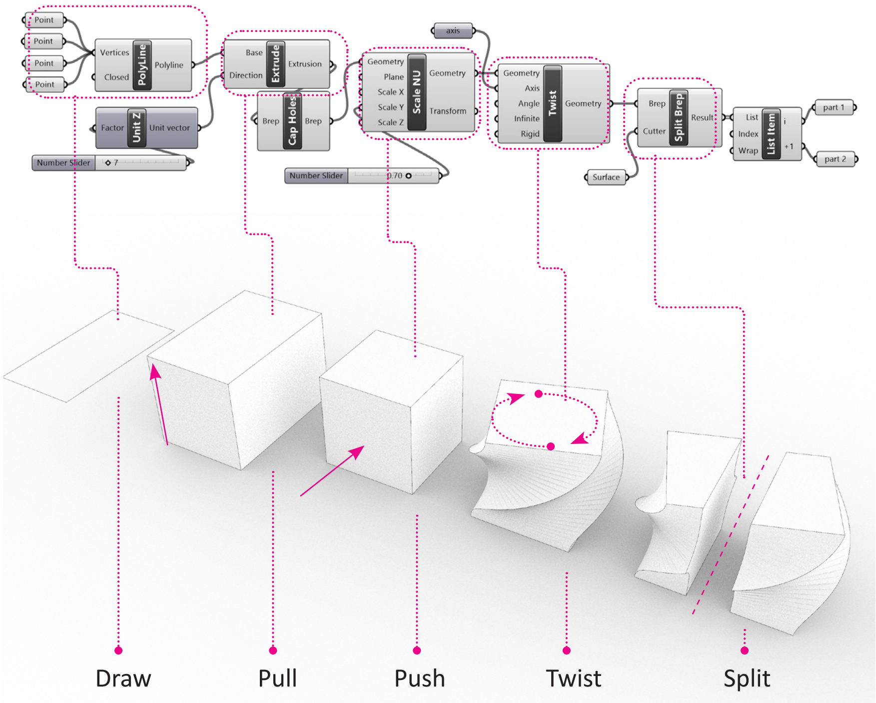
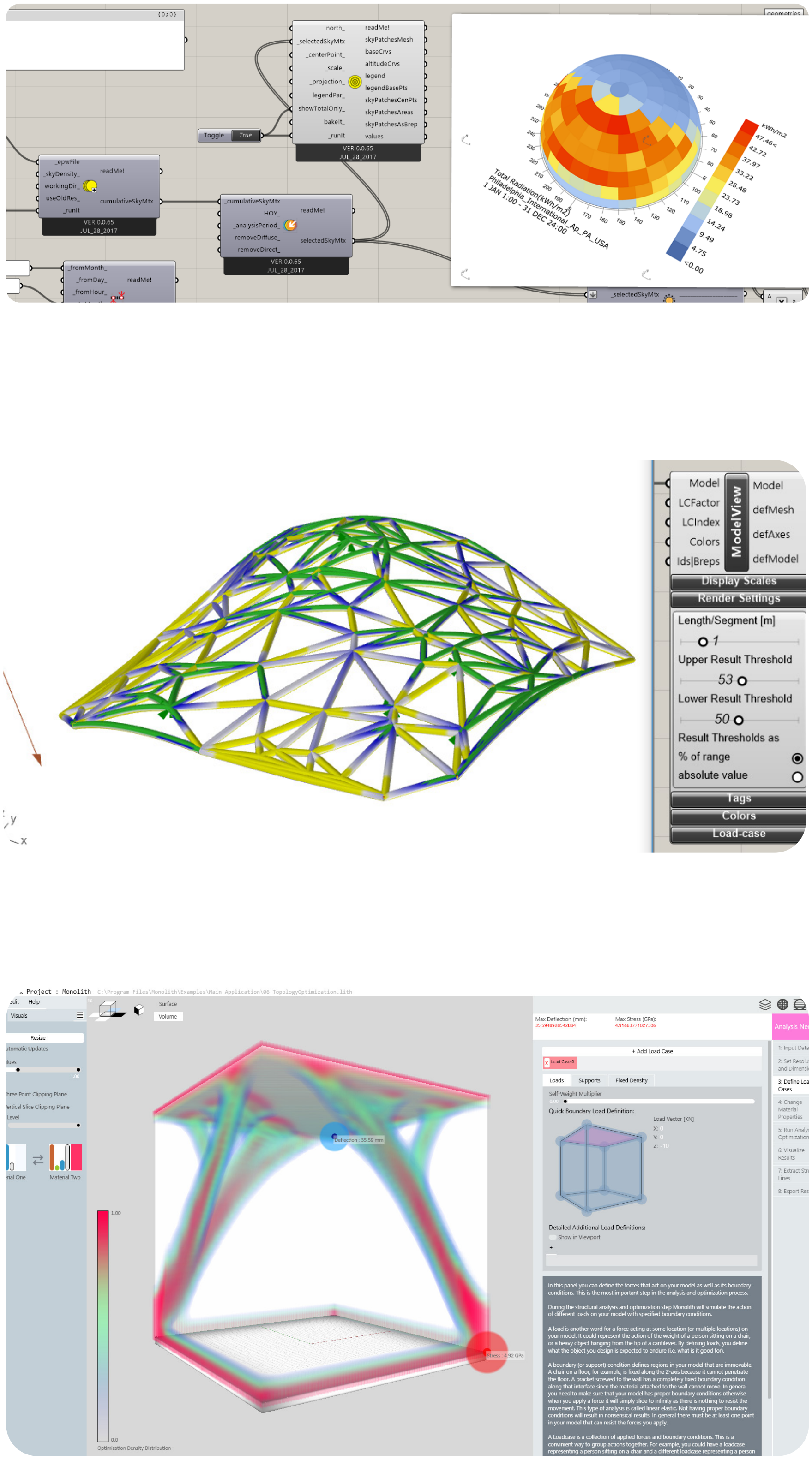


Figure 24
Geometry generation and manipulation pipeline using the Grasshopper Visual scripting platform inside Rhinoceros 7.
Source: author

software packages in which operations such as 'pulling,' 'pushing,' 'trimming,' 'extending,' 'splitting,' 'twisting,' and others -referring to specific actions- are encapsulated, compiled and enacted by one click, and differentiated by quantity. How large, twisted, shrunk, or expanded an object will appear inside a software package will depend on something distant from the nature of manipulating an actual physical object and closer to operations used represent it (figure 24). The disembodied design paradigm established by using digital software for design is highly determined by the trichotomy: first, I think, then I represent, then I make.

Whereas in the past 10 to 15 years, the explosion of parametric design delivered some alternatives to traditional 3D design software expanding designers' capabilities to generate and manipulate topologies with unprecedented freedom, it also allowed the addition of metrics to evaluate, for example, design's structural or structural performance. That's how visual programming languages allowed the construction of flexible graphs to generate not only 3D models but mostly tools to generate, explore, analyze and evaluate design spaces that could integrate qualitative and quantitative metrics inside the



Max Deflection (mm): 35.5948928542884

Max Stress (GPa): 4.91683771027306

Self-Weight Multiplier 0.00

Load Vector [KN]
X: 0
Y: 0
Z: -10

In this panel you can define the forces that act on your model as well as its boundary conditions. This is the most important step in the analysis and optimization process.

During the structural analysis and optimization step Monolith will simulate the action of different loads on your model with specified boundary conditions.

A load is another word for a force acting at some location (or multiple locations) on your model. It could represent the action of the weight of a person sitting on a chair, or a heavy object hanging from the tip of a cantilever. By defining loads, you define what the object you design is expected to endure (i.e. what is it good for).

A boundary (or support) condition defines regions in your model that are immovable. A chair on a floor, for example, is fixed along the Z-axis because it cannot penetrate the floor. A bracket screwed to the wall has a completely fixed boundary condition along that interface since the material attached to the wall cannot move. In general you need to make sure that your model has proper boundary conditions otherwise when you apply a force it will simply slide to infinity as there is nothing to resist the movement. This type of analysis is called linear elastic. Not having proper boundary conditions will result in nonsensical results. In general there must be at least one point in your model that can resist the forces you apply.

A Loadcase is a collection of applied forces and boundary conditions. This is a convinient way to group actions together. For example, you could have a loadcase representing a person sitting on a chair and a different loadcase representing a person

Figure 25
Top: Ladybug (Environmental analysis)
Middle: Karamba (structural performance)
Bottom: Monolith (topology optimization and isosurface modelling)

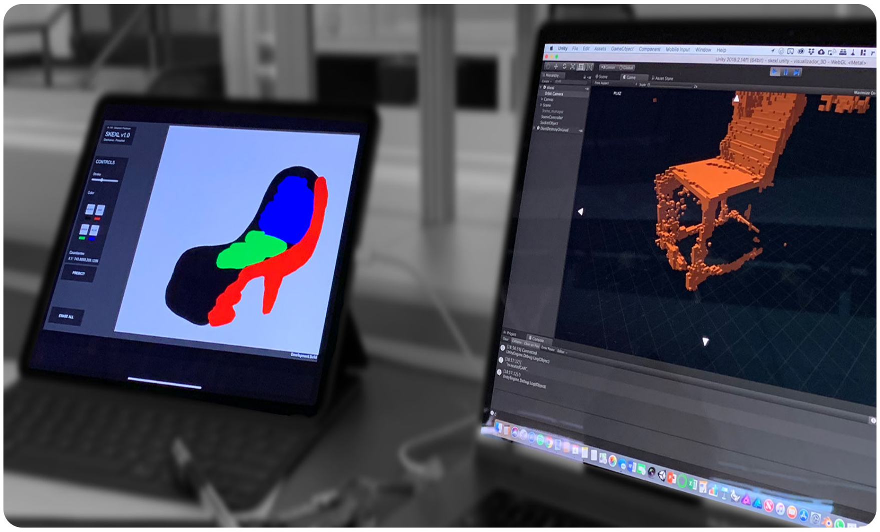


Figure 26
Sketch to shape: Generating 3D shapes from sketches (Pinochet and Danhaive, 2018)
source: author

same design process (figure 25). However, the generation of graphs implies the generation of a flexible network of operations to explore the design spaces in accordance with one design in contrast to their capacity to explore different design ideas. Consequently, the designer is more concerned with developing the sequence of operations to bring forth ideas rather than developing the design itself[187]. Although quite powerful for driving design exploration towards convergence, there are challenges in using technology to embrace the divergent nature of the design process. Is it possible to reframe how we use digital tools to alter the design workflow and address the problems discussed in the previous sections? Moreover, is it possible to extend the ideation process in the design workflow to develop ideas in more fluid ways?

3.12. SKEXL: A sketch-to-shape tool for the production of 3D models.

I created 'SKEXL,' Sketch to voxels: a collaborative 3D modeling tool based on the work previously developed in 'sketch to shape'[188] (figure 26 and figure 27). The project seeks to explore the unfolding

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[187] See Pinochet, Diego in 'Antithetical Colloquy' ACADIA // 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines [Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-0-692-77095-5] Ann Arbor 27-29 October, 2016, pp. 402-411

[188] Pinochet, Diego, and Danhaive, Renaud, 'Generating shapes from sketches' for the course 6.198 Deep Learning practicum at MIT.

Figure 27
Sketch to shape: Generating 3D shapes from sketches (Pinochet and Danhaive, 2018)
source: author

of design ideas while reframing the concept of design workflows, knowledge encapsulation, disembodiment, and representation in 3D CAD processes. Using machine learning and interactive computation, 'SKEXL' is an experiment that links user actions as sketches to generative 3D modeling. By encapsulating expert knowledge related to 3D modeling, it seeks to eliminate intermediate representations -such sections, elevations, floorplans- in the design process to engender immediate real-time 3D model generation from hand sketches (figure 27). This experiment aims to answer, among others, the following questions:

- Can the use of machine learning reframe the generation of 3D models in a more embodied way?
- Is it possible to capture design intentions from sketches to generate 3D shapes using machine learning?

- Can we design and explore ideas inside a computer without representing them?

The project starts from the premises discussed in this chapter concerning the fluid development of ideas through technology. Iof 3D modeling, is considered a complex task that requires investing time and experience to get satisfactory results. Conversely, sketching represents a more natural way to express, develop, and communicate design ideas. However, while offering many advantages for design ideation, sketching lacks the many advantages of 3D modeling to visualize (render in different visual styles), evaluate (perform structural or thermal analysis), fabricate (3D printing), and manipulate shapes using, for example, parametric software. At the same time, while sketching allows for the free and fluid hand gesturing to develop ideas 'on-demand,' 3D modeling implies the sequential use of pre-compiled operations enacted typically through clicking and typing. Is there a way to combine the best qualities of both sketching and 3D modeling for the fluid development of ideas in 3D environments?

Just like diffusion models that allow the generation of so-called 'ai art' without any participation from the 'user' apart from text, 3D GANs can explore 3D modeling by inputting a latent vector. However, generating a text prompt to generate an unexpected result as an image or using a random number (seed) for generating a latent vector, has little or no relation to the act of design itself. Is there a way to use designers' gestures to generate meaningful and functional outcomes from software using machine learning?

3.12.1 From sketches to volumes

As discussed before, using generative models for design presents challenges regarding what is generated and how it is generated. Whereas image generation techniques based on GANs have improved over the years, what a GAN can generate will depend on the quantity, diversity, and quality of the data. In addition, assuming that a GAN can produce good outcomes in terms of diversity and quality of the images, how they are generated relates directly to their relevance in a design scenario. Moreover, the way GANs generate content is by inputting a latent vector (200-dimensional) that will generate, for example, a new image or, in this case, a new 3D model. Furthermore, the way this latent vector is generated is not trivial if we want to ensure that the model's output correlates with our design intentions. For the purpose of this chapter, the inquiry wanders around the most effective way to capture a design intention and how to translate it into the shape of a latent vector that could potentially generate meaningful results.

While image GANs generate outputs in the form of 2D arrays, the challenge of this implementation is to generate a model capable of

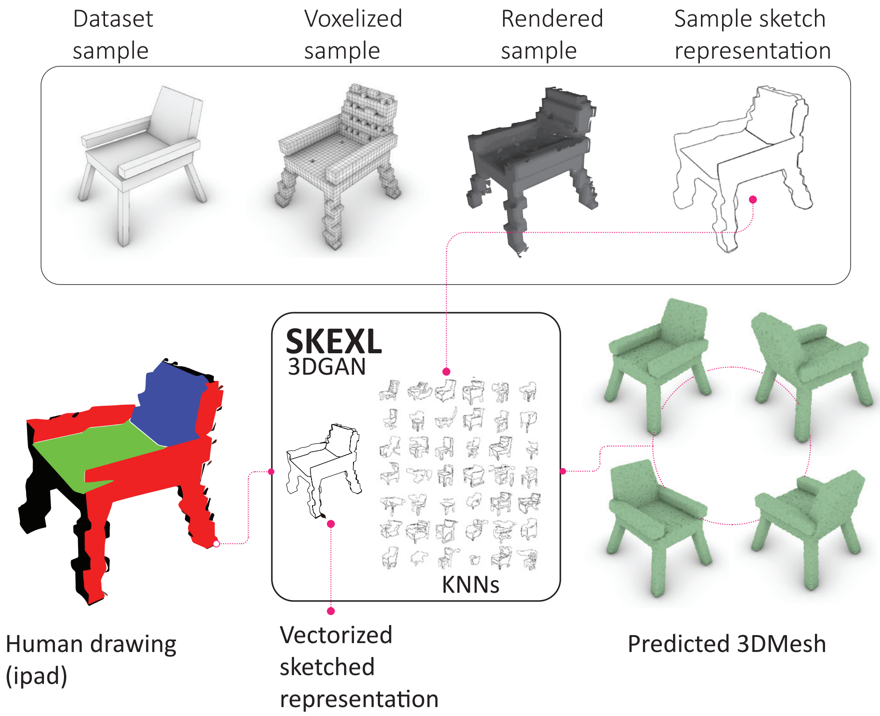

Figure 28
General overview of the project SKeXL (sketch to Voxel). Human drawings are processed and interpreted by a ML model that predicts a voxelized 3D shape based on the human sketch.
Source: author

generating 3D arrays describing volumetric information in the form of a binary representation of density values (0 or 1). In this case, each value in the 3D array represents a binary state, either as a void (a 0) or a solid region (a 1). Starting from the work developed by Wu et al.[189], this project uses the original 3D-GAN described in Wu's paper to generate voxelized representations of 3D models. The voxelized models are rendered as 2D images, which are later converted into a sketch-like representation. Furthermore, by pairing sketches and latent vector data, a model was built to map sketch information onto a latent vector. Consequently, the resulting latent vector is fed back into the original network to infer a new 3D model. Finally, an interactive drawing application was developed to translate human-drawn sketches by processing, predicting the corresponding latent vector, and finally generating a new 3D model. The general pipeline is shown in figure (Figure 28). Since the original implementation

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[189] Wu, Jiajun, Chengkai Zhang, Tianfan Xue, Bill Freeman, and Josh Tenenbaum. “Learning a probabilistic latent space of object shapes via 3d generative-adversarial modeling.” Advances in neural information processing systems 29 (2016).

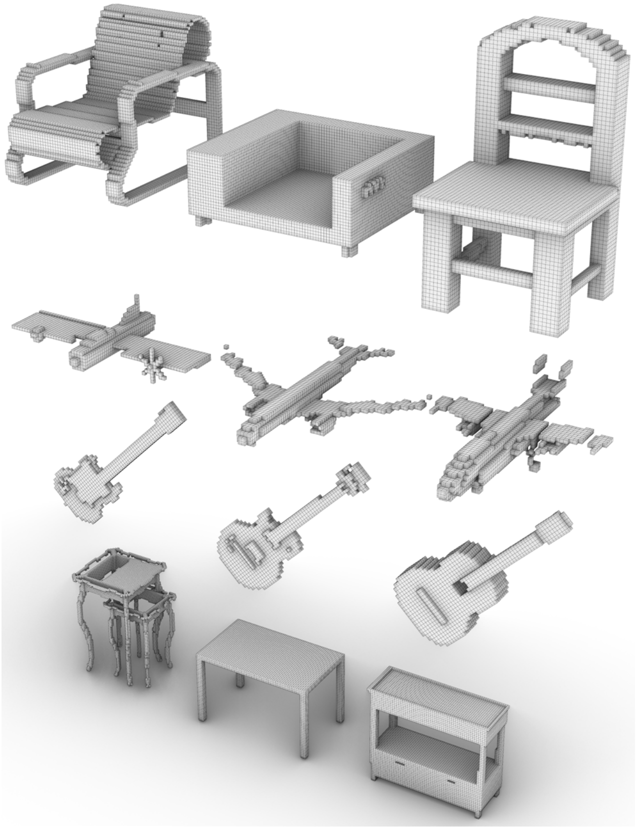

Figure 29
Voxelized models from the ShapeNet dataset.
source:author

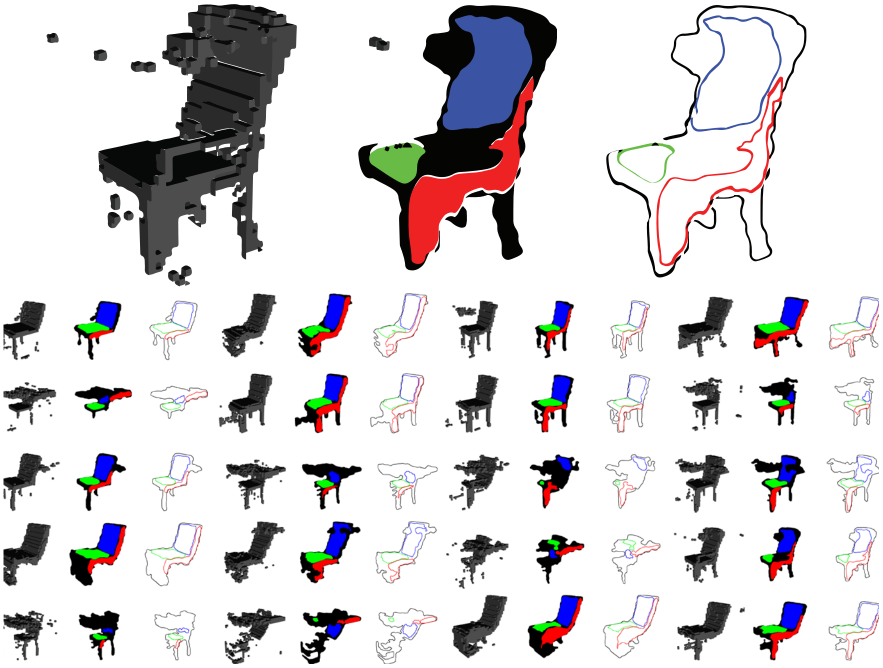

Figure 30
sketch/model data samples trained on the chair category of Shapenet. every model is represented as voxels and processed as sketches.
source: author

in 2018[190], the project has undergone various changes and improvements addressing the main challenges and difficulties of generating complex 3d models from simple hand drawings[191].

3.12.2 Generating data

The project seeks to provide a natural and fluid way of enabling 3d modeling through human-machine interaction employing interactive sketching. While generating novel 3D shapes from the model using a 200-dimensional latent vector is a straightforward task, the main issue with using a 3DGAN for exploring ideas is that most of the dimensions of the input vector represent no meaning for a designer. Additionally, because of its large number of parameters, exploring the design space is a challenging endeavor. Consequently, the first challenge was to implement a way to capture and map design intentions from sketches and pair them with 3D models.

In the first iteration of the project, one of the drawbacks was the difficulty of finding paired sketch/model data to feed the model. In the case of hand sketches, the datasets available online are limited either in quality or diversity of the data. For example, it is possible to find large (50 million sketches) drawing datasets such as Google's Quickdraw dataset[192] available for use, however, the type and quality of the drawings are not useful for the purposes of this project[193]. In the case of 3D models, it is easy to find large and good quality datasets such as ShapeNet[194], ModelNet[195], Thingy 10k[196], Redwood-3DScan[197], Objectnet3D[198],

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[190] Pinochet, Diego, and Danhaive, Renaud, 'Generating shapes from sketches' for the course 6.198 Deep Learning practicum at MIT.

[191] For the class '4s42 Creative Machine Learning for Design' (Mueller, Caitlin. Spring 2020) I introduced changes to the pipeline, trying alternative deep 3D convolutional architectures, custom Datasets, and improvements in the sketch representations that resulted in better results in terms of 3D generation, stable training and diversity of results.

[192] https://github.com/googlecreativelab/quickdraw-dataset

[193] The Quickdraw-Dataset consists in 50 million sketches captured from a simple interface where fifteen million users were asked to draw using a mouse through the Quick, Draw! game https://quickdraw.withgoogle.com/. The qualities of the drawings are closer to what am infant would doodle, therefore are not useful for design purposes.

[194] https://shapenet.org/

[195] https://modelnet.cs.princeton.edu/

[196] https://ten-thousand-models.appspot.com/

[197] https://hkust-vgd.github.io/scanobjectnn/

[198] https://cvgl.stanford.edu/projects/objectnet3d/

ScanObjectNN[199], 3DFuture[200] , that are useful for training more accurate models. Therefore, one alternative for producing the necessary data to train and deploy the model was to generate it artificially.

Initially, a combination of ShapeNet and ModelNet was used to train a new 3D GAN in different categories (airplanes, chairs, tables, and guitars) to test the generation of paired sketch/model data (figure 29). Once trained, a 10,000 set of 200-dimensional latent vectors was sampled (in the domain[-1,1]). To cover in a more efficient way the high-dimensional design space, Latin Hypercube Sampling was employed. Afterwards, each vector was fed into the 3DGAN to generate voxelized representations that were sequentially rendered from a fixed perspective view (figure 30). Subsequently, to translate the 3D perspectives of the models obtained from the previous step, each 3D render was converted into sketch-like images using edge detection and B spline approximation techniques. Although the results did not accurately resemble the qualities of human drawings-resulting in lines that were too wiggly or noisy- this technique allowed the generation of a valuable dataset to test the mapping from sketches to latent vectors (figure 31).

Since the early versions of the project, the conversion from 3D models inferred from the 3DGAN to sketches involved, different techniques to get good quality results in terms of simplicity and appearance as close as possible to a human sketch. Using edge detection[201], the best technique to identify the different regions of a 3D model was using a specific light configuration for the rendering to separate the different faces of the model according to their orientation according to specific shades of gray. For example, it is possible to isolate all the faces with a color value of [7,7,7] that represent the seat of a chair or the roof of a house. After the different regions are identified and isolated, it is possible to filter small edges (associated with noise) and keep the more prominent contours for each color. Following this process, three different techniques were used for translating renderings into sketches: image-based, vector-based, and sequence-based representation.

The image-based representation of sketches consisted in extracting

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[199] https://hkust-vgd.github.io/scanobjectnn/

[200] https://tianchi.aliyun.com/specials/promotion/alibaba-3d-future?spm=5176.14208320.0.0.66293cf7asRnrR

[201] Canny edge detection (https://docs.opencv.org/4.x/da/d22/tutorial_py_canny.html) and Holistically-Nested Edge Detection (Xie, Saining, and Zhuowen Tu. “Holistically-nested edge detection.” In Proceedings of the IEEE international conference on computer vision, pp. 1395-1403. 2015.)

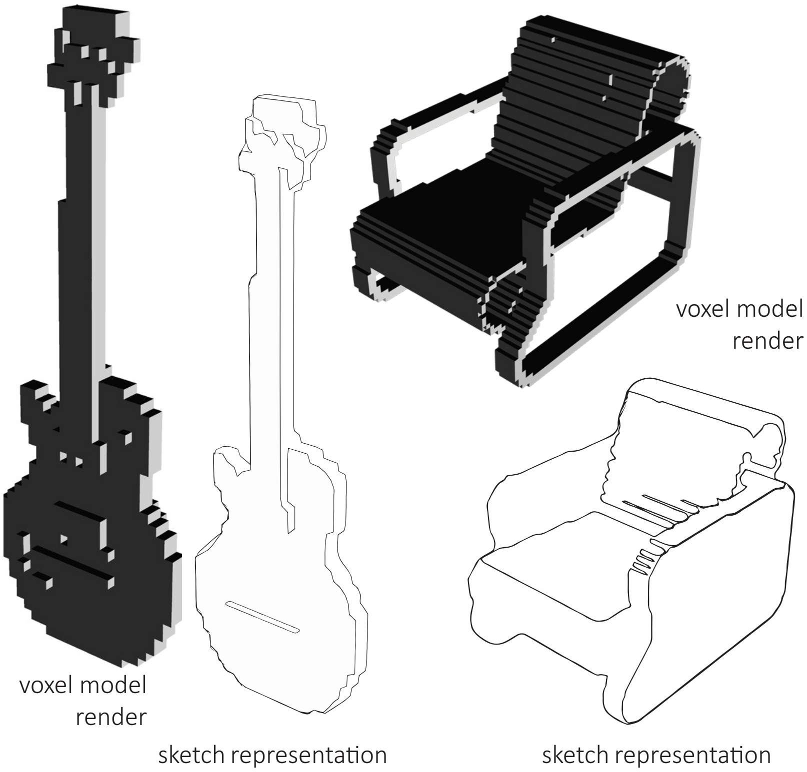

Figure 31
rendered and sketch
representations from models
source: author

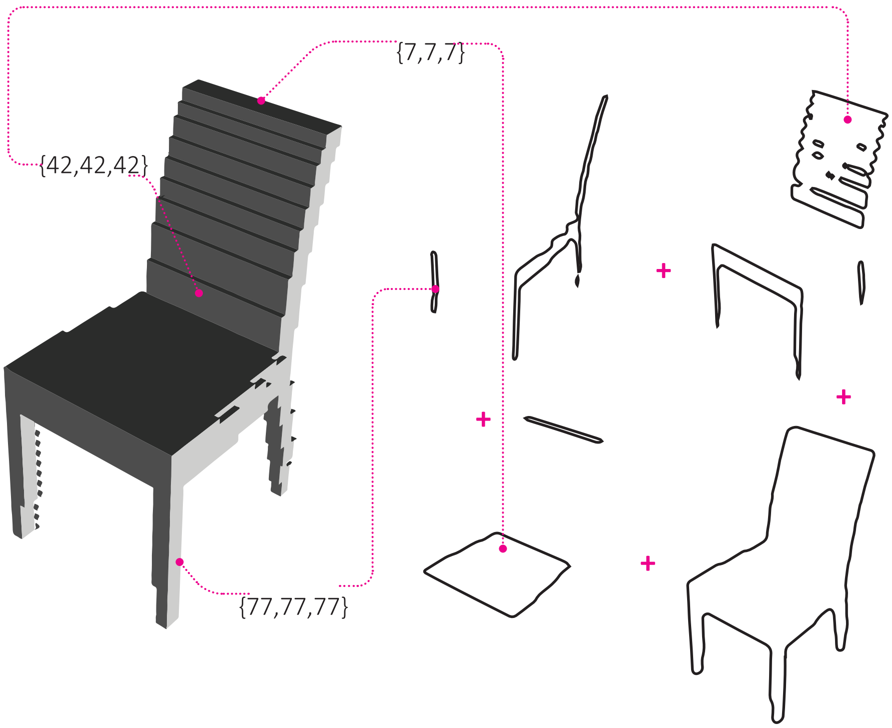

Figure 32
Vectorized Sketch
representation of a render
according to grayscale values
source: author

contours from the image and in filtering according to the width or height of the bounding rectangle containing the identified shapes. By filtering the smaller shapes, a cleaner sketch representation of a 3D render can be achieved. Each contour that is below the filtering threshold is discarded and the ones remaining are added to an image of 139x139 pixel resolution with a white canvas

The vector-based representation followed a more straightforward approach. Before identifying the region contours, blurring filters are added to the image to minimize artifacts that resulted from the voxel reconstruction. For each image region (front, side, top, full shape), only the biggest one is preserved and approximated by a B-Spline evaluated with 200 points. To maintain a consistent feature representation across the entire dataset, 4 contours are extracted from each image. This resulted in a 1600-feature representation of the whole image (400 features per contour)[202]. This approach resulted in a more straightforward and effective way to filter information and process good quality results that resembled human sketches (figure 32).

A sequence-based approach consisted of extracting temporal-like information from the identified contours. Following the ‘stroke-3’ format specified by the SKETCH-RNN implementation for working with the QUICKDRAW dataset, each stroke was represented as a list of coordinate offsets: Δx, Δy, and a binary value (0 or 1) that represents if the ‘pen’ is drawing. In this way, a more accurate representation of how a drawing is made could potentially lead to better prediction results. The process of conversion from contours to the ‘stroke-3’ format was achieved by an alternative to the vector based approach for generating the image, and converting the resulting contours to SVG format. Each rendered image is processed through a Photo-to-Sketch[203] model that uses a conditional GAN to generate human-like drawings in a sequential order. After generating the new sketch representation, each contour is processed and represented as a

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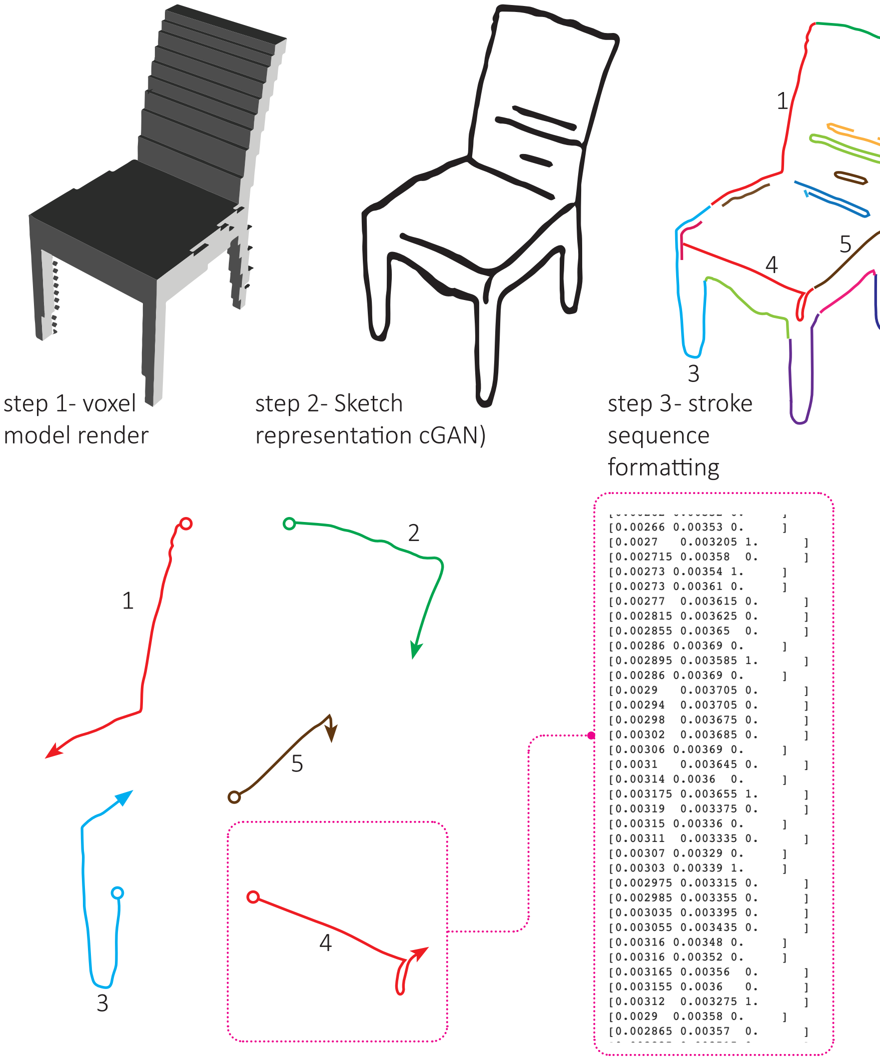
[202] Each coordinate of the contours was normalized by a process that consisted in subtracting the minimum X-coordinate and dividing it by the total width of the contour. This technique ensures that the size of the sketch remains irrelevant for prediction.

[203] Li, Mengtian, Zhe Lin, Radomír Měch, Ersin Yumer, and Deva Ramanan. “Photo-Sketching: Inferring Contour Drawings from Images.” In WACV, 2019.



step 1- voxel model render

step 2- Sketch representation cGAN)

step 3- stroke sequence formatting

```
[0.00266 0.00353 0.     ]
[0.0027   0.003205 1.       ]
[0.002715 0.00358  0.       ]
[0.00273 0.00354 1.     ]
[0.00273 0.00361 0.     ]
[0.00277  0.003615 0.       ]
[0.002815 0.003625 0.       ]
[0.002855 0.00365  0.       ]
[0.00286 0.00369 0.     ]
[0.002895 0.003585 1.       ]
[0.00286 0.00369 0.     ]
[0.0029   0.003705 0.       ]
[0.00294  0.003705 0.       ]
[0.00298  0.003675 0.       ]
[0.00302  0.003685 0.       ]
[0.00306 0.00369 0.     ]
[0.0031   0.003645 0.       ]
[0.00314 0.0036  0.     ]
[0.003175 0.003655 1.       ]
[0.00319  0.003375 0.       ]
[0.00315 0.00336 0.     ]
[0.00311  0.003335 0.       ]
[0.00307 0.00329 0.     ]
[0.00303 0.00339 1.     ]
[0.002975 0.003315 0.       ]
[0.002985 0.003355 0.       ]
[0.003035 0.003395 0.       ]
[0.003055 0.003435 0.       ]
[0.00316 0.00348 0.     ]
[0.00316 0.00352 0.     ]
[0.003165 0.00356  0.       ]
[0.003155 0.0036   0.       ]
[0.00312  0.003275 1.       ]
[0.0029  0.00358 0.     ]
[0.002865 0.00357  0.       ]
```

Figure 33
Sequence-based approach for sketch representations.
Source: author

sequence of strokes. In this way, each contour is now represented by a sequence of points closer to how a sketch not only looks but how it is really generated (figure 33).

3.12.3 Learning the mapping

Once data is generated, three approaches were pursued to create a model that could predict a latent vector for the 3DGAN generation based on a sketch input. The first strategy was based on the image-based representation, the second on the vector-based representation, and the third one on the sequence-based representation.

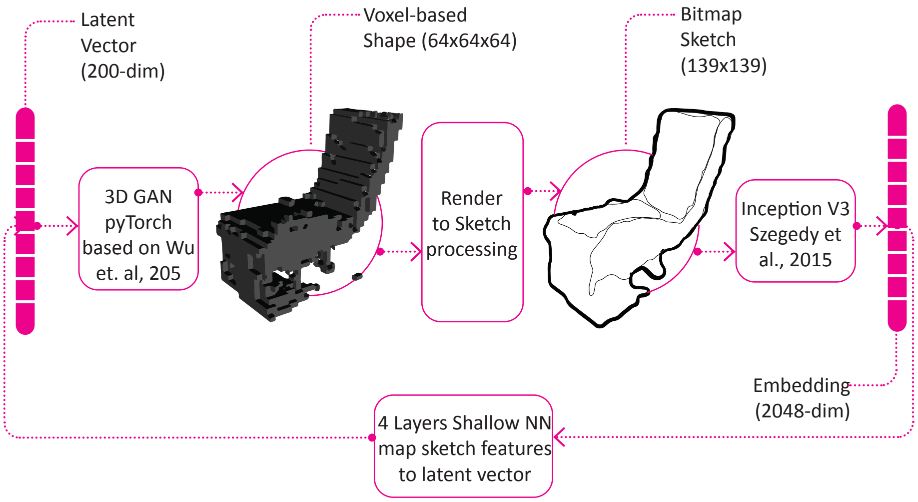


Figure 34
Pipeline for embedding sketches using a pretrained CNN (Inception-v3)
Source: author

A pre-trained model on the ImageNet dataset[204] was used to compute embeddings for each layer. Instead of building a Convolutional Neural Network (CNN) from scratch, Inception-v3 model without the prediction layer was used to retain the bottleneck features[205] (2048-dimensional embedding) for each sketch. A shallow neural network (4 layers deep) was used to learn the mapping between the embedded drawing features and the latent vectors (figure 34). This approach presented problems as the network showed signs of collapse post-training on the mean of the training latent vectors. This collapse problem made the network predict only one value no matter the input drawing, even after tuning hyperparameters or adding other improvements to the network. The image-based representation failed potentially because of two reasons. First, Inception-V3 embeddings result in a considerable loss of information compared to the original

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204 Szegedy, Christian, Vincent Vanhoucke, Sergey Ioffe, Jon Shlens, and Zbigniew Wojna. "Rethinking the inception architecture for computer vision." In Proceedings of the IEEE conference on computer vision and pattern recognition, pp. 2818-2826. 2016.

205 The bottleneck features correspond to the last activation maps before the fully connected layers. This allows performing transfer learning for customized image classification.

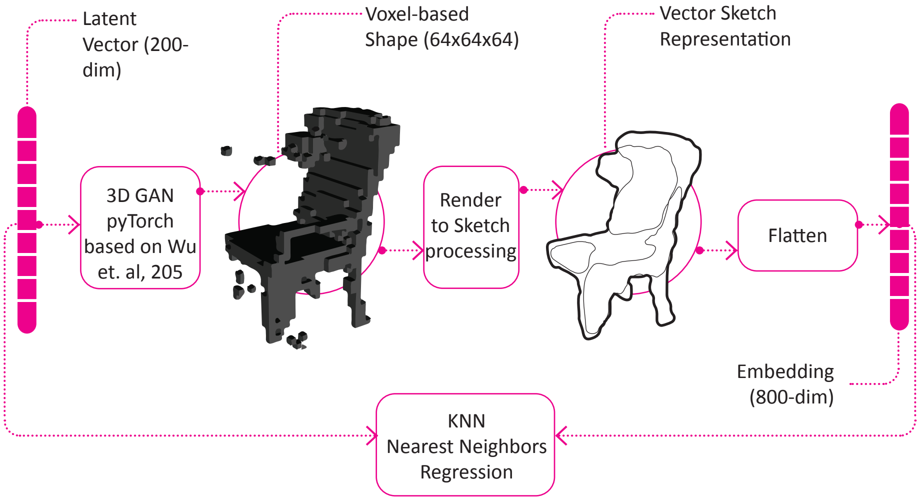

Figure 35
Vector-based approach for sketch representations.
Source: author

sketch. Second, similar images might generate many different latent vectors, making a parametric model approach very hard to train.

A more successful and straightforward implementation considered using vector representations and K-nearest neighbor for predictions. Identifying drawings in the dataset that are close (in terms of Euclidian distance) to the curves from a test sketch became a more practical and intuitive approach (figure 35). Using a non-parametric approach resulted in better performance than the first implementation while avoiding mean collapse. Through cross-validation, the best number of neighbors was 5, and the contribution of each neighbor was weighted inversely proportionally to the distance to the input test sketch (figure 36).

The final approach considered the use of Sketch RNN, a Recurrent Neural Network that works as a Sequence-toSequence variational Autoencoder model. Although the vector-based approach showed a good performance from a qualitative perspective, improvements were needed to improve data representation. Moving to a representation unrestrained in length (number of contours) allows for the inclusion of sequential data for a more accurate representation of sketches in time. Understanding sketch data as a sequence of actions as traces

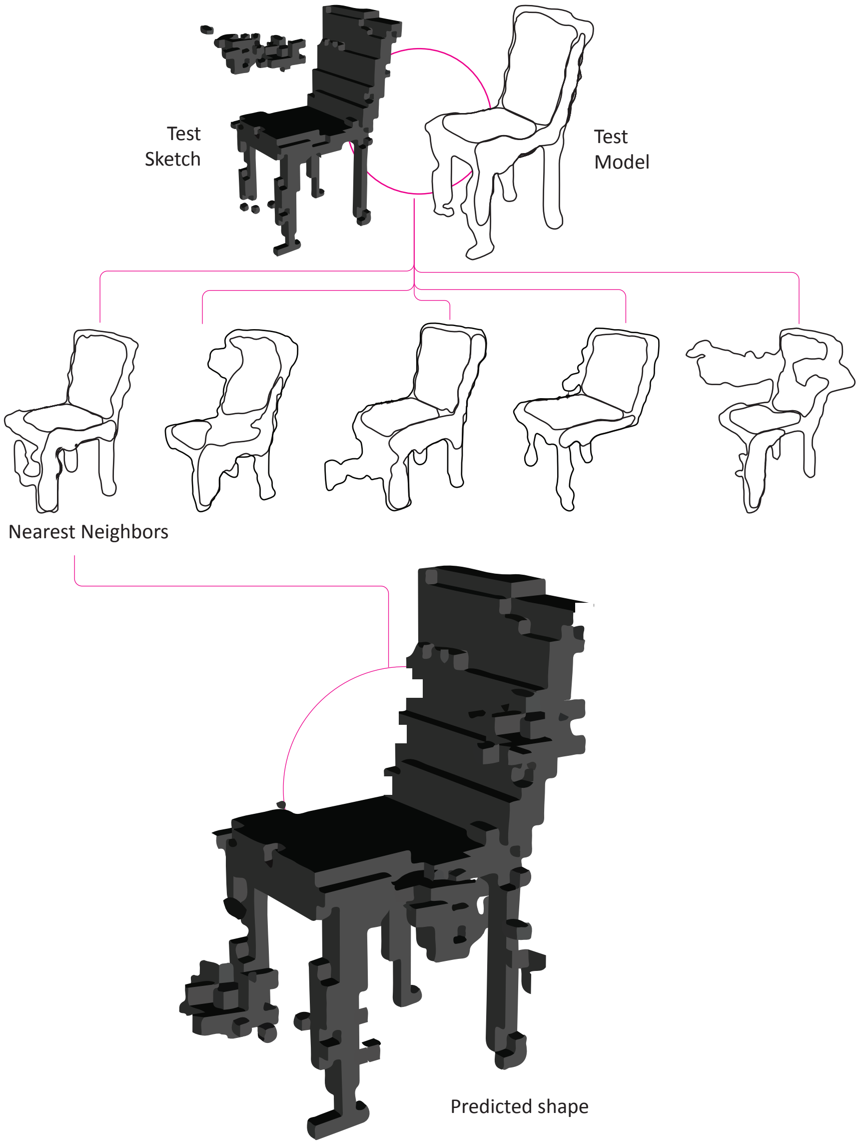

Figure 36
KNN implementation diagram
Source: author

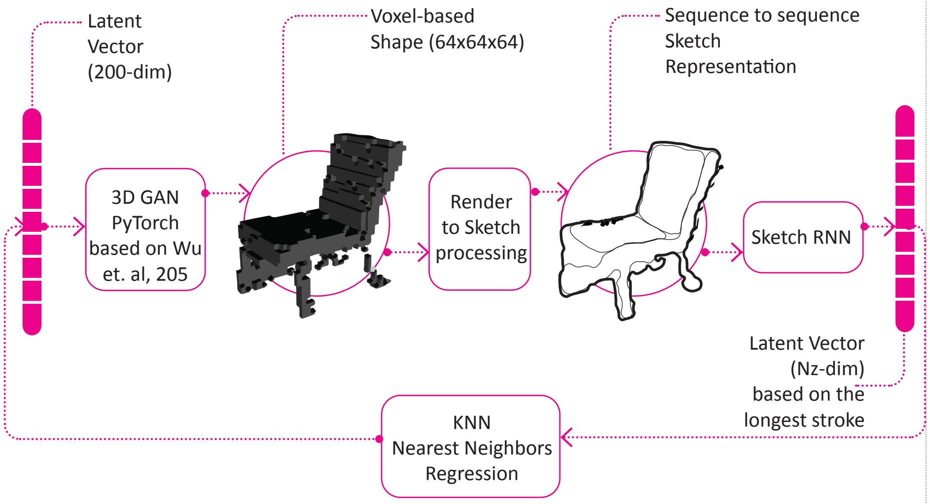

Figure 37
Vector-based approach for sketch representations.
Source: author

allows for a better representation of how sketches are generated over time. Nevertheless, converting synthetic data (rendered image data) into a sequence of traces in the format resulted in a complex endeavor. How people sketch varies in myriad ways, as some people focus more on general shapes and afterwards go into details, or vice-versa. For the purpose of this project, the way data was generated from renderings comprised randomizing either a top-down (bigger traces to more minor details) or a bottom-up (going from details to general traces) fashion. The pipeline (figure 37) proved to work surprisingly well in terms of quality. Nevertheless, for quick and simple sketches and basic 3D models, it didn't show significant improvement over the simple vector-based approach while requiring a more complex process to train. This approach showed potential for pairing sketches with an unlimited amount of traces with more detailed 3d representations.

3.12.4 Capturing user's intentions as gestures

Whereas generating the training data from the 3DGAN architecture and image processing functions represented a challenging endeavor, capturing human-drawn sketches involves a different process.

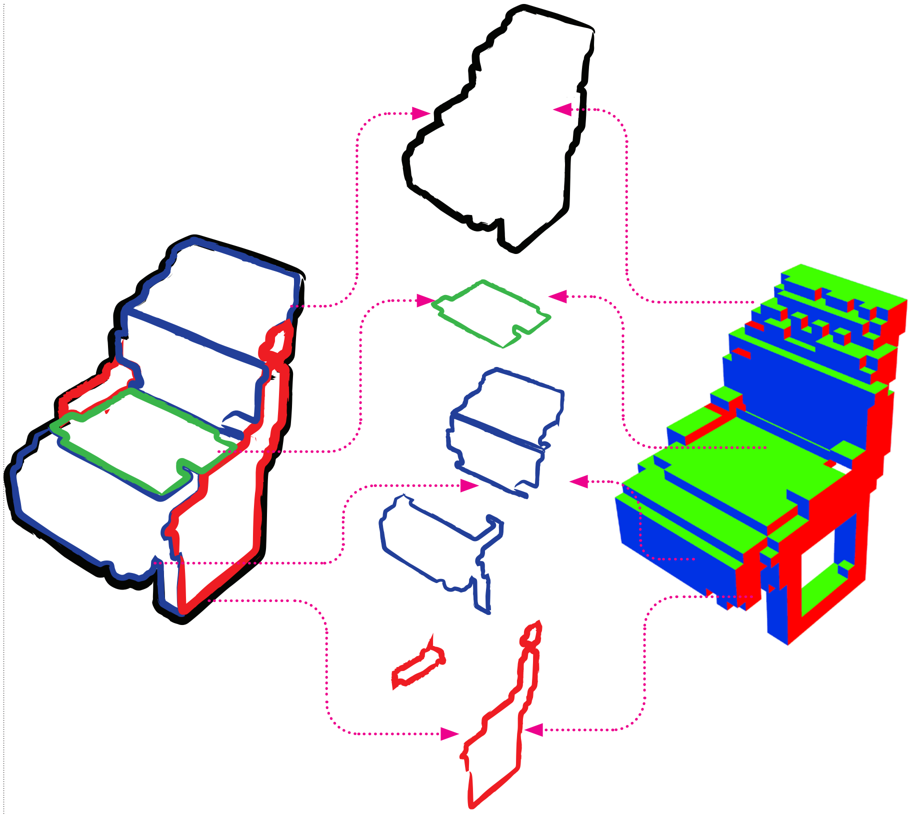

Figure 38
Color traces according to orientation
Source: author

Describing and understanding the spatial structure of a drawing requires more complex models (such as the sequential-based approach described before). Thus, by using specific colors to define the same regions detected in the vector-based approach (front, side, top, full shape), it was possible to establish a rule that could help a better understanding of the spatial qualities of drawings concerning its machine-generated counterpart (figure 38). Specifically, users use three colors to construct a drawing while indicating spatial qualities according to these colors. As an example, green is used for the horizontal surfaces, red for faces oriented to the right of the image, and blue for the faces oriented to the left of the image. The color black is reserved for specifying general details (such as the outline of a drawn shape and has no specific assignment in terms of spatial qualities. For each color the user draws, only the most prominent contour is selected, allowing the translation of the human-drawn sketches into an identical format as the one generated from rendered images. As a result, each user's drawing is converted into the 1600-feature format in the dataset[206].

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[206] 200 points (2 coordinates) per contour (4 contours) or 1600 features.

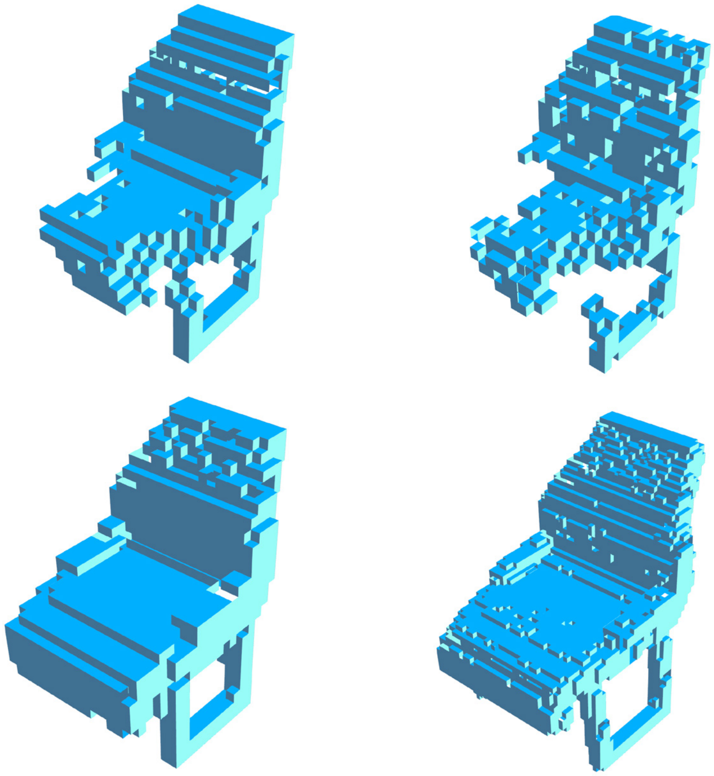

Figure 39
Above. sample from the 64x64 voxels Model trained on SHAPENET (2019)

Below.samples from the 64x64 voxels (left) and 128x128 voxels (right) model trained on custom 3D data.
Source: author

3.12.5 Training the model

After implementing all the parts of the project, two significant challenges that were present since the beginning of the project were, on the one hand, the difficulty of training a better resolution 3D GAN model and, on the other hand, the difficulty of training on a wide variety of data. By introducing changes to the original model architecture by tuning hyperparameters and using more efficient dataset processing techniques, it was possible to train a more precise model locally. Using two 24 GB NVIDIA RTX 3900, it was possible to train an improved 3D GAN that yields better resolution models with fewer artifacts. (figure 39)

Because most of the implementations for 3D generation are tested on generic datasets such as SHAPENET, the importance of generating custom data is crucial for design endeavors. In the case of this project, the model was trained on different custom datasets created from an automated Grasshopper 3D definition (figure 40) Each of the dataset categories were created from different parametric models.

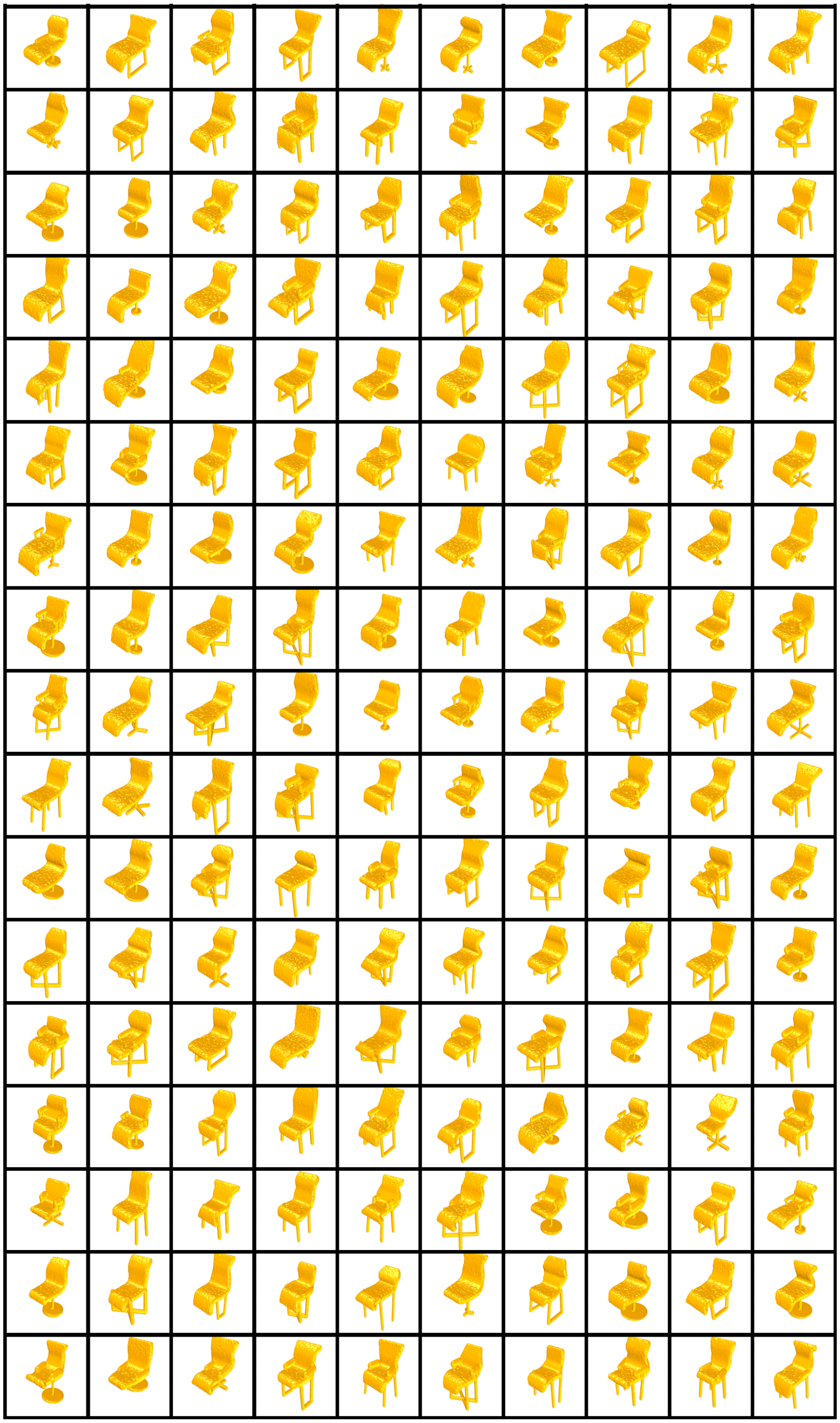

Figure 40
170 Samples from a custom mesh dataset produced in Grasshopper
Source: author

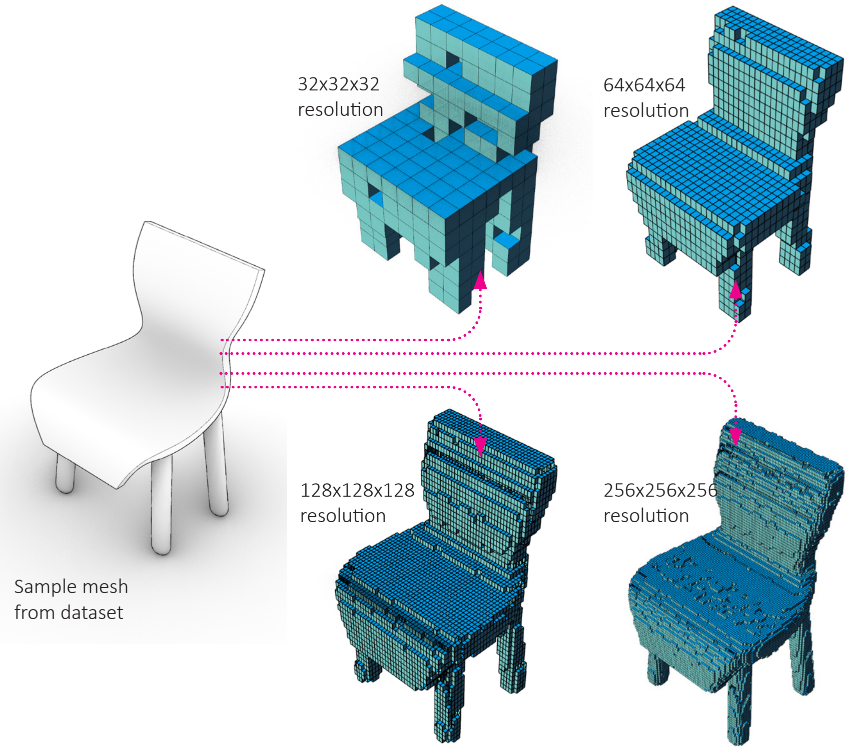

Figure 41
Mesh to Binvox translation.
Source: author

Using Latin Hypercube sampling, it was possible to generate a script for efficient design space sampling and to generate enough data for an efficient training process. The grasshopper definition used a custom python script for encoding each model into a binary voxel format[207]. In each sampling step, models are generated using different parameters and encoded into BINVOX[208] format for readability (figure 41). Additionally, moving to a different deep learning framework (Tensorflow to PyTorch), applying modifications to the architecture, and tuning the model's hyperparameters became an easier task. Adjusting different learning rates for the Discriminator and the Generator, respectively, and using Leaky RELU as the activation function, the training became more stable, and it was possible to avoid model collapse. Each category was trained using 30,000 models with a resolution of 64x64x64 voxels over 1000 epochs.

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[207] The Procedure for creating a custom dataset can be found at https://youtu.be/QoJd1VDeV8Ein which I go step by step into the process of batch generating custom 3D models from scratch.

[208] Nooruddin, Fakir S., και Greg Turk. 'Simplification and Repair of Polygonal Models Using Volumetric Techniques'. IEEE Transactions on Visualization and Computer Graphics 9, τχ. 2 (2003): 191–205.Min, Patrick. 'binvox', 2004- 2019.

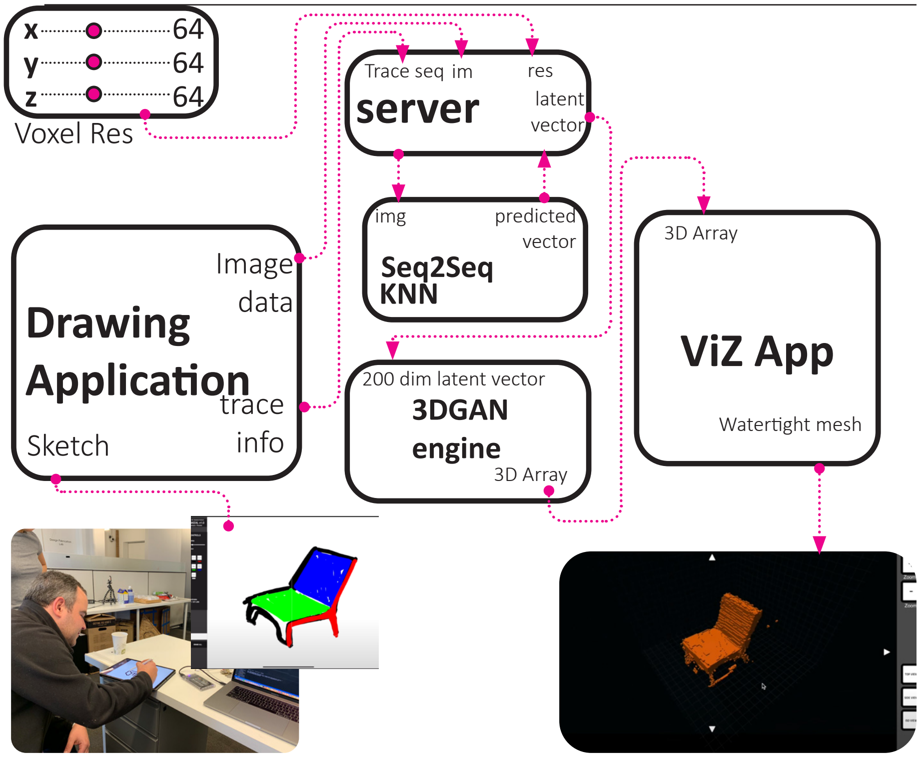

Figure 42
Client-server
Pipeline implementation
Source: author

3.12.6 Full pipeline implementation

Once the prediction system was finalized, the implementation of the project consisted of a modular client-server configuration constructed in three parts: the server, the drawing application, and the visualization application (figure 42). The server application was configured using a Web Sockets server hosted in a cloud service[209] to allow communication between the different devices used in the project. The server is a simple node.js program that allows the exchange of information between a drawing application, the inference model, and the visualization program.

A drawing application was developed in Unity 3D and deployed in an IPAD PRO 2021 model. The drawing application was written in C# using Unity3D game engine and built for iOS. I used a 2020 iPad Pro tablet as the primary device for the project. The drawing application implements a ray casting system over a rendered texture to generate the 2D pixel information. Once the user finished a sketch, by pushing the ‘predict’ button, the app transformed the render texture into

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[209] The server was hosted using the online service http://glitch.com

an array of RGBA values sent as a JSON object through Web sockets communication to the Glitch Server. The server receives the JSON object and processes the pixel information in our system to be transmitted to the prediction engine. Consequently, the prediction engine receives the information from the web server, encodes it, and predicts the latent vector using the prediction model. Finally, from the latent vector predicted, a 64x64x64 array is generated and sent as a JSON object to the third client to visualize the 3D Model. The C# visualization application comprises a 3D navigator that renders a procedural watertight mesh from the array (figure 43). A procedural mesh algorithm is used to achieve speed and fluidity in the visualization and avoid rendering occluded meshes. Because the application uses Unity 3D engine for development, the visualization engine can be built and deployed either as a WebGL application- and can thus be hosted on any server- or mobile devices as an application for iOS or Android OS.

3.13. Discussion and future steps.

The implementation of SKeXL proved that machine learning could be used in original ways to extend and keep the creative process active during 3D modeling. By enabling natural ways to interact with a generative system, the project showed a path to extend ideation by integrating human actions and the generative power of machine learning models toward developing ideas. As a proof of concept, the project pursued enabling technology-mediated design processes that could reframe the computational design trichotomy by the unfolding of ideas in real time. In this case, considering the development of a 3D model as the final goal instead of a representation, the project attempted to situate human action as gestures as the primary driver of creation as well as the interactivity of the process as the medium for exploration and originality.

In terms of results, the project implementation proved to be successful in all of its iterations. Since the development of the first version of the project in 2018, it has been possible to improve the system's accuracy by working on the primary limitations detected in the early implementations. Among these initial challenges, it Is possible to mention improvements in the sketch representations, availability and quality of the data, and the use of alternative techniques for 3D model generation. Furthermore, moving to a better sequential vector-based model, it was possible to generate more accurate results for

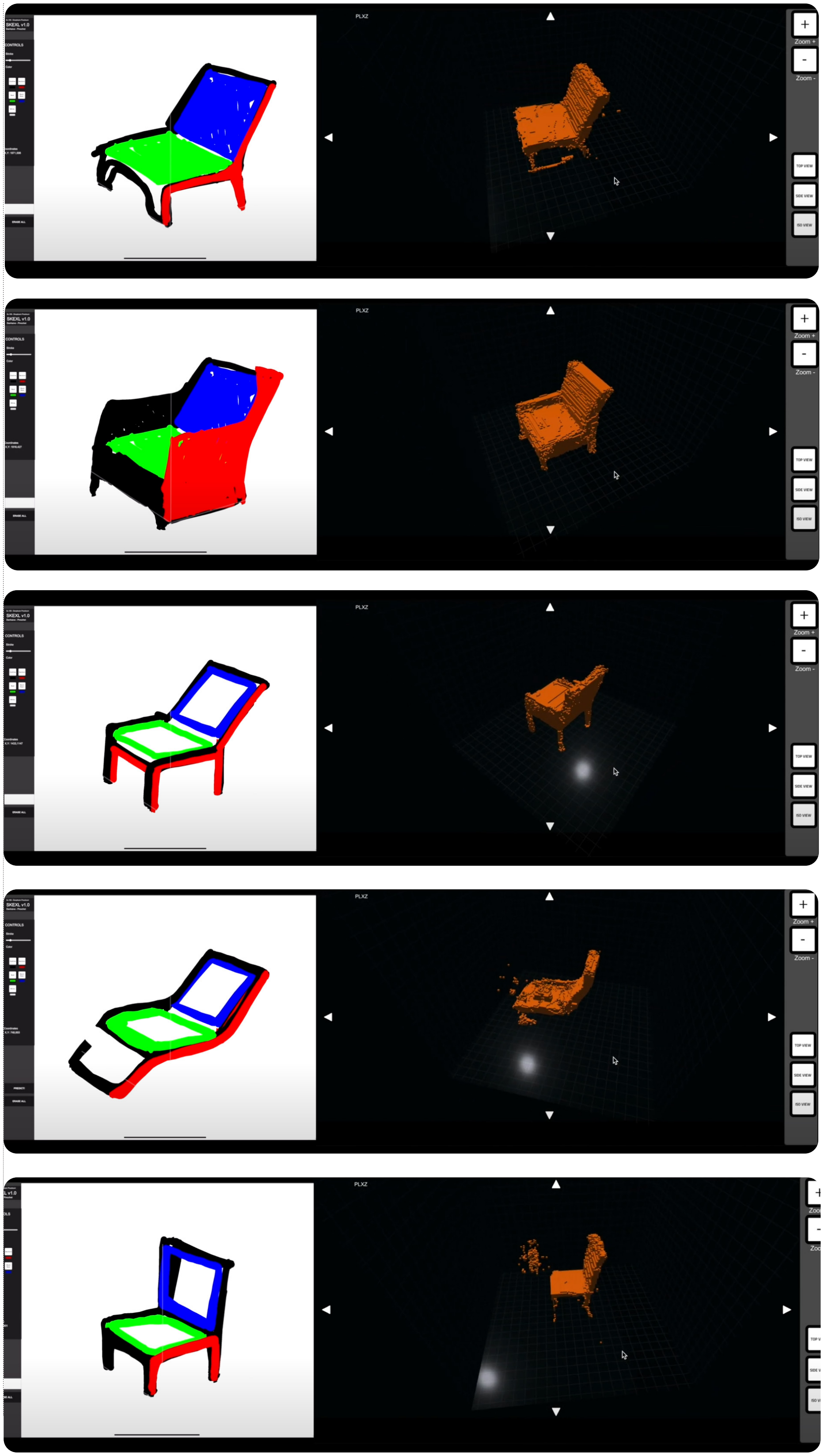

Figure 43
SkeXL interface
Source: author

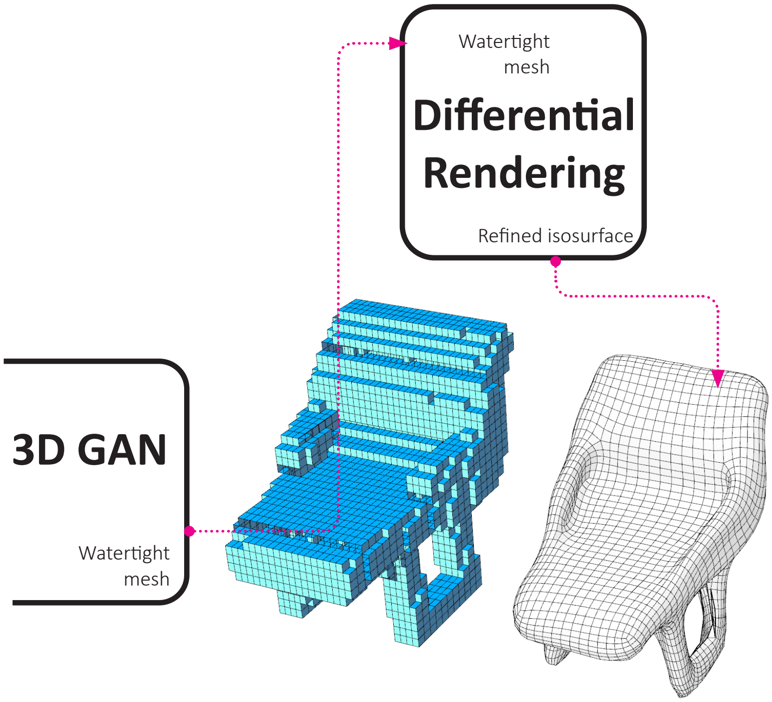

Figure 44
Differential Rendering optimization added to the 3D Gan resulting shape
Source: author

the prediction of 3D models. At the same time, generating synthetic data in a voxelized format helped expand the possible outcomes of the system by generating different models beyond chairs or any of the categories from ShapeNet or ModelNet datasets. Additionally, using faster and more capable hardware expedited the process of training, overcoming initial limitations not only about finding usable data but also about how to train it efficiently in terms of time and cost. Although most of the examples show the generation of 3D models of chairs (to keep the consistency with the first version of the project), the model can be trained on any category of 3D models.

Finally, alternative methods for a 3D generation were tested for this project. Moving from a voxelized representation of 3D models from a 3DGAN, alternative mesh generation techniques were tested. Using an optimization process based on a differential silhouette rendering to generate solid, more accurate 3DModels, it was possible to add promising modifications to the original system (figure 44). Adding a differential rendering at the final step of the

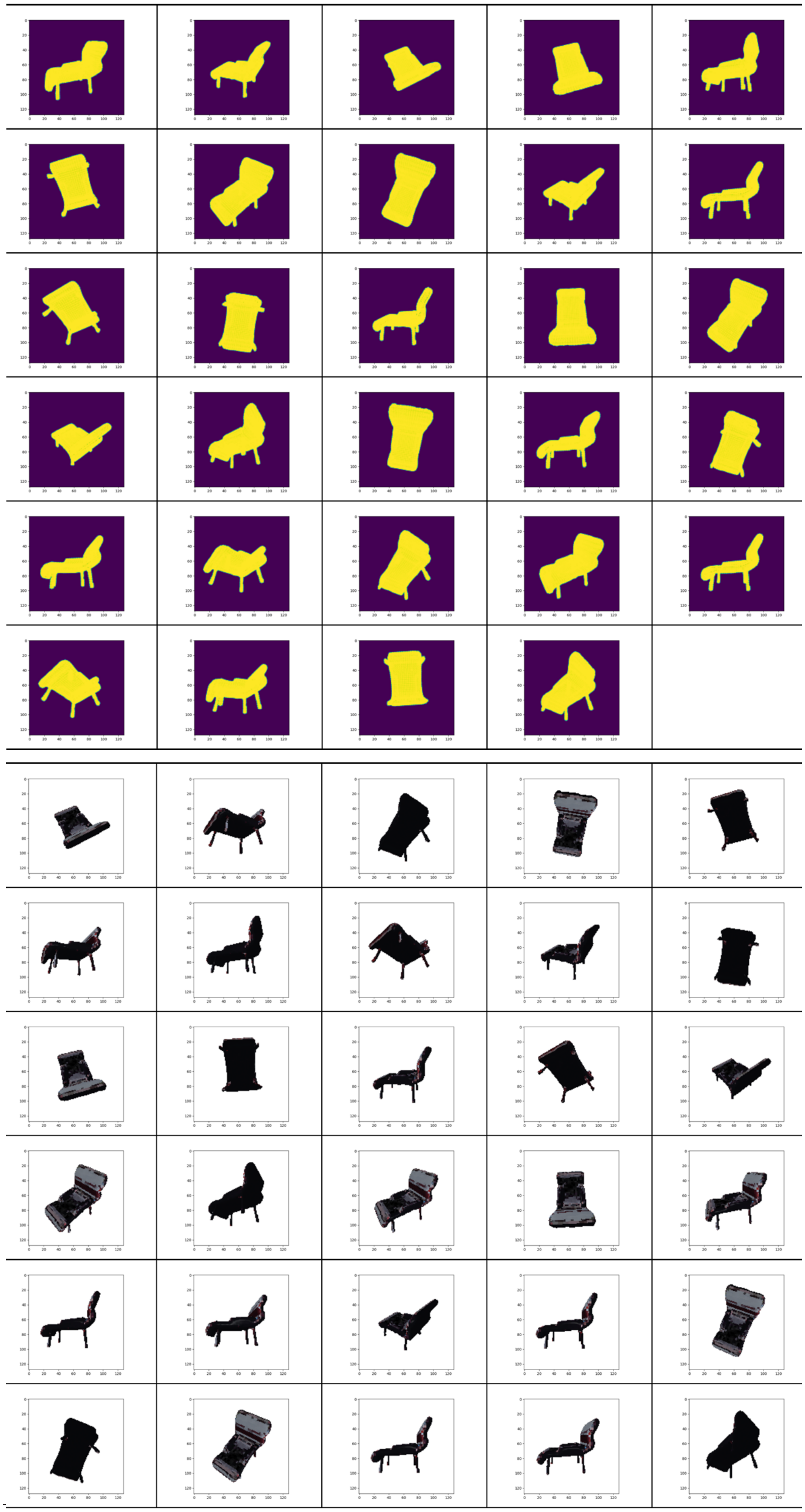

Figure 45
Image captures for differential rendering calculation
Source: author

pipeline allowed the addition of a final step for refining the output meshes and avoiding voxelized or noisy models reconstructed via iso surface reconstruction. Once a model is predicted by the system, the predicted 3D mesh is processed using PyTorch 3D to generate a small dataset (20 to 30 images) from different camera positions (figure 45). The images are later segmented by calculating the probability of each pixel belonging either to the mesh or the background. After the silhouette dataset is created, each image is used to predict a mesh by deforming a Mesh sphere into the voxelized predicted shape as depicted in figure 46. The optimization learns to deform and optimize a sphere mesh by learning the vertex offsets as the predicted mesh silhouette gets closer to the target silhouette at each optimization step. The optimization loop refines the predicted mesh to match the silhouettes extracted from the original voxelized model.

Beyond the technical implementation details, it is important to discuss how this project is inserted inside the main discussion of this dissertation. Pairing sketching with real-time 3D modeling generation presents many challenges in terms of connecting unique trace sequences to a standardized dataset of 3D models. Whereas in traditional 3D modeling workflows a 3D shape is in general the direct result of combining standard parameterized operations such as extruding, trimming, etc. this prototype proposes an atypical approach in which the machine acts as a sort of counterpart of the designer. This implies interesting topics that are further developed in the following chapters.

In response to the inquiry, "Is it feasible to utilize machine learning to extract design intentions from sketches and create 3D shapes?" I posit that indeed it is. The proposed mechanism, in which the machine acts as an agent capable of interpreting gestured traces as three-dimensional shapes, serves not only as a means of capturing design intentions but also as a tool for bidirectional communication between humans and machines. Furthermore, can the application of machine learning reframe the generation of 3D models in a more embodied fashion? The answer remains affirmative.

This undertaking addresses the theme of language as a communication mechanism, in which unique trace sequences function as the designers' language, deciphered as 3D models that serve as the machine's language. As such, this project endeavors to reframe 3D

Figure 46
Mesh optimization process
using Differential Rendering
Source: author

modeling by employing the most prevalent and powerful mechanism employed by designers to conceptualize and convey design concepts.

Lastly, assuming that sketches and 3D models represent the objects of design, can we ideate and explore ideas within a computer without representing them? This project blurs the boundaries between the components of the trichotomy by enabling sketching as the *sine qua non* mechanism for designing and ideation. Sketches are not regarded as representations serving as prescriptive manufacturing instructions but as a gestural thinking mechanism, the methods utilized by designers to generate 3D information can be reformulated. In this instance, designers engage in a dialogue in which their concepts are communicated and expressed through their own gestures and not by standardized, pre-compiled operations. Nevertheless, it is important to acknowledge that additional work is necessary to investigate how imprecisions and irregularities of traces impact the resulting 3D shape. That is, what is the machine's ability to interpret the peculiarities of traces as parts of a cohesive whole.

Beyond

REPRESENTATION:

Human – Machine interactions

4

4.1 Building the path for Interactive Design and Making

In this chapter, I delve into the rich and nuanced discourse surrounding the role of representation in contemporary design. I begin by examining the historical function of representation as a conduit for abstract concepts and rationalized plans. Building upon this foundation, I argue that many technological advancements in design have focused on facilitating the representation of designs rather than the ideation and conceptualization of them. Furthermore, I delve into the complex and dynamic nature of representation, exploring its various incarnations as a design, an execution plan, and a preliminary representation for further elaboration. I also expand the discussion by contrasting the traditional role of representation in architecture as a “freezing” of ideas with the role of sketching and model-making as “unfolding” mechanisms for exploration, keeping the creative process alive throughout the design process. Given this context, I pose the question: Can we harness the power of technology to transform computers into active thinking tools rather than mere representational devices, bridging the gap between ideas and construction? What steps are necessary to overcome the boundaries between ideas, representations, and physical objects, breaking free from the constraints of the current computational design paradigm?

Following the discussion about design as an active process, I expand it around the topic of interaction and design intelligence as a process of meaningful exchange among the participants of a design. I explore the fluid and contingent nature of design and the possibilities that arise from incorporating interactive design systems through computational techniques. Additionally, I delve into the concepts of cybernetics and constructivism to provide a framework for understanding the interactive and collaborative aspects of mutual intelligibility and the role of computation as a collective effort that can provide the foundation for implementing interactive design systems. I argue that design, as a recursive endeavor, engenders not only objects but behaviors as stable interactions to create, from an infinite continuum of possibilities, identifiable entities as designs. Thus, considering machines as non-trivial devices, I argue that it is possible to embrace interactivity and account for the non-linearity of interactions that can arise in a design process.

The theoretical discussion in this chapter is enriched by the introduction of two projects that probe into the ideas of interaction and mutual intelligibility. First, I introduce NNN (Network of Neural Networks), a research project developed as a researcher in the Design Intelligence Lab at MIT. In this research, I introduced my work on human-machine interactive systems based on gestures using a visual programming tool to chain different machine learning models toward implmenting interaction with physical systems. Through this work, I present software and hardware systems that were developed around the topics discussed in this chapter related to conversation, computation as a collective endeavor (not only between two or more humans but with tools.) I present interactive systems for emergent creation beyond intermediate representations that were developed using the NNN system.

I then delve further into the topic of interactivity by examining the significance of gestures as a means of communication and thought. In answer to the question of why gestures are essential, I argue that while much of the theory in the field of cognitive science focuses on the functional relationship between action and perception, in this research, the importance of gestures lies in their ability to generate unique outcomes through their ability to shape motion for creative purposes. To illustrate this concept, I introduce *"Deep Enactions,"* a first prototype of the Computational Gestural Making framework that aims to integrate computational systems for human-machine interaction through the use of different machine learning models for computer vision, gesture detection, and intelligent robotic motion.

I developed “Deep Enactions“ as a first attempt to implement a multimodal body-centric approach to interactive fabrication aimed to test the conversational aspects of a design framework focusing in the development of a gesture language as the primarly mode of communication. To do so, I first developed a gesture recognition system that aims to establish fluid communication with a machine based on three types of gestures: symbolic, exploratory, and sequential. Second, I developed a system for machine vision to detect, recognize and calculate physical objects in space. Third, I developed a system for robotic motion system using path-planning algorithms for collision-free machine movement. Finally, I integrate those three modules into a system for human-robot interaction in real-time based on gestures The ultimate goal of this implementation is to establish a framework for interactive design that is based on human-robotic interaction through the use of gestures as a mechanism for generating unique and original designs.

4.2 Object vs. process: The unstable historical role of representation in Design

Following the discussion from the previous chapter around the technology’s mediating role in the creation, development, and externalization of design ideas, it becomes crucial to tackle the role and purpose of representation in design. As one of the components of the computational design trichotomy, it is paramount for this research to discuss the role of representation and its relation to the development of new designs. From a historical point of view, it is possible to argue that since the invention of architectural design in the Renaissance, the role of representation has experienced several transformations according to society’s technological developments and the increasing complexity of projects. Representation has been the vessel by which architects, engineers, and designers, in general, have formalized, as Carpo argued[210], a notational system to share project information while simultaneously detaching ideas from representation and construction. In that scenario, representation became a vessel for communication between different actors that

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[210] As Mario Carpo suggests, the invention of a notational system allowed Alberti to develop a way to represent designs completely by specifying measurements and instructions for constructing a building. Carpo, Mario. 2011. The alphabet and the algorithm. Page 71. Cambridge, Mass: MIT Press.

reinforced the creation of design workflows in which one designs (thinks), another one represents (rationalizes), and someone else builds (executes.) The representation of a design became something different from the act of designing itself, turning into a communication device rather than a thinking device. For example, the nature of architectural drawings as a prescriptive tool for production became something different from sketching as a thinking device[211]. In that regard, the role of representation has been shaped by the emergence of new tools and technologies to represent designs. Historically, the development of tools and technologies played a crucial role in the formalization of design representations, reinforcing its productive role. The quest for a system of abstraction, precision, and efficiency pushed technological developments that shaped how things were thought of, represented, and constructed. The point stressed here is that computers and technology, in general, have been oriented to aid with those representational parts of a design and not so much on the thinking part of it.

The increasing role of representation as a tool for production and communication reinforced the increasing objectification of design throughout history. The rationalization of ideas into a drawing or a model became the very purpose of representation as both prospective (a plan) and retrospective (analysis) devices for designs. Consequently, the mechanisms to achieve abstraction and precision of the represented design turned into a sequence of operations related to the structure and construction of a drawing or a model and not to the ideation or thinking process of design. This assertion resonates with the famous quote from Ivan Sutherland about Computer Aided Design in which he pointed out that “the need to describe the structure of a drawing to the computer makes computer drawings sufficiently different from paper and pencil drawings so as to be an entirely kind of activity.”[212] Sutherland made two crucial observations about using a computer-aided design that illustrate the

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[211] A similar distinction was made by Alberti in De Re Aedificatoria, in which he pointed out the differences between the drawings of a painter and the architect. To Alberti, while a painter´s drawings represent qualities to emphasize appearance, the architect’s drawings are precise and are based on controllable measures. See Perez-Gomez, Alberto. Architectural representation and the perspective hinge. Cambridge: MIT Press, 1997. Prelude, page 27.

[212] Sutherland, Ivan “Structure in drawings and the hidden surface problem”In Reflections on Computer Aids to Design and Architecture, ed. Nicholas Negroponte. 17-26. New York; Petrocelli/Charter, 1975

problem of representation addressed in this chapter regarding aspects of creativity or the development of an idea. First, he pointed out that the initial excitement around the use of computer-aided drafting systems was due to their capacity to be, on the one hand, precise and, on the other hand, efficient[213]. Secondly, he referred to the inherent differences in how computer drawings and sketches are generated. Whereas the draftsman is concerned with the evolution of the design represented by 'dirty marks on paper,' the 'programmer' of a computer-generated drawing is concerned with the objects' topological and geometrical structures. He remarked that in the case of a computer drawing, 'it has properties quite independent of the properties of the object it is describing.'[214]

Beyond the hardware and software limitations at the time, Sutherland remarked that the power of CAD is its potential to become a computerized description of a building being designed instead of a tool to produce graphical outputs[215]. Sutherland's hopes and aspirations about CAD became a reality as, today, the primary use of computerized systems in design is oriented to represent, rationalize, optimize, and communicate a design. Although this has been debated for decades, if we analyze the production of designs through the use of technologies under the perspective of computational trichotomy, we can observe that the creative aspects of the process remain as peripheral stages. The advent of personal computation and fabrication machines empowered new discourses about, for example, designers regaining complete control of the creative process by centralizing information and processes (knowledge) inside a computer or, more recently, the discourse around augmented creativity using machine learning (as a form of "prosthetic imagination"). Mitchell and Mccullough's motto, "new tools and new thinking go together,"[216] clashes with their claim that "with the computer comes to a further disengagement of ideas from matter,"[217] strengthening the role of computers as vessels to expedite production-via automation-instead of vessels to develop creative ideas.

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[213] Sutherland wrote "... there were several very promising aspects which excited all observers... Straight lines were straight and circles were circular with very little effort on the part of the draftsman". Ibid. P,16

[214] Ibid

[215] He refers to the power of CAD beyond the production of an image as a tool capable of producing quantity takeoffs, a model collaboration between designers, an analytical tool among other characteristics

[216] Mitchelll, William J., and Malcom McCullough. 1995. Digital design media. New York: Van Nostrand Reinhold. p.422

[217] Ibid.

The role of representation in design has been unstable and in constant change. Since the invention of architectural design and the emergence of tools developed to extract ideas from the designer's mind to be constructed by others, the nature of how ideas are thought of and developed has remained almost the same. Entrenched in the middle of a design workflow between the construction of ideas and the construction of designs, representational methods have changed from developing construction plans and specifications to developing complex 'digital twins' to eliminate inconsistencies and maintain fidelity to the original idea. In the case of CAD, it is possible to see how its emergence and early implementations resonated with new theories about the human and the artificial mind and the idea of representing and structuring thought. In that regard, much of the Design theory that emerged in the 60s and 70s aimed to expand the capabilities of computers to aid design based on the tools of artificial intelligence and operations research[218]. Moreover, Simon wrote about the quest to make design theory explicit by introducing computers into the process. To Simon, design consisted of giving structure to an ambiguous solution by employing a problem-solving logic. In his perspective, design is a 'searching process' within the fixed solution space of a design problem to arrive at a satisfactory answer.

According to Simon, because designers can arrive at different solutions to a problem, the heuristics to find a 'good enough' solution instead of an optimal one was at the core of what the 'design is.' To that end, Simon's view of design as a goal-oriented process involved the symbolic representation not only of design but the process of thought. In that sense, Simon's 'logic of design' determined a decisive view of designing as goal-oriented activity in which the 'satisfactory answer' to a design problem was concerned with the prospective (a goal), prescriptive (a plan,) and evaluative (analysis) stages of the process[219].In his view, by generating a structure of thought about a problem and making a process explicit, designers can search for alternatives and come up with a final design built 'from a sequence of component actions.'[220] In that sense,

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[218] Herbert A. Simon, "The Science of Design: Creating the Artificial," in The Sciences of the Artificial , MIT Press, 1996, pp.114.

[219] See Visser, Willemien. The Cognitive Artifacts of Designing. Mahwah, N.J: L. Erlbaum Associates, 2006. Print.

[220] Herbert A. Simon, "The Science of Design: Creating the Artificial," in The Sciences of the Artificial, MIT Press, 1996, pp.114.

Simon highlighted the crucial role of representation in his design theory, in which solving a problem was equal to representing it to make the solution transparent[221]. Similarly, Amarel argued in 1966 that creativity -when using computers- was inherently a problem of representation, evaluation, and efficient search[222]. He argued -explicitly leaving aside the phenomenological or 'unexplainable' dimension of creativity- that a computational model for creativity needed to be efficiently represented, parameterized, and directed efficiently within the 'most appropriate' (design) space.

As a theory-formation problem, the mechanization of creativity aimed to solve the problem of searching for the optimal or 'good enough' solution through intelligent systems that can manage the evolution and selection of representations that could handle the ambiguity or complexity of designs. The problem with Simon's and Amarel's views is that both consider designing a course of action based on a preconceived problem that determines the structure of the solution[223]. At some levels, this view correlates with the computational design trichotomy problems presented in chapter 1; this theory of design was well suited for the application of computers to architecture and design in general. Within complex design workflows, representing a design not only as a set of drawings but as an algorithmic process in which discrete steps are combined and recombined in the search for an optimal or good solution became the

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[221] Ibid p.132 Nevertheless, Simon was explicit about the generative characteristics of design in relation to making. He wrote about the complexity of designs that are implemented over long periods of time and are continuously modified in the course of that implementation He compares complex design with oil painting. He wrote:" Each step of implementation [of a design] created a new situation; and the new situation provided a starting point for fresh design activity. Making complex designs that are implemented over a long period of time and continually modified in the course of implementation has much in common with painting in oil. In oil painting every new spot of pigment laid on the canvas creates some kind of pattern that provides a source of new ideas to the painter. The painting process is a process of cyclical interaction between painter and canvas in which current goals lead to new applications of paint, while the gradually changing pattern suggests new goals" Ibid pp 186.

[222] S. Amarel, "On the mechanization of creative processes," in IEEE Spectrum, vol. 3, no. 4, pp. 112-114, April 1966, doi: 10.1109/MSPEC.1966.5216589.

[223] It is worth noting that over the years, Simon's view of design changed based on different criticism from different scholars. You and Hands, make an interesting reflection on the evolution of Simon's view of design as a science. See Xinya You & David Hands (2019) A Reflection upon Herbert Simon's Vision of Design in The Sciences of the Artificial, The Design Journal, 22:sup1, 1345-1356, DOI: 10.1080/14606925.2019.1594961

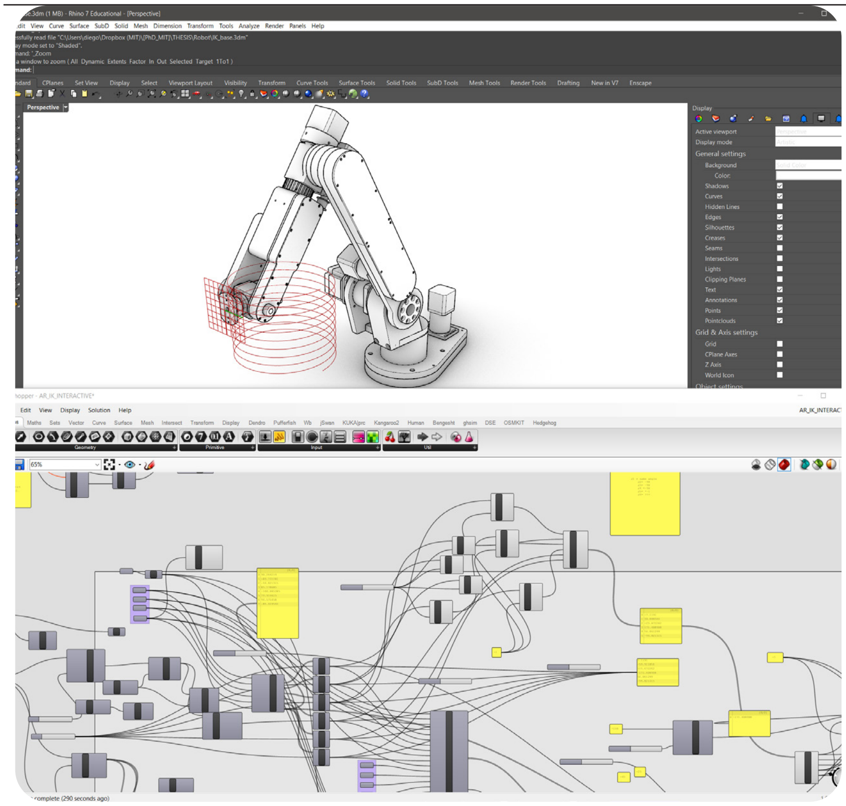

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Figure 47
Node-based program definition for robotic movement.
Source: author

very business of computers in design. Decades after the invention of CAD, parametric tools and now machine learning models focus on representation to search, navigate design spaces and find optimal solutions.

Representation in computational design falls into the same considerations as much of the scientifically oriented research about design cognition, design knowledge, and design intelligence since the early 60s that upheld Design as a combinatorial endeavor. For example, connecting 'nodes' in a 'canvas' (Figure 47) has become, in the last 15 years, the weapon of choice for many designers to 'solve' design problems producing a myriad of variations according to parameters and topological relations. In that regard, whereas models using precompiled geometrical operations have proven to be very efficient and powerful in terms of design iteration, optimization, and a more interactive way of developing design information, they inherently rely on pausing the development of ideas to focus on the development of structures to represent those ideas. When it comes to the pure act of creation and idea development, as Cross writes, problems are ill-defined, ill-structured, or wicked[224] and cannot be considered puzzles,[225] as all the pieces of information necessary will never be available[226]. Cross's words tackle two fundamental problems with the trichotomy view of design and the problem with the representation part of it. On the one hand, it addresses the problem-seeking nature of Design. On the other hand, the problem-seeking nature of Design allows working on ill-defined, ill-structured problems to engender new patterns and new knowledge.

4.3 The creative power of the sketch

Sketching has been at the core of art, design and architectural education for centuries. Beyond discussions around technological implementations that changed the way designs have been represented and communicated, sketching has remained the primary and more elemental way of expressing and developing design ideas. Often regarded as a reflective practice[227], involving observation and action, the creative power of sketching, has been regarded as an elemental conversational practice[228]. As a first approach to a material engagement with our surrounding environment, sketching has served a different purpose than architectural drawings or 3D modeling in merely describing a design. The interplay between observing and acting in a sketching process is related to the power of interaction with a material medium to 'identify patterns and give them meanings beyond themselves.'[229] This interactive dialog has served as a vessel to develop a thinking process that allowed designers to address the complexity of a design problem more abstractly and selectively. In the act of design, as Schön argues, one deals with a vast number of domains and characteristics inside those domains, so consequently, 'our

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[224] Cross, Nigel. Design Thinking : Understanding How Designers Think and Work. Oxford ;: Berg, 2011. P.7

[225] Ibid p.7

[226] Cross adds that 'They are not problems for which all the necessary information is, or ever can be, available to the problem-solver. They are therefore not susceptible to exhaustive analysis, and there can never be a guarantee that 'correct' solutions can be found for them. In this context a solution-focused strategy is clearly preferable to a problem-focused one: it will always be possible to go on analyzing 'the problem,' but the designer's task is to produce 'the solution.'' Ibid p.7

[227] Schön, Donald A. (1987). Educating the reflective practitioner (1st ed.). San Francisco: Jossey-Bass.

[228] Schön, Donald A., and Glenn Wiggins. "Kinds of Seeing and Their Functions in Designing." Design Studies 13, no. 2 (1992): 135–56.

[229] Ibid. p1

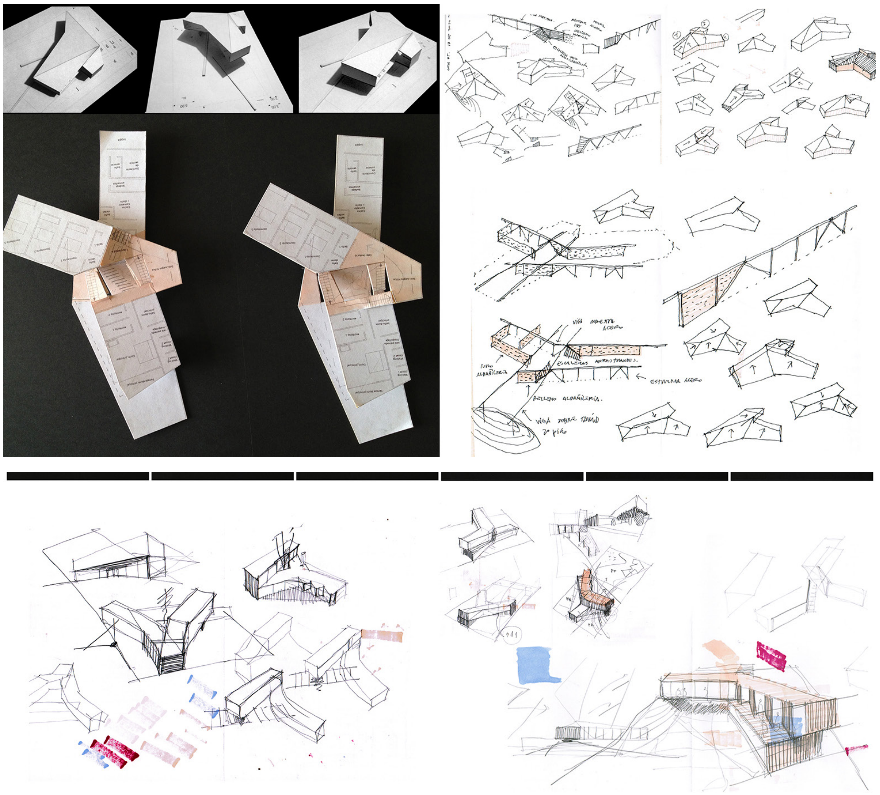

Figure 48
The process of sketching as a thinking process. Drawings from TFPS architects on the process of designing the FT house (2013).
source: author

moves produce important consequences in more than one domain.'[230] In that sense, working across or with different domains refers to our designer's capacity to select and make decisions according to the patterns and meanings that emerge from what is in front of us. Second, it is not despite human's 'limited information capacity' - addressed by Simon in his design theory- but thanks to it that humans have the power to navigate complexity in an open-ended way. In that regard, sketching became a tool that helped designers to think, select, and reason about the things we see and do. Schön's limited awareness concept illustrates the capacity of humans to have a 'conversation with a design' engaging in a see-move-see process to recognize 'the unintended as well as intended consequences.'[231]

Whether sketching involves selection, pattern synthesis, and so on, what's of interest here is the enactive and concurrent nature of sketching as a reflective conversation that uses the designer's ability to recognize, imagine and act upon things that are not necessarily explicit (figure 48).

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[230] Ibid. p.142
[231] Ibid p.43

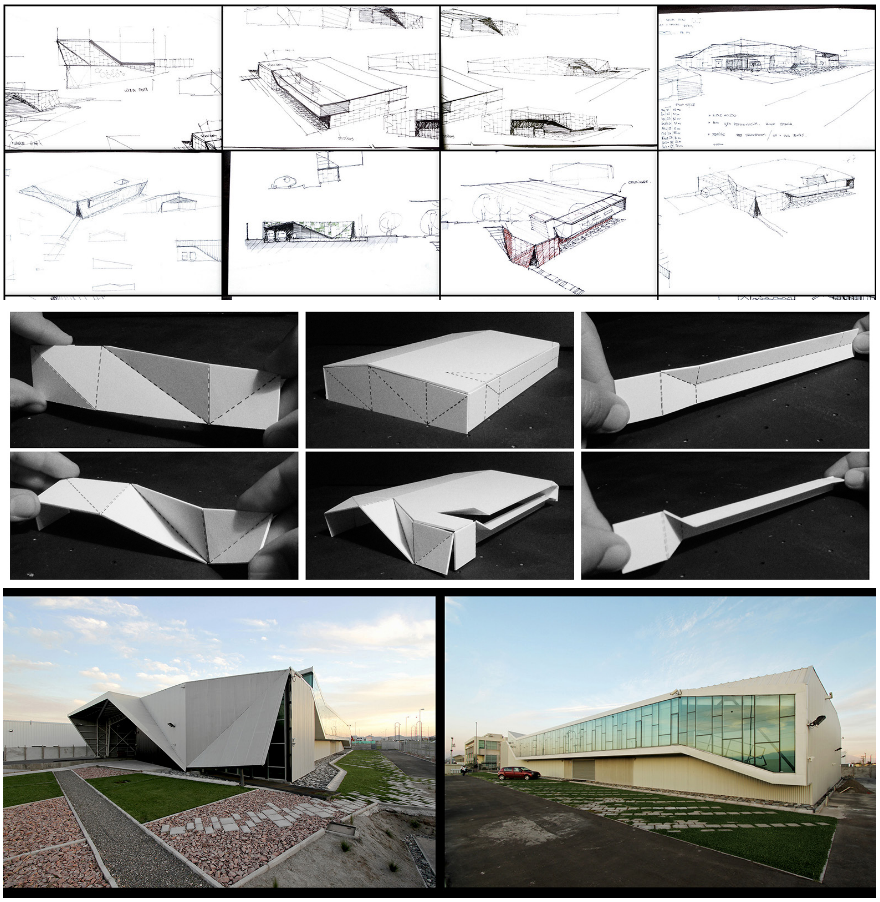

Figure 49
Sketches, model and final building of Huanacu warehouse and offices building in Santiago, Chile.
Source, author

Through this reflective conversation, sketches give designers the power to handle different levels of abstraction, select and reveal new knowledge about the problem at hand, and 'think on the fly.'[232] Sketching involves a process where the concurrent interaction with the object of design (the design as a drawing) replaces 'the early stage' in a design process. This is a valid argument when considering designers' wanting to explore new design ideas. Cross wrote about the role of sketching in design, citing different designers using sketching to become 'unstuck,' a device for thinking, discovery, etc.[233] In Cross's words, drawing is a kind of 'intelligence amplifier' because it enables something crucial for dealing with the ambiguous nature of design: the ability to explore. In that sense, it can be argued that drawing amplifies the design process because it enables a special kind of

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[232] Suwa, M. and Tversky, B. (1997). What architects and students perceive in their design sketches? A protocol analysis. Design Studies 1997, 18, 385-403
[233] Cross, Nigel. Design Thinking: Understanding How Designers Think and Work. Oxford ;: Berg, 2011. P.34-38

interaction with design and keeps the 'thinking alive' during the process. The contingent and interactive nature of sketching empowers designers to explore ideas freely and generate new meanings and knowledge by being detached from pre-structured plans.

4.4 The creative power of physical model making.

What about physical models, prototypes, and mockups? Whereas most of the literature around sketching wanders around its purpose as a communicating, externalizing, thinking, or representational device[234], understanding the distinction between sketches as designs or sketches as a representation of a design is somewhat complicated (Figure 49). While the creative power of sketches in design relies upon their interactive and concurrent nature, being bound to a bi-dimensional medium remains an intermediate step toward realizing a design as a physical object. The volumetric and spatial nature of physical models delivers new ways of interacting with materials and actively enhancing other types of relations with designs. For example, Alberti wrote about using models in architecture and establishing new relations and dialogues with his designs. To him, often what was envisioned in his mind and later translated into drawings (the 'lineamenta'), showed errors and inconsistencies that could be verified only in the translation to a physical model[235]. Alberti recognized the utility of models beyond representation and used it as a thinking device, in this case, to amend his 'errors.'

The tridimensionality and the materiality of models enable new ways

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[234] See Schön, Donald A., and Glenn Wiggins. "Kinds of Seeing and Their Functions in Designing." Design Studies 13, no. 2 (1992), as well as Cash, Philip, and Anja Maier. "Understanding Representation: Contrasting Gesture and Sketching in Design through Dual-Process Theory." Design Studies 73 (2021): 100992. Also see Suwa, M. and Tversky, B. (1997). What architects and students perceive in their design sketches? A protocol analysis. Design Studies 1997, 18, 385-403 also Bilda, Zafer, and Halime Demirkan. "An Insight on Designers' Sketching Activities in Traditional versus Digital Media." Design Studies 24, no. 1 (2003): 27–50.

[235] In his IX book, Alberti wrote: "I have often conceived of projects in the mind (multas incidisse persaepius in mentem coniectationes operum) that seemed quite commendable at the time; but when I translated them into drawings (ad lineas redegissem), I found several errors in the very parts that delighted me most, and quite serious ones; again, when I return to drawings (perscripta), and measure the dimensions, I recognize and lament my carelessness; finally, when I pass from the drawings to the model (modulis exemplaribusque), I sometimes notice further mistakes in the individual parts, even over the numbers" Alberti, Leon Battista. On the art of building in ten books. Cambridge: MIT Press, 1988. Translation by Joseph Rykwert, Neil Leach, Robert Tavernor. Book IX, chap. X, 1988, 317)

of interaction for designers. Casting concrete, folding paper, modeling clay, stacking blocks, weaving threads, and so on, incorporate a different type of physicality, skills, and bodily engagement than sketches. While sketching is a type of interaction that entails visual and motor mechanisms to develop a design idea, model-making adds a physical , tactile, and phenomenological third dimension to the process. Although some authors consider that sketching is a process of visual thinking[236], I consider that sketches are also devices for physical thinking that obey to a different nature than model-making. Sketching in a paper is as physical as folding, cutting or folding paper. In that sense, model-making can be addressed as a different way of visual and physical thinking[237] that is concern with operations that hold a more direct relation to spatial and objectual thinking.

In the same way as sketching involves what Wittgenstein differentiated between 'seeing as receiving' and 'imaging as doing,'[238] the physicality of model-making engages designers into a 'construction' that unfolds in the interaction with the very objects they design. However, while much of the literature related to sketching and model making in design is focused on their benefits in developing design concepts at the 'early

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[236] As Gabriela Goldsmith points out, sketching is a form of visual thinking that deals with not only "follow ideas from the mind, but precedes them" Goldschmidt, G. (1994). On visual design thinking: the vis kids of architecture. Design Studies Vol 15 No 4:158-174.

[237] For example, Schön wrote about the use of objects and materials in the design process. "Given a stock of available materials, different designers often select different objects, and even appreciate the 'same' objects in different ways, in terms of different meanings, features, elements, relationships, and groupings, all of which enter into characteristically different design worlds" Schön, D. (1992) Designing as reflective conversation with the materials of a design situation. Knowledge-Based Systems, Volume 5, Issue 1, Pages 3-14.

[238] Wittgestein wrote: 'I learn the concept 'seeing' along with the description of what I see. | learn to observe and to describe what I observe. I learn the concept 'to have an image' in a different context. The descriptions of what is seen and what is imaged are indeed of the same kind, and a description might be of the one just as much as of the other; but otherwise the concepts are thoroughly different. The concept of imaging is rather like one of doing than of receiving'

design phase,'[239] the questions that are relevant for this research work are how the creative, exploratory, cognitive, and related qualities can be extended and extrapolated to the entire design-making process. In other words, can we enable similar interactions with software and hardware to use computers as active thinking tools instead of representational devices to bridge ideas and construction? What is needed to dissolve the gaps and boundaries between ideas, representations, and physical objects to avoid the computational design trichotomy?

4.5 Beyond automation and operation: The need for interaction

So far, there is one keyword that constantly appears in the work here when addressing topics in design and its relations with exploring, learning, knowing, and so on; that word is interaction. In the view of design as a problem-finding endeavor -as opposed to a problem-solving one- the ambiguity of design problems and the quest of designers to find the right questions about a design problem, demands an active engagement of the designer and their environment. In the case of the computational design field, the addition of new layers of technology and knowledge from other fields has propelled the emergence of more experimental streams of thought and research looking to enhance, expand, optimize and understand the design practice. However, adopting the 'next big thing' in the design process, such as industrial robotics, artificial intelligence, and material science, has been focused on the benefits of the automation capabilities they deliver to produce new things. The transformations brought about by the use of automated technologies in design come with questions and discussions about their contribution in terms of product versus process.

The emergent properties of complex algorithms that can be simulated inside a computer facilitated the use of automated algorithmic processes in which different combinations of parameters can result in surprising results. In that regard, Picon's question, "why are we moving from a

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[239] On the benefits of sketches and sketches as aids in the early design stages, see: Qifang Bao, Daniela Faas & Maria Yang (2018) Interplay of sketching & prototyping in early-stage product design, International Journal of Design Creativity and Innovation, 6:3-4, 146-168, also, Deininger, Michael, Shanna R. Daly, Kathleen H. Sienko, and Jennifer C. Lee. "Novice Designers' Use of Prototypes in Engineering Design." Design Studies 51 (2017): 25–65. Also , Yang, Maria C.. "A study of prototypes, design activity, and design outcome." ***Design Studies*** 26 (2005): 649-669. Also, Bilda, Zafer, and Halime Demirkan. "An Insight on Designers' Sketching Activities in Traditional versus Digital Media." Design Studies 24, no. 1 (2003): 27–50.

discourse on robots to a discourse on AI in architecture?"[240] reflects that the fascination with adopting state-of-the-art technologies in design comes from the enchantment of processes we usually don't fully understand. For example, the fascination with using GANs and text-to-image models comes from the automated capabilities of these models to produce a novel result and not so much from the interaction with the tool itself. Perhaps this is because many of the ML implementations in design are constrained by the advances made by computer scientists. Seeing 'under the hood' to 'hack a model' or to generate one from scratch requires specific knowledge that is difficult to acquire and put into practice by the untrained. Hence, most of the implementations of ML in design are based on a 'quid pro quo' exchange of information and not so much on the mutual intelligibility of the actors and processes involved in the exchange. In that sense, the knowledge gained from the design process is often relegated to the peripheries of the design workflow, as something that is considered and understood before a plan is made, or as something learned through analysis and reflection after the plan has been executed. In that regard, the automated nature of technology in design privileges operation based on automation and the exchange of a 'prompt' for an image, a series of latent vectors for a design space, or a parameter combination for the 'good enough' solution. The operational paradigm of most design tools leaves aside the conversational aspects of creation, in which the qualities of sketching or model-making are not present.

The limited interaction (clicking and typing) offered by digital design tools is based on automating and structuring action plans. The use of the digital in design, whether an ML model for image production or a program for picking and placing blocks using a robotic arm, remains entrenched within the boundaries of the computational design trichotomy, in which a designer needs to think, then externalize that thinking into a representation or plan and finally make according to that plan. Therefore, understanding design not only as a product but as a process opens the door to discussing the importance of design as an interactive and experiential endeavor and its relationship to design intelligence and knowledge. Cross argued that asking 'Can a machine think?' was no different from asking 'Can a machine design?' He argued that designers build knowledge by a 'designerly way of knowing' in which the interface between a human and a computer was at the core

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[240] Picon, Antoin. Open lecture at the Estonian Academy of Arts. May 2022. https://youtu.be/aj86RMnHEAc?t=828

of the problem to capture and computationally formalize part of that knowledge[241]. Moreover, he adds that AI-in-design research should look at Design from the computational perspective to learn about the nature of human design cognition. Doing so would lead researchers to develop systems that can do not only the things that are difficult for humans but to develop machines that do things that designers cannot do unaided.

4.6 Towards Design Intelligence

Concepts like the ones mentioned by Cross are essential to understand the relevance of the type of research presented in this research. Nevertheless, beyond understanding or formalizing human knowledge in design, the interest here is in exploring the dialog and exchanges between humans and machines and the mechanisms that can allow that interaction. In that sense, I propose that given the situated nature of design, developing interactive computational systems that can incorporate the contingency of the interactions between humans, machines, and the physical environment, it is possible to dissolve the boundaries of the computational design trichotomy. I assert that the development of systems that capture human gestures as intentions and enable meaningful 'machine action' in response to human gestures are needed. Incorporating particular sensory aspects that are synthesized with general intellectual concerns while generating new meanings and -in the unfolding of life- new ways of making can enable the generation of new knowledge about the design problem in front of us.

The apparent creative freedom delivered by technology (primarily digital computers and digital fabrication machines) revealed that their use as cognitive tools remains scarcely unexplored. As Lyon suggests, design is related to the meaningful production of artifacts through using and manipulating knowledge[242]. In that regard, design can be understood as a cognitive process that involves a component of investigation and inquiry where a design problem is not only solved but defined, expanded, and transformed into new questions. Therefore, design is concerned with the production of new design knowledge that encompasses how things are and how things are made. Design as an experiential and transformational process (of things, materials, and even people) deals

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[241] Cross, Nigel. Designerly Ways of Knowing. London: Springer, 2006. P.39

[242] Lyon suggests that "the consensual production of meaningful artifacts through a knowledge capture, generation, manipulation, synthesis, and communication process" (Lyon 2005);

with producing knowledge using design intelligence which is the ability to acquire, generate and apply design knowledge. In this case, we can understand design intelligence as a process by which an agent shows a kind of behavior that can be called intelligent (by an observer) about the connotative relations between them and their circumstances, as suggested by Maturana[243]. In that regard, understanding design as an intelligent process involves considering design as both concurrent and contingent. Thus, it is valid to hypothesize and consider it like so because this transformation comprehends a temporality, an environment, and a series of interactions between humans, tools, and materials for it to take place; therefore, it is situated (in time and space). Moreover, considering design as a situated intelligent process[244] points to a definition of design as a process that, taking place in the interactions of the systems (humans, materials, machines), leads to the relational situation that the designer calls intelligent design behavior[245]. Hence, by defining design in this way, this dissertation challenges the notion of design as:

a) Problem-solving: Because design can be viewed as the use of design intelligence to produce design knowledge, and this intelligence can be viewed as an expression of a set of interactions of the systems involved and not as an pre defined action (representation) directed towards the future realization of an object.

b) Essentially representational: By considering design as a situated process, it is valid to argue that the use of design intelligence is a behavior or conduct whose peculiarity (uniqueness) consists in its enaction in a particular context as a result of a particular history of interactions of the actors involved and/or their medium. Therefore, this view considers as 'medium' the world of objects and material things in which representations are ephemeral constituents of the whole design endeavor.

Making as a way of designing is a concurrent and contingent endeavor that involves the use of design intelligence happening in a specific time and space (a medium or design environment) where design knowledge can be generated. Based on this premise, the very purpose of design

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[243] Maturana, Humberto R., and Gloria D. Guiloff. 1980. "The Quest for the Intelligence of Intelligence." Journal of Social and Biological Structures 3 (2): 135–48. Also,

[244] by which new knowledge is acquired, generated, transformed, and applied

[245] Maturana R Humberto and Jorge Luzoro G. 2004. Desde La Biología a La Psicología. 4a. ed. Santiago Buenos Aires: Universitaria ; Lumen. P.26

as an intellectual endeavor is to generate, transform and expand design knowledge. In that case, making as a definitive way of designing gains ultimate relevance in the presence of technology as the interface between ideas and objects. Moreover, making is a holistic creative process in which the maker (as a designer) is highly engaged in perceptual and sensory ways. Designing as making is a process of pure experience closely related to the definition of aesthetic experience[246], in which particular sensory aspects are synthesized with general intellectual concerns generating new meanings and, in retrospect, new ways of making. Nevertheless, a main challenge is to establish a new conception of making as designing considering the computational design trichotomy present in most of the contemporary design processes and the need to reconfigure the way we interact with technology for such purposes. Moving from an interaction based on operation toward an interaction based on a reflective dialogue with tools and materials can engender new ways of creating things and inherently new knowledge about those things and the processes that engender them. Hence, the challenges are in implementing such systems that can allow for an intelligent exchange of information between a designer, their tools, and the material environment.

4.7 A cybernetic approach to design for intelligibility

Cybernetician Paul Pangaro asserts that the foundations of creative work are in the capacity of problem framing[247]. Similarly to Schön[248], he acknowledges that in the continuous reframing of problems, designers can ‘see anew’ when engaging in an iterative “observe, reflect, make” approach. Pangaro suggests that design is, by definition, a cybernetic endeavor because it involves purposive systems toward purposeful action. In Pangaro’s view, design as a creative act is essentially cybernetic because it deals with understanding how to act-and see-; in his words, it

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[246] This dissertation considers Dewey’s definition of aesthetic experience encompassing perception, actions, emotions and meanings in the presence of the material and time. To Dewey, an experience is an aesthetic one as new orders emerge, and new unities (as wholes meaning new things) stands out from general experiences in daily lives. In that regard, Dewey’s aesthetic experience is contemplative and active. See, The Philosophy of John Dewey, Two Volumes in One. Edited by John J. McDermott, p.50.

[247] Pangaro, Paul in, Henriksen, D., Mishra, P., Warr, M. et al. A Cybernetic Perspective on Design and Creativity: a Conversation with Dr. Paul Pangaro. TechTrends 62, 6–10 (2018).

[248] Schön, Donald A. The Reflective Practitioner: How Professionals Think in Action. United Kingdom: Taylor & Francis, 2017.

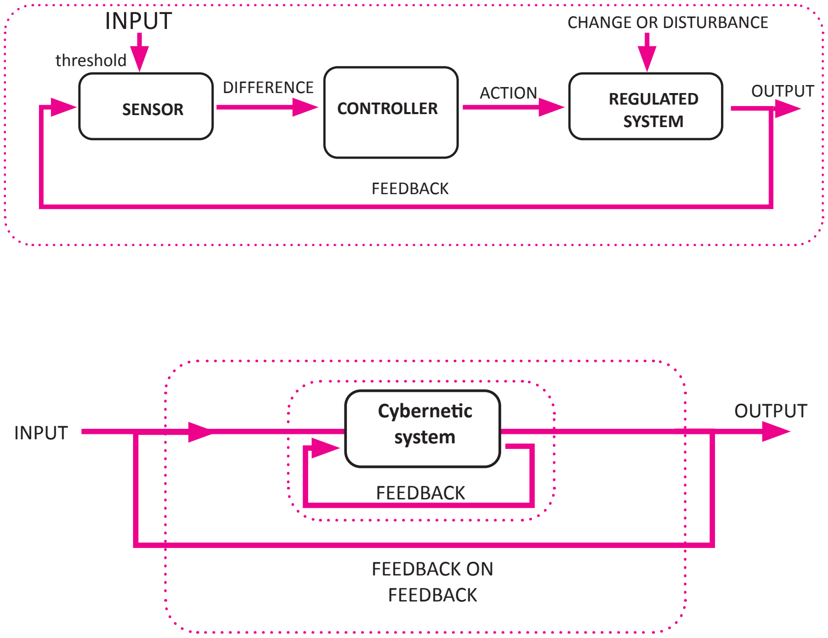

Figure 50
First order and second order cybernetics diagram
Source: author

is about how to get somewhere ‘you want to be, other than where you are’ (figure 50). Just like Schön, Pangaro considers Design as conversation, a dialog product of a constant spiral in which we ‘act’ to ‘see.’[249] He proposes that given the ubiquity of technology and the consequent repercussions in how we communicate, Design as a domain has expanded from giving form to creating systems that can support the interactive nature of creation. Pangaro and Hubberly offer the rationale[250]:

- If design, then systems: Systems literacy is necessary for design
- If systems, then cybernetics: Interaction is the science of Cybernetics

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[249] ‘We see as a result of action. We don’t first ‘see’ and then know and then act. This is because I don’t always know what my goal is – I don’t always know where I want to be – so it’s not about pre-thinking and then acting’ Pangaro, Paul in, Henriksen, D., Mishra, P., Warr, M. et al. A Cybernetic Perspective on Design and Creativity: a Conversation with Dr. Paul Pangaro. TechTrends 62, 6–10 (2018).
[250] Dubberly, H., Pangaro, P. (2019). Cybernetics and Design: Conversations for Action. In: Fischer, T., Herr, C. (eds) Design Cybernetics. Design Research Foundations. Springer, Cham.

Author	First order cybernetics	Second Order Cybernetics
Von Foerster	Cybernetics of observed systems	Cybernetics of observing systems
Gordon Pask	purposeful systems	Conversational systems
Humberto Varela	Controlled systems	Autopoietic systems
Stuart Umpleby	Interaction among system variables	Interaction between observer and observed

Figure 51
Second order cybernetics according to authors.
Source: author

- If cybernetics, then second-order cybernetics: Wicked problems require incorporating subjectivity and epistemology of second-order cybernetics.
- If second-order cybernetics, then conversation: Design requires conversation and collaboration for effective action.

Pangaro and Dubberly propose that second-order cybernetics (figure 50) can enable what they call ‘second-order design’ to allow conversations for learning and acting[251]. In that sense, cybernetics implies that design is inherently computational as it inherently involves ‘computing’ between different entities. In that regard, ‘Computare’ - the Latin root word for ‘computing’ - means’ settling things together,’ referring both to the act of ‘putting things in order,’ and to the ‘togetherness’ of calculating as a collective endeavor. Furthermore, ‘Com’ (together) and ‘putare’ (to contemplate) imply that we are computing their relationship by observing two or more entities together. Seeing design as a computational endeavor, one can understand its relation to cybernetics and interaction. In the presence of technology, specifically digital computers, moving from

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[251] Ibid. page 1

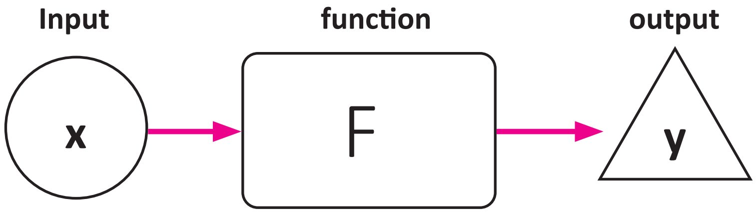
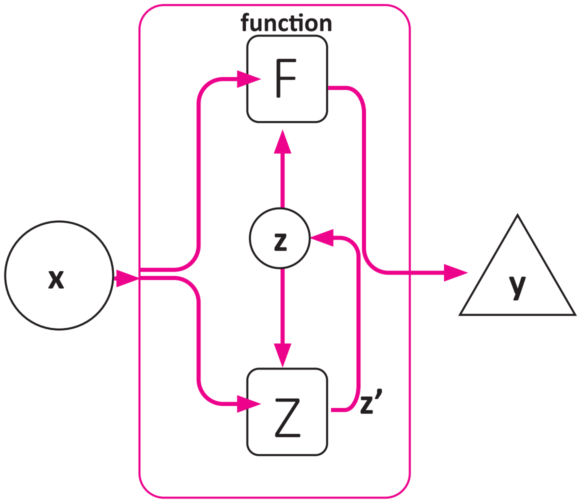


Figure 52
Trivial Machine diagram
Source: author based on Von Foerster Diagrams



Driving function: y = F(x,z)
State function: z’=z(x,z)

Figure 53
Von Foerster’s Non Trivial Machine diagram
Source: Author based on Von Foerster’s diagrams

i- Read input x
ii- Compare x with z, the internal state of the machine
iii- write the output y
iv- change internal state z to new state z’
v- Repeat with new input z’

A		B	
x	yz’	x	yz’
α	0A	α	1A
β	1A	β	0B
γ	1B	γ	0A
δ	0B	δ	1B

a paradigm of computational design based on operation towards one based on interaction requires the emergence of new paradigms and systems to enable proper communication and intelligibility between the actors involved in a design.

4.8 From trivial to non-trivial machines

From a cybernetic and also constructivist perspective, enabling interactive systems and machines for Design requires moving from their conception as 'trivial machines' to 'non-trivial machines.'[252] A trivial machine is considered a system of three parts: input, function, and output (figure 52). Independently of any experience or history, a trivial machine is a 'prototypical model for predictability and certainty' when every time you give the same input, the machine will give you the same output[253]. Conversely, non-trivial machines are - as Von Foerster calls them - "extremely tricky devices"[254] that incorporate an internal state that changes every time a computation is performed by it (figure 53). These machines are recursive and can change their transform functions in every computation. Moreover, the unpredictability of non-trivial machines hides something quite interesting for design purposes as they present complex behavior, operate in the present, and incorporate the idea of experience that, in practice, can transform them into a different machine every time. Non-trivial machines (NTM), as a paradigm, points to their recursive nature in which a NTM becomes a new machine or system every time its internal stage changes. The trivial and non-trivial discussion provides a practical conceptual framework to understand how we compute our experience. While the trivial machine 'epitomizes our quest for certainty,'[255] the non-trivial machine 'models the reality with which we are working'[256] opening the door to interactivity and intelligibility.

In cybernetics, interactivity involves circularity and recursion. In addition, humans use a kind of infinite recursion that occurs in

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[252] Concepts discussed by Lynn about the theory of Von Foerster about constructuvism in Segal, Lynn. The Dream of Reality : Heinz von Foerster's Constructivism. 2nd ed. New York: Springer, 2001.

[253] Segal, Lynn. The Dream of Reality : Heinz von Foerster's Constructivism. 2nd ed. New York: Springer, 2001. Ch. 5 P-87

[254] Ibid, page 89.

[255] Ibid, page 95.

[256] Ibid, page 95.

our nervous system to engage in sensorimotor behavior with our surroundings. The constructivist approach of Von Foerster, which formalized Piaget's description of cognitive activity, defines the circularity of sensorimotor interaction between observation and action as coordinated movement. We use recursion to compute and operate on the material world generating 'eigenvalues,' also known as objects of perception[257]. From a constructivist and cybernetic perspective, recursiveness allows us to reach stability. In that regard, stability can be related to meaning-making in the sense that in the myriad ways we can interact with our surrounding environment, we make sense of things by reaching stable perceptions of objects every time we attend to them. As Von Foerster points out, our surrounding world becomes a landscape of objects that work as tokens for *Eigen* behaviors or ways of acting[258]. The world presents to us as invariant until we experience it by interacting with it. Therefore, if we extrapolate these concepts into the design endeavor, we can assert that the creative power of design relies upon its interactivity. Design, as a recursive endeavor, engenders not only objects but *Eigen* behaviors as stable interactions to create, from an infinite continuum of possibilities, identifiable entities as designs. Thus, considering machines as non-trivial devices, it is possible to embrace interactivity and account for the non-linearity of interactions that can arise in a design process. I ask, how does representation fits into this view of design as interactive?

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[257] Ibid, page 127
[258] Ibid, page 128

4.9 Interactive machines: A work on interactive physical environment

The example provided at the end of chapter 3 showed a system in which a machine can interpret human sketches to produce a 3D model. Thus, the communication between the designer and the machine was mediated by a model capable of pairing shapes or shape sequences to 3D models. In that case, although the interface allowed designers to sketch and generate 3D models freely, the outcomes from such interactions were bounded by possible outcomes according to the data trained. Whereas the sketching part of the process replicated a typical design ideation process through drawings, allowing free exploration of shapes, the outcome was determined by the categories trained and the predictions according to a latent vector that was the 'closest neighbor' to the model's latent vector. Therefore, not every model produced corresponded directly to a sketch produced, while at the same time, the material aspects of models were not considered. Understanding human actions and engaging in conversations with a machine and the material world requires creating multimodal systems that can engender more meaningful interactions.

4.9.1 NNN – A visual programming system for human-machine interaction

One of the main challenges in interactivity is addressing the effective communication between two or more entities and establishing a language of mutual understanding and meaningful exchange of information. As a researcher in the Design Intelligence Lab at MIT[259], I worked on the implementation of interactive light systems as a way to engage with our surrounding environment. The research developed was focused on establishing a multimodal system for interaction that could be applied at different scales in our built environment. The research involved the creation of software and hardware components that could be used for designing interactive environments based on light. As a first approach, the research considered how light could be used to carry information that humans could understand or interpret while interacting

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[259] Between September 2018 and December 2021, I worked as a research assistant under the supervision of Dr. Marcelo Coelho, director of the Design Intelligence lab at the Massachusetts Institute of Technology.

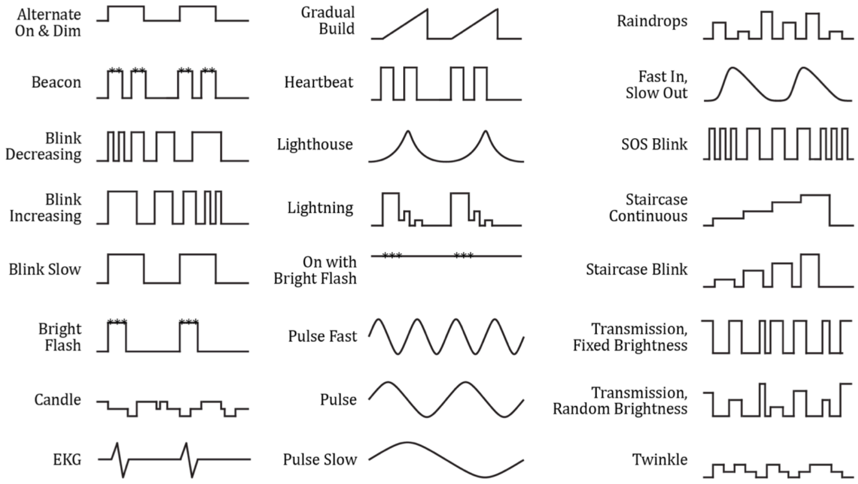

Figure 54
Representation of 24 light behaviors over time according to light intensity and pulse. Harrison et al. 2012
Source: author

with space. As an example, the work of Harrison et al.[260] studied the generation of meaningful behaviors through the generation of light patterns. In his research, Harrison establishes a language based on how a simple point of light could convey different meanings through the most elemental and straightforward behaviors (Figure 54). Taking Harrison's work as a reference, the research was focused on developing emergent light behaviors that could emerge from human action. For such purpose, NNN[261] was oriented toward generating a visual programming platform for designing interactive light systems.

4.9.2 The interface problem

Starting from the question: How can designers and the public create content and interaction for public lighting? My work focused on the problem of the interfaces involved. First, there was an interface problem regarding the availability of current platforms for creating interactive systems and the knowledge needed to implement

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[260] Harrison, Chris, John Horstman, Gary Hsieh, and Scott Hudson. 'Unlocking the Expressivity of Point Lights'. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1683–92. CHI '12. New York, NY, USA: Association for Computing Machinery, 2012.

[261] NNN stands for Networks of Neural Networksl. The work commissioned by Signify (https://www.signify.com/en-us) required the work on LED light strips and the creation of a platform for designing and deploying light shows at an urban scale.

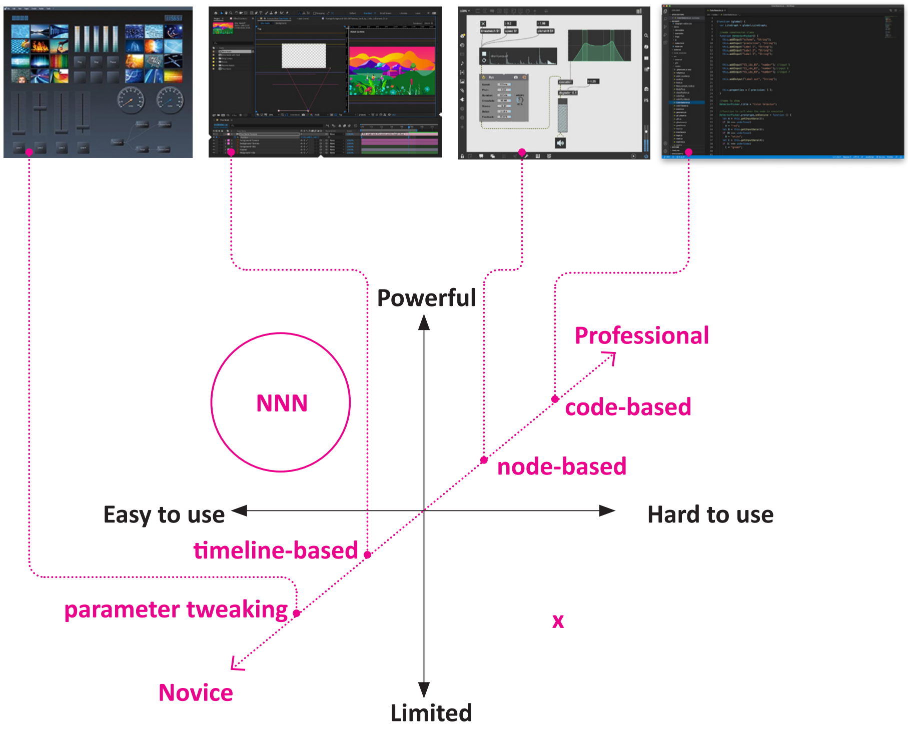

Figure 55
Content creation map about four type of tools. Powerful and professional tools are hard to use and required specific knowledge that belong to other domains (i.e. software engineering). Source: Design Intelligence Lab MIT. Source: Diego Pinochet and Marcelo Coelho

interactive systems. Second, there was a problem establishing the nature and characteristics of such interfaces that could result in meaningful user experiences. Therefore, implementing a platform for designing interaction started by identifying four classes of interaction models derived from the study of different platforms for content creation and then mapping them into a plot to guide the development of an interactive design tool for light interaction (figure 55). From this study, a research question was framed. How can machine learning be used to create interfaces for public lighting by extracting and recomposing meaning from existing data? The research question different strategies regarding software and hardware were formulated.

In the case of software, the project considered implementing machine learning models to

a. Recognize features, patterns, and behaviors
b. Perform real-time training adapting to contingency
c. Using generative models for complex output.

In the case of hardware, the project considered implementing a distributed lighting network running machine-learning models directly on the luminaires.

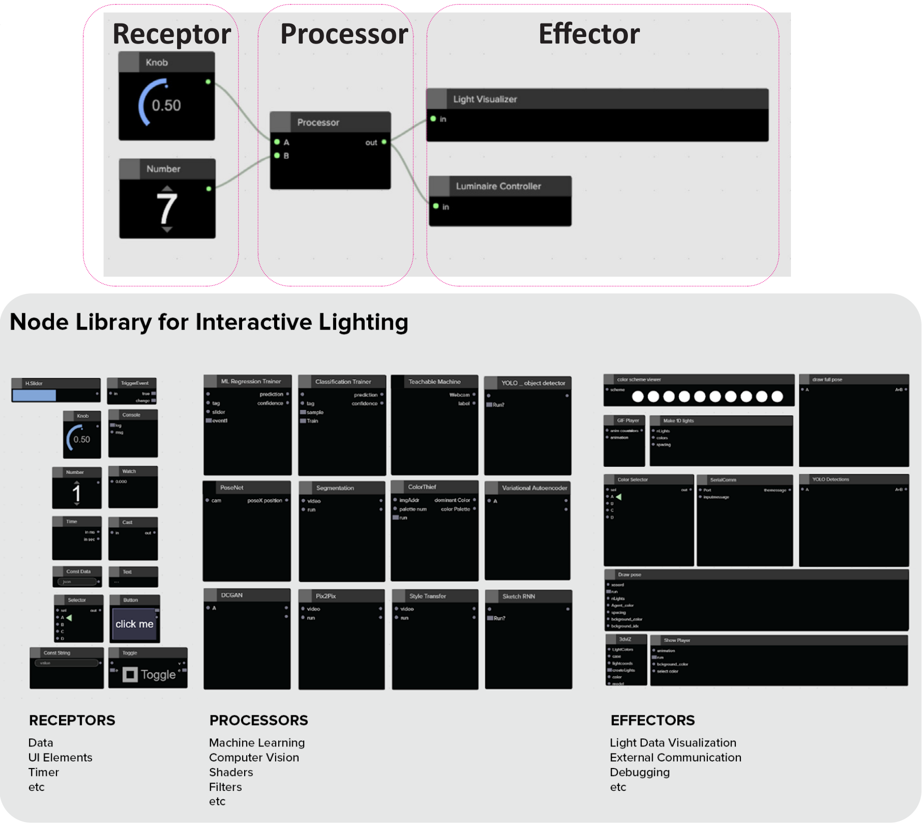

Figure 56
NNN node types
Source: Diego Pinochet and Marcelo Coelho

NNN was developed as a visual programming platform using a node-based architecture to generate light interactive interfaces. The platform was structured considering three different categories of nodes: receptors, processors, and effectors (figure 56). Based on the concept of a non-trivial machine, the platform allows the creation of complex behavioral machines due to their interactive nature, allowing them to sense, process, and act in real-time. Built as an electron app, it was programmed in JavaScript[262] and Node.js[263] to deploy it on almost any device with web capabilities. Using a front-end interface based on electron[264] allowed

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[262] JavaScript, often abbreviated as JS, is a programming language that is one of the core technologies of the World Wide Web, alongside HTML and CSS. See http://www.javascript.com

[263] Node.js is a cross-platform, open-source server environment that can run on Windows, Linux, Unix, macOS, and more. Node.js is a back-end JavaScript runtime environment. See https://nodejs.org

[264] Electron is a free and open-source software framework developed and maintained by GitHub. The framework is designed to create desktop applications using web technologies that are rendered using a version of the Chromium browser engine and a back end using the Node.js runtime environment. See https://electronjs.org

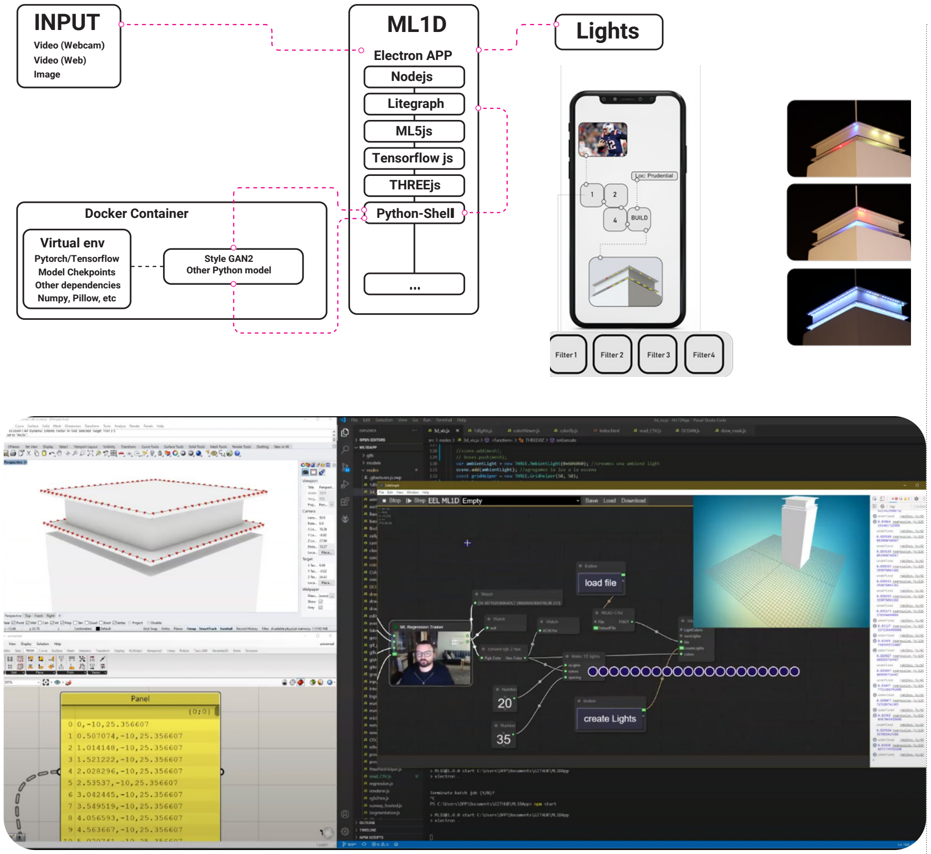


Figure 57
NNN for Interactive light games in urban landmarks. Design Intelligence Lab.
Source: Marcelo Coelho and Diego Pinochet. 2019

the application of different mechanisms to integrate different types of hardware, such as cameras, sensors, serial communication devices, etc., and to communicate with modules written in C, C++, C#, or Python.

The node architecture was framed as a creative tool based on three principles:

a. Decompose image or sensor information into symbolic elements
b. Recompose information by mixing and matching.
c. Encapsulate a node network into simpler, reusable ones.

Envisioned as a platform for leveraging interactive public lighting, the program’s structure allows the creation of different scenarios for conversation between humans and their surroundings. Through a series of examples, ranging from the city’s gamification (figure 57) to the generation of interactive building components (figure 58), the project resulted in a fertile paradigm for studying interactivity, focusing on building an interface for communication and mutual understanding.

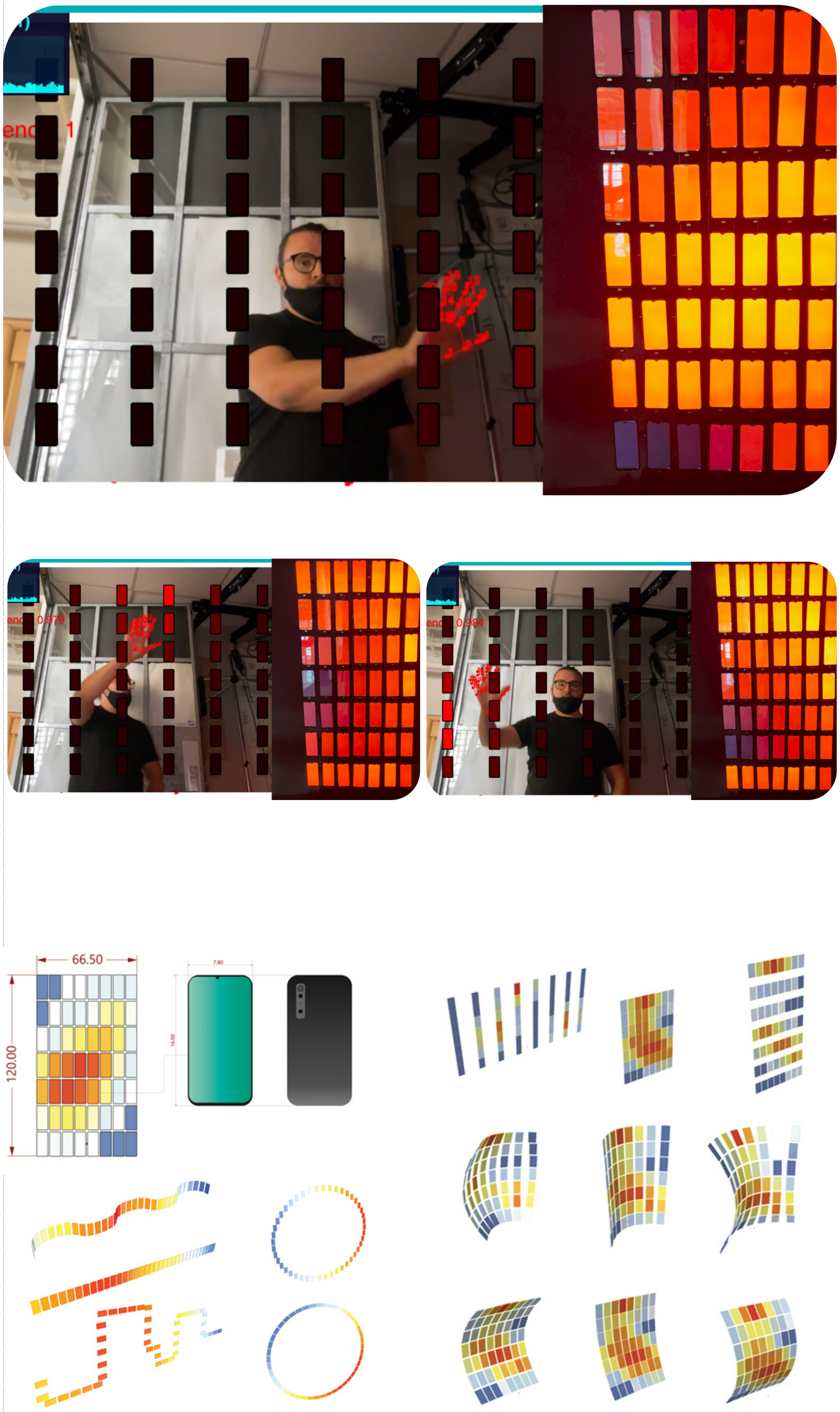


Figure 58
Distributed light network
working on NNN
source: Diego Pinochet and
Marcelo Coelho

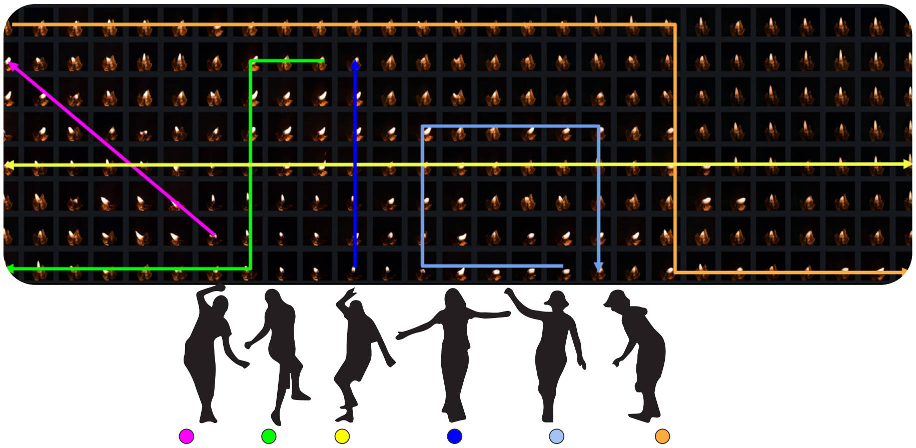
4.9.3 Implementing an interactive design system: Distributed lighting network

One of the interactions generated with NNN was crucial to frame a type of multimodal interaction that could be useful for design purposes. Using the generative capabilities of machine learning models, an interactive light wall was built on top of NNN to explore the conversational aspects of interactive systems. For such purpose, an interactive distributed lighting network (DLN) was implemented to test three main aspects of an interactive system:

a. Conversation through gestures: Enable real-time interaction between a user/designer and the built environment using gestures as the vessel for communication.
b. Real-time content generation: From the gestural interaction and conversation between the user/designer and the built environment, content can be generated in real time.
c. Distributed intelligent Network: Where each component of the system is running NNN and computing inputs and outputs in real-time.

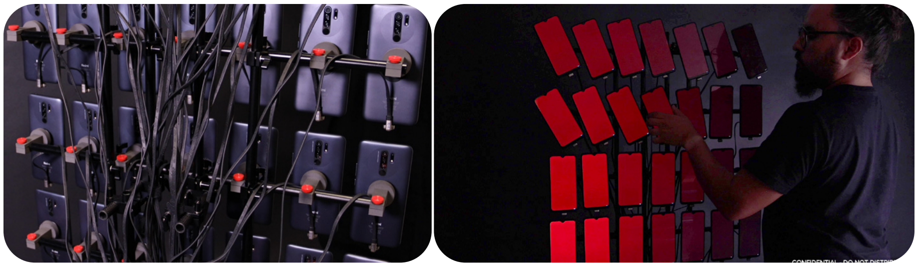
The DLN was implemented using an array of 49 mobile devices as proxies for luminaires. Each mobile device had the computational power to run a headless version of NNN, running machine learning models for pose and gesture detection, network communication, and graphical/audio output. Each mobile device was built as a single pixel embedded with the capacity to run as a non-trivial machine that senses, computes, and acts according to the interactions with the entities involved. A central server running on the cloud was implemented to coordinate the communication between units and also to run larger models that can't be deployed in a mobile device (i.e., a GAN). Once implemented, the system has the capacity to locally compute inputs from the camera and send the information to the central server that coordinates the outputs for each unit. In the case of DLN, each pixel detects a pose from a human user while the server receives the information and calculates the average skeleton for gesture tracking.

According to the gestures enacted, the system computes an output (I.e., a generative image from a GAN model) that is distributed among all the pixels in the system. In this way, users get graphical feedback according to their movements as different generative patterns



Latent space exploration according to pose detection

New content is created in real-time based on poses and mapped onto a light network



Detail of the distributed light network built in July 2021

Figure 59
Distributed light network reacting to gestures
Source: Diego Pinochet and Marcelo Coelho

are formed in the network (figure 59). The implementation of NNN in a project like DLN represented an opportunity for testing a human-machine interactive system that left important insights that could be extrapolated to interactive design and fabrication systems. Whereas the system successfully integrated human gestures coupled with intelligent machine action in a physical prototype using a multimodal approach, the development of a system for dialog based on gestures and the creation of a language was an important achievement.

4.10. If Design… then gestures

I argued in 2014 that creativity emerges in the very moment of the impression of the self onto the material world as an improvised choreography between humans and objects (materials and tools) by using body gestures[265]. This interaction refers to a skillful one that can be accounted for through the concept of 'Eigen behaviors' in which stable actions lead to stable configurations that we can call designs. In that regard, stable actions involve learning and deploying motor skills according to our being in the material world. In the cognitive science field, gestures emerge as the manifestation of a continued motor regulation in the action, perception, and anticipation cycle. Maldonato views body movements or gestures as a product of the interplay between anticipatory (feed-forward) and compensatory (feedback) mechanisms. These mechanisms allow humans to respond not only reactively but also proactively to certain situations[266]. Feed-forward is employed by the body to prepare for action, while feedback is utilized to adjust movements based on sensory information received from various receptors[267]. Moreover, Maldonato refers to the enhancement of these mechanisms' efficiency through experience as "Embodied action." This concept refers to a system of sensory and motor schemas and habits that function as an active motor schema capable of recalling bodily perceptions[268].

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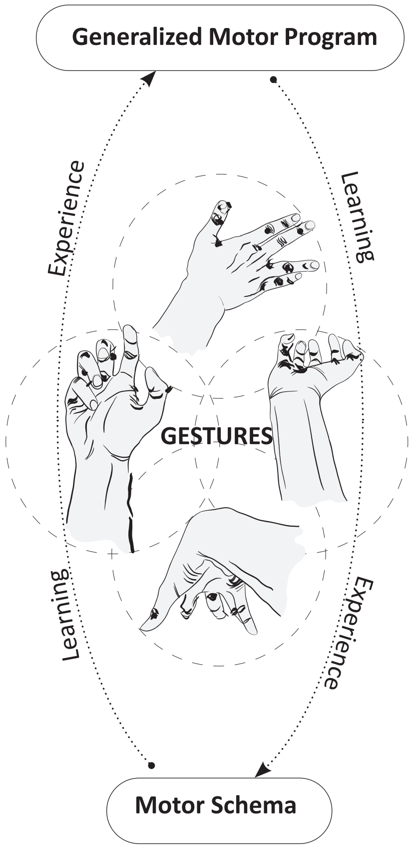
[265] Pinochet, D.I.: Making gestures: design and fabrication through real-time human-computer interaction (Master of Science Thesis). Massachusetts Institute of Technology (2015). P.61

[266] Maldonato, Mauro. "The Predictive Brain: Consciousness, Decision and Embodied Action. Sussex Academic Press. 2014. 112 Pp. ISBN: 9781845196394." The British Journal of Psychiatry 206, no 6 (2015), 524–24. doi:10.1192/bjp.bp.114.161554. pp 59.

[267] Ibid pp 60.

[268] Ibid pp 60.



motor pattern of gestures (sequence of muscles implied, relative force applied, temporal structure of motion).

Selection of parameters of the GMP according to specific situation requisites collected to our multiple receptors.

Figure 60
How gestures work according to Schmidt's schema theory.
Source: author

One can argue that gestures and their uniqueness as manifestations of the self are enacted due to a constant relationship between action, perception, and memory (which emerges from experience and learning). Furthermore, as Magill and Anderson argue, learning specific skills involves overcoming the difficulties that emerge when performing in a dynamic environment and developing a coordinative structure to cope with contextual perturbances[269]. Moreover, in 2015 I argued[270] that the uniqueness of every gesture could be explained by Schmidt's schema[271] theory based on two concepts: The Generalized Motor Program (GMP) and the Motor Schema (figure 60). While the GMP provides a motor

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[269] Anderson, David I.., Magill, Richard A. Motor Learning and Control: Concepts and Applications. Singapore: McGraw-Hill, 2013.

[270] Pinochet, D.I.: Making gestures: design and fabrication through real-time human-computer interaction (Master of Science Thesis). Massachusetts Institute of Technology (2015). P.62

[271] Schmidt, R.A (1975) A Schema theory of discrete motor skill learning. in Psychological Review, vol 82. American Psychological Association.

pattern deposited in memory that possesses different characteristics[272] that are invariant in the desired gesture, the motor schema adjusts specific selected parameters of that motor response to adapt to the situational demands. Finally, Maldonato sserts that because of the relationship between these internal mechanisms, the repetition of a movement- a gesture will never be identical[273].

Design -as discussed in chapter 2- has many definitions according to fields of application. However, one point of agreement is that design is inherently concerned with purpose. Although Schön's and Simon's views are commonly situated against each other, the idea of design as purposeful is one point where both agree. Moreover, 'purpose' does not necessarily have to do with having a goal a goal, but having an intention that redefines on the go the mechanisms by which we engage in experiences toward the different vectors that open in front of us. Having a purpose and acting according to that purpose, we generate a cluster of possibilities of what to do and see next shaped by experience and the meaning derived from that experience. Furthermore, making sense of things as we move toward something defined by our experience leads us to 'know-how' and build the necessary 'skills' to deal with things. To Dreyfus, 'knowing how' -as opposed to 'knowing that'- concerned intuition and what he called "background" as a type of knowledge that was not stored in our brains symbolically but intuitively[274]. According to Dreyfuss, intuition or 'know-how' as a 'background' is concerned with an active way of being in the world by discriminating between the essential and the inessential that, and which when coupled with analytical reason, leads humans to learn and acquire new skills. Similar to Polanyi's definition of 'tacit knowledge,' Dreyfuss's approach to skill acquisition is inherently cultural and based on experience. Hence it is personal and situated.

Similarly to Foerster's idea of Eigen Behaviors, Merleau-Ponty argued that we learn new things based on our capacity for picking flexible 'styles of behavior' instead of picking up rules (as cited by Dreyfus). We understand and learn by a recursive 'perception and action coupling' –

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[272] Such as a) sequence of muscular contractions implied in a gesture, b) the temporal structure of the gesture and c) the relative force of each muscle applied in the gesture, (Maldonato 2014. p61)

[273] Maldonato, pp 61.

[274] Based on Heidegger's present-at-hand (vorhandenheit) and ready-to-hand (Griffbereit) distinction, Dreyfus wrote a criticism to symbolic representation and approach to knowledge. See Dreyfus, Hubert L., Stuart E. Dreyfus, and Tom. Athanasiou. Mind over Machine : the Power of Human Intuition and Expertise in the Era of the Computer. New York: Free Press, 1986.

essential for accounting skillful performance– that refers to our capacity to gather critical information from our environment and the movement regulation involved in performing a certain action[275]. Thus, in the recursive coupling of perception and action, humans perform gestures to adapt to contingency, 'make sense,' and build skills as embodied knowledge. While Flusser argued that a gesture could be defined as "A movement of the body or of a tool attached with the body, for which there is no satisfactory causal explanation."[276], he also suggested that a gesture can be distinguish from regular body movement "because it represents something that is concerned with a meaning"[277]. Following the question, why gestures? Whereas much theory in the cognitive science field explains the relationship between action and perception from a functional perspective, in this research, the importance of gestures relies on how they define motion for creative purposes as generators of uniqueness based on contingency. Gesturing relates to a motion not only as an intention -which refers to a backward understanding process that requires decoding a movement in terms of its results and the causal explanation for it - but with a meaning - which is related to a forward understanding of the unfolding processes, as Ingold (2008) calls, 'always in the making.'[278]

4.11 Computing the unique: from human gestures to machine actions.

As a dialogue, the interactive nature of design becomes an intelligent exchange that embraces the unpredictability of design. The question that arises is whether gesture-based computation can serve as the foundation for interaction between humans, machines, and materials, and at the same time, reshape the way we design, make, and think through technology. What kind of computation is needed to establish methods that seamlessly merge thinking and making through the interaction of the designer, tools, and materials?

As previously demonstrated, creativity and originality are not born from preconceived ideas or plans but from the interplay between perception

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[275] Ibid. p.107

[276] Flusser, V. (2014). Gestures. (N. A. Roth, Trans.). Minneapolis: Univ Of Minnesota Press. pp 3.

[277] Ibid pp 4.

[278] Hallam, E., & Ingold, T. (Eds.). (2008). Creativity and Cultural Improvisation. New York, NY: Bloomsbury Academic. pp 3.

and action, where real-time interaction is the key to unlocking more imaginative uses of digital tools. I propose a computational design method based on gestures, transcending mere representations to embrace the contingency of design. However, to fully realize this vision, systems must be created to facilitate interaction and conversation between the agents involved. In "Making Gestures"[279], I posited that gestures are the means through which humans can communicate with machines and achieve a fluid interaction, capturing the moments where creativity and unique work emerge.

With gestures serving as the vehicle for interaction between designers and machines, developing the necessary systems to communicate and engage with machines becomes a crucial aspect of this research. Overcoming the operational and representational limitations of computational design to facilitate conversation and interaction with machines presents numerous challenges, including the need for the machine to sense, comprehend, and respond to human input accurately. To address these challenges, I propose a framework that couples human gestures with intelligent machine action.

4.13 Deep enactions: a gesture-based system for human-machine interaction

In this part, I elaborate on the tools and systems for establishing a human-machine interaction framework based on gestures. The proposition of a system based on events and actions aims to move beyond operational human-machine interactions based on representations toward a system that can regulate the execution of actions based on perceptions facilitating experimentation and creative inquiry. Following my previous work at MIT in 2015[280], I develop here a system for machine interaction based on three components.

First, I developed a gesture recognition system that aims to establish fluid communication with a machine based on three types of gestures: symbolic, exploratory, and sequential. Second, I developed a system for machine vision to detect, recognize and calculate physical objects in space. Third, I developed a system for robotic motion system using path-

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[279] Pinochet, D.I.: Making gestures: design and fabrication through real-time human-computer interaction (Master of Science Thesis). Massachusetts Institute of Technology (2015).

[280] Pinochet, 2015.

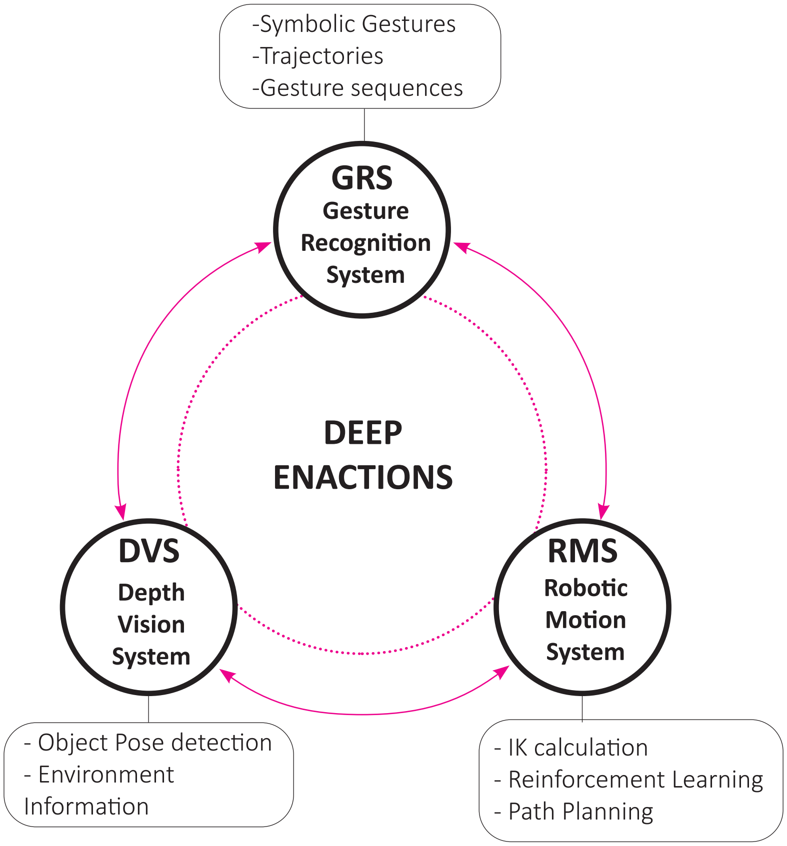

Figure 61
Deep enactions general diagram
Source: author

planning algorithms for machine movement. Finally, I integrate those three systems into a system for human-robot interaction in real-time based on gestures (figure 61).

4.13.1 Gesture recognition system

The first step to developing a gesture-based system interactive system for design was the implementation of a system that could not only detect hand positions but predict -as understanding- human intentions from those gestures. For such purpose, I developed a system for gesture training and recognition that could be trained in real-time and deployed on the go by a machine.

Hands are the most important part of our bodies to interact with the physical world. Along with the power of eyes to see and capture visual information about the world in front of us, the uniqueness of the 'gesturing hand' to sense, communicate, grasp, shape, and interface with the world constitute an essential mechanism by which we learn and think.

As Lakoff asserts, “the very structures on which reason is based emerge from our bodily sensorimotor experiences” [281]. In the case of digital computers, beyond the use of keyboards and mouse-like devices, the addition of touch-based interfaces has increased with the development of hand-held devices such as mobile phones and tablets. In addition, the advancements in augmented and virtual reality applications have pushed the development of gesture-based interfaces. In the case of the latter, detecting hand features from image have come a long way in the past decade, aided by developments in the field of computer vision and artificial intelligence[282]. In that regard, especially the video game industry in particular has pushed developments (software and hardware) to leverage body tracking and pose detection enabling real-time feedback, including full body tracking, face recognition, gaze detection, and hand detection, among others. However, detecting and tracking 3D spatial information from the body has been challenging due to the inherent ambiguities that emerge in the process of detecting a person’s features due to occlusions, fast movement, poor light conditions, and so on. In the case of full body and hand detection, the systems employed range from specialized hardware to detect body features in real-time using stereo or depth cameras to more simple approaches like monocular detection systems (to be deployed in almost any mobile device with a single RGB camera). In the case of the latter, recent developments in computer vision and deep learning have allowed the emergence of several techniques that made monocular pose estimation more affordable in terms of computation and hardware, making it almost a trivial task to implement using state-of-the-art models that can run inexpensively on almost any hardware. In the past two years, models such as GOOGLE’s MEDIAPIPE[283], META’s MEgATrack,[284] and minimal hand have improved the methods to predict hand position with high accuracy and speed, essential characteristics for hand skeletal representation and gesture prediction.

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[281] Lakoff, G. (1987). Women, Fire, and Dangerous Things (1 edition). Chicago: University Of Chicago Press. pp 371

[282] Devices like Microsoft’s Kinect or UltraLeap’s Leap Motion, or Intel’s Real Sense Cameras.

[283] Lugaresi, Camillo, Jiuqiang Tang, Hadon Nash, Chris McClanahan, Esha Uboweja, Michael Hays, Fan Zhang et al. “Mediapipe: A framework for building perception pipelines.” arXiv preprint arXiv:1906.08172 (2019).

[284] Han, Shangchen, Beibei Liu, Randi Cabezas, Christopher D. Twigg, Peizhao Zhang, Jeff Petkau, Tsz-Ho Yu, et al. 2020. “MEgATrack: Monochrome Egocentric Articulated Hand-Tracking for Virtual Reality.” ACM Trans. Graph. 39 (4). https://doi.org/10.1145/3386569.3392452.

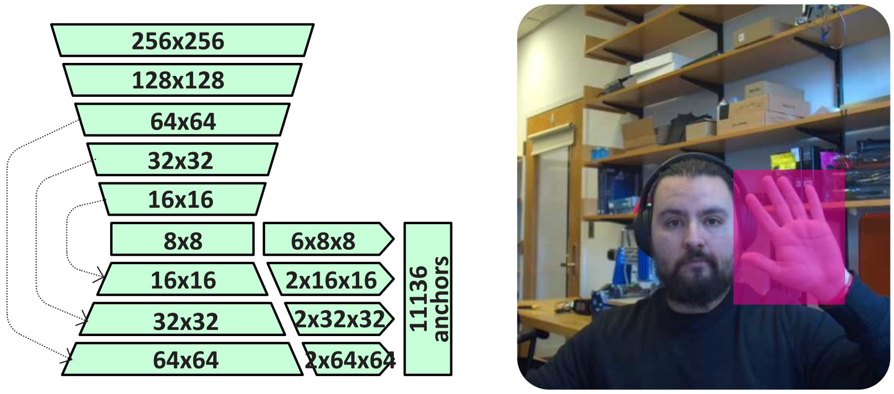

Figure 62
Blaze Palm SSD architecture
Source: author

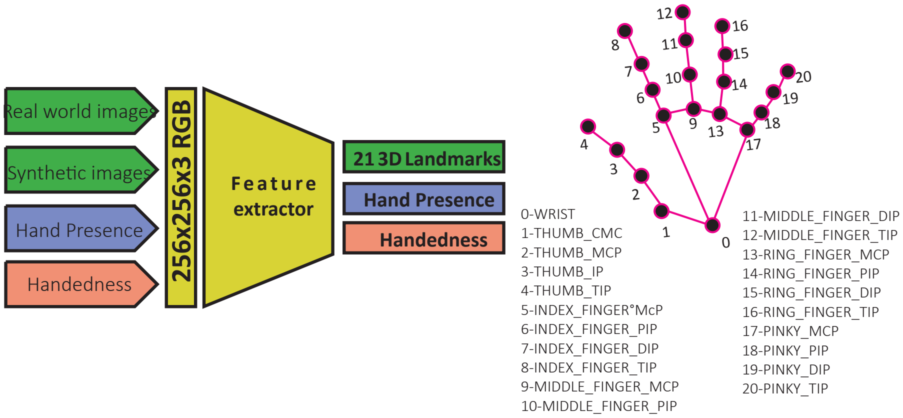

Figure 63
Hand landmark detector
Source: author

4.13.1.1 Hand detection and tracking

In this research, MediaPipe Hands[285] is used for real-time hand tracking due to its high accuracy and speed in predicting a detailed 21 points skeleton model from a single camera RBG camera. MediaPipe hand is built from two models – a palm detector and a hand landmark model- to estimate the position of a hand and its articulations, returning a list of x, y, and z coordinates. Trained on over 110K images[286], the system uses the Blaze Palm detector model (figure 62) to locate the hand in an image, get the bounding box, crop the image, and feed it to the hand landmark detector. Consequently, the hand landmark detector (figure 63) performs mark localization of 21 2.5D images (getting Z coordinate from depth estimation).

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285 Zhang, Fan, Valentin Bazarevsky, Andrey Vakunov, Andrei Tkachenka, George Sung, Chuo-Ling Chang, and Matthias Grundmann. "Mediapipe hands: On-device real-time hand tracking." arXiv preprint arXiv:2006.10214 (2020).

286 According to the paper, the dataset consisted of three groups of annotated images. 6k images of in-the-wild scenarios, 10k in-house examples with hand gestures from various angles, and 100k images generated from a synthetic dataset.

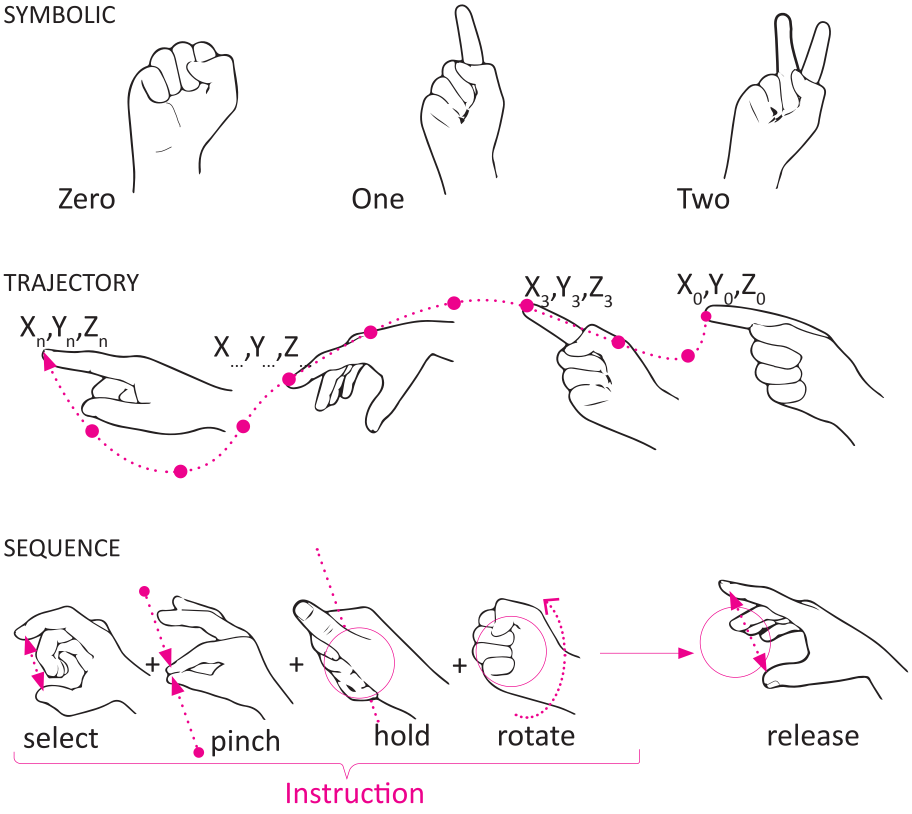

Figure 64
types of gestures
Source: author

4.13.1.2 Gesture recognition from detected hands

Performing gesture recognition from a detected hand in Media Pipe requires implementing a model that can predict gestures based on the 21 joints skeleton predicted. Distinguishing between different types of gestures becomes an essential part of the implementation. Different models can be used to discriminate regular hand movement from static gestures or gesture sequences (figure 64). Implementing different types of gesture recognition models and integrating them into the same pipeline opens novel opportunities for implementing human-machine interaction systems for design.

4.13.1.3 Types of gestures

For this implementation, three types of gesture recognition are considered: Sequence of movements, static symbolic gestures, and sequence of symbolic gestures. Each type of gesture requires different model architectures to achieve proper prediction of either a trajectory (movement sequence), a symbol (static gesture), or a

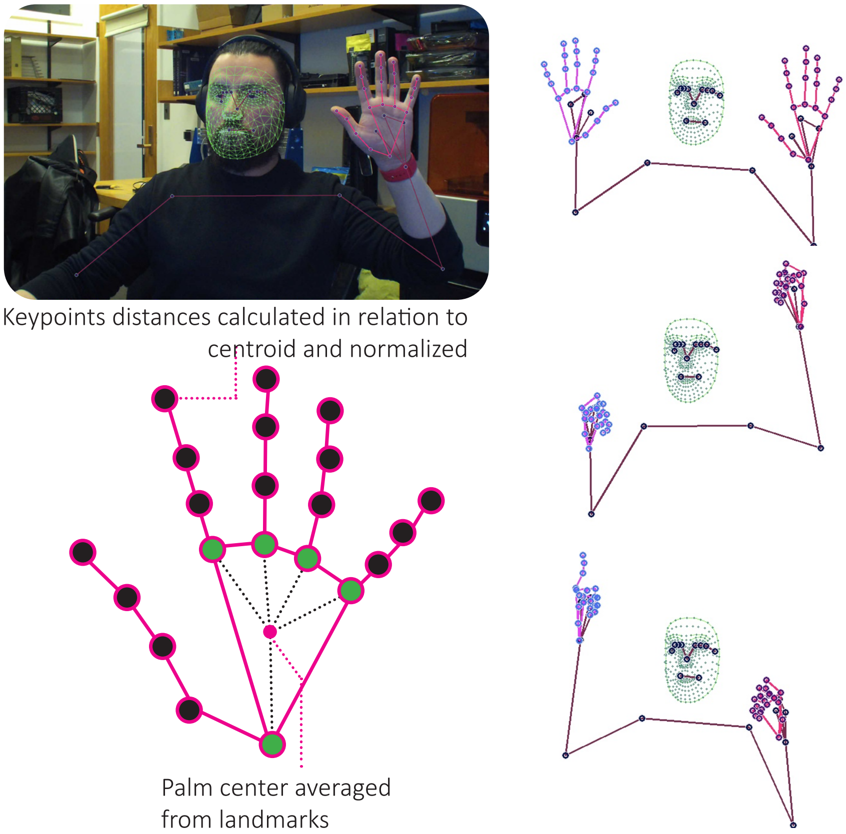

Figure 65
Gesture detection
Source: author

sequence of symbols that could be paired with a meaningful message (sequence of gestures). Because training the model is performed using MediaPipe using a dataset collected from a single RGBD camera, the data collected from each key point is normalized and calculated using relative coordinates according to the hand detected. This ensures that all the values are scale and resolution-independent (figure 65)[287].

4.13.1.4 Model description

In the case of static symbolic gestures, a simple Feed Forward Network (FFN) is implemented to learn from a collection of samples recorded as a one-dimensional vector and labeled into different categories. The model is trained from an input of 42 values (x and y coordinates from 21 key points) and N categories using a small sequential network with 3 dense layers (figure 66). The model's

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[287] A similar approach was developed for the 'design intelligence' class taught by Marcelo Coelho, Diego Pinochet, and Roy Schilkrot during the 2022 spring semester at MIT. A tutorial implementing gesture recognition was developed and can be found at https://youtu.be/3L-Z8vJeCXk

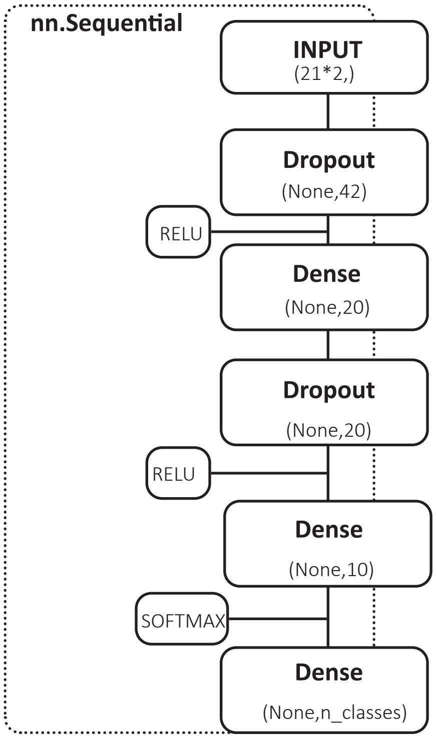


Figure 66
Feed Forward Network
Pytorch Model
architecture
Source: author

output is an array with the probabilities of every category being the predicted gesture, the one with the highest value. Using a simple FFN, it is possible to classify symbolic gestures and potentially use them for machine action.

For trajectory prediction, a Long Short-Term Memory Network is implemented. LSTMs are a type of neural network capable of learning order dependence in sequence prediction. This makes them highly suitable for classifying hand trajectory sequences from x and y coordinates. In this case, the model takes N number of sequences of X and Y samples for N categories. The sequential model uses the LSTM to predict the sequence returning a list with the probabilities of each category being the predicted category, the one with the highest value. In the same way, as symbolic gesture prediction, predicting sequences of movements could be paired with specific machine actions.

Finally, for gesture sequence prediction, a more holistic approach is needed. Whereas for classifying static gestures or movement sequences, the data from one or two hands would suffice, using

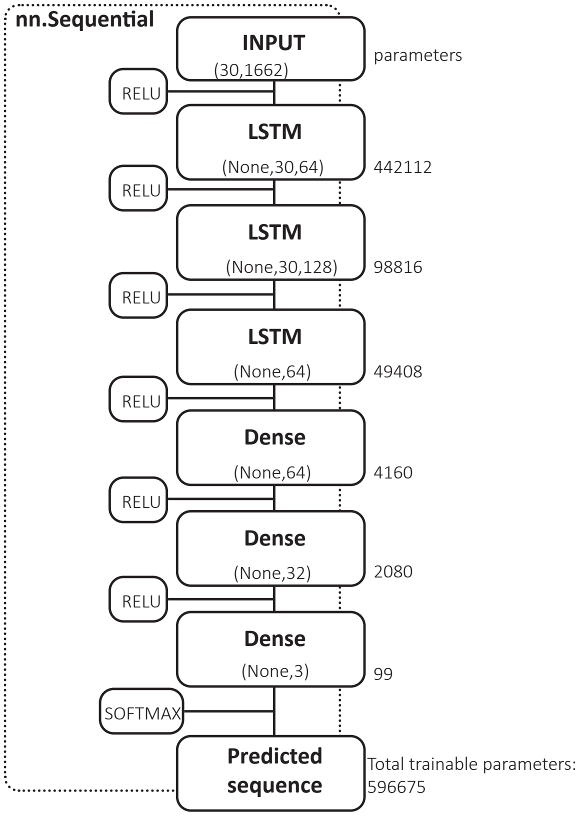


Figure 67
LSTM model
architecture
Source: author

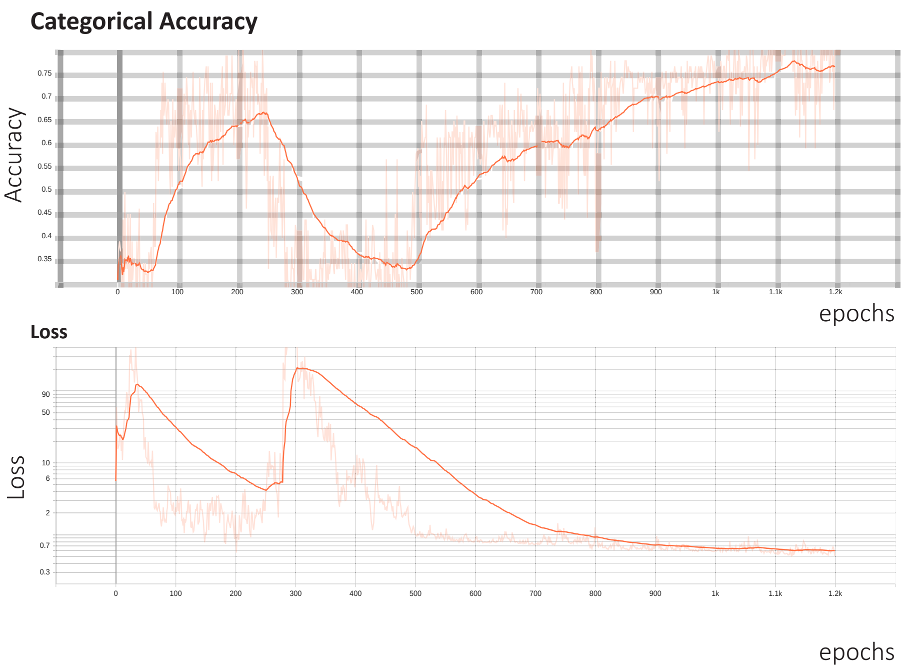
a more holistic approach using body pose estimation combined with hand tracking is needed. Although using more information (keypoints) makes training computationally more expensive and slower, having extra information to reference hand positions in relation to a sequence helps with the accuracy and success of the implementation. Implemented using Tensorflow and Keras, the different modalities that MediaPipe offers for body, face, and hand prediction, a model is built to capture n sequences of n frames and 1662 key points. The combination of MediaPipe body detection models with a sequential model using three LSTM layers allows the prediction of gesture sequences (and combinations of them) that could be paired with specific machine actions (figure 67). For example, in creating the model for predicting three gesture sequence categories, a total of 596,675 parameters are trained.

4.13.1.5 Capturing and training the data

Capturing data for each model is achieved by using a single RBG camera at 30 frames per second. Depending on the type of model used, the data is recorded in NumPy format. While the static gesture and trajectory models are relatively simple and quick to train (allowing training on the go), the gesture sequence model takes more time due to the size of the network. All the models require a different amount of data. In the case of static gesture recognition, 30 samples per category are enough to get acceptable results. For trajectory classification, more than 30 sequences per category are needed. Finally, for gesture sequence prediction, at least 30 sequences of 30 frames per category are needed. Using a dual GPU configuration (2x NVIDIA 24 GB RTX 3090), the training time ranges from 10 to 40 seconds for the static gesture model, 1.6 to 4 minutes for the trajectory model, and 45 mins to 1.2 hrs. for the gesture sequence model (figure 68).

4.13.1.6 Detecting Gestures

Once trained, it is possible to develop a system capable of detecting and classifying in real-time from a camera feed three types of gestures. Running inference over 20 fps is essential for enabling a human-machine interaction based on gestures (figure 69).


Categorical Accuracy

Loss

Figure 68
Categorical Accuracy and Loss.
Source: author

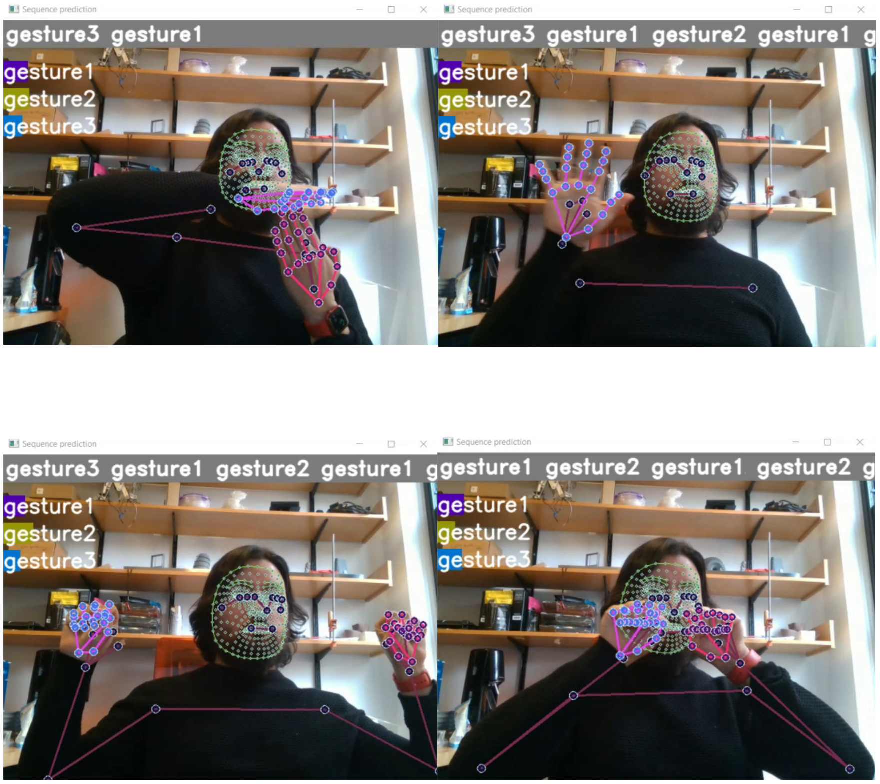


Figure 69
Gesture sequence Inference.
Source: author

4.13.2 Depth Vision System

Giving a machine the capacity to gather information about its surroundings to recognize and track objects in real time is essential for implementing a human-machine interaction framework. For this purpose, a system that gathers information from RGB-D cameras becomes necessary as physical information from the machine's surroundings is needed to perform object pose detection (6 DOF), get objects' volumetric information from point clouds, and perform path planning movements while avoiding obstacles.

Machine learning systems for object detection, object recognition, and pose estimation has seen incremental improvement over the recent years- pushed mainly by the automotive industry- to enable autonomous self-driving vehicles. Recognizing an object's main characteristics (a bounding box) and estimating its location in real-time to make inferences and take corresponding actions to enable level-3 autonomous driving and above has been a quest pursued for many years[288]. Techniques range from single-camera, multi-camera, multi-depth cameras, and LIDAR-enabled systems that can perform accurate and fast detections based on the data trained from hours of video feed. In the case of computer science and robotics, areas like robotic manipulation require the implementation of a more accurate system that perceives not only an object's general characteristics but also its finer detail to calculate grasping and manipulation. In both cases, the development of systems that not only detect and track in a fast and accurate way but also generalize -adapt correctly to new information- is a goal for deploying systems in the wild. Although recent techniques for implementing machine perception have come a long way in implementing robust monocular or depth-based 6DOF pose estimation for robotic manipulation based on deep learning models, training and implementing such systems from scratch requires a gargantuan task requiring teams of computer scientists and the hardware capable of training from 3D information[289]. Therefore, for the purpose of this research, a combination between computer

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[288] That is the case of companies like Tesla's FSD, comma.ai's OpenPilot, Rivian's Driver+, or General Motor's Super Cruise.

[289] As an example, the work of the robotic locomotion group focuses specifically on implementing systems for machine interaction with the physical environment based on robotic manipulation and planning. See https://groups.csail.mit.edu/locomotion/pubs.shtml

vision techniques and machine learning for a machine vision system is implemented. Using a combination of marker-less and marker-based approaches is used to implement a simple yet effective system for robotic vision.

4.13.2.1 Marker-based approach

A marker-based system based on synthetic binary square fiducial markers (ArUco)[290] is implemented (figure 70). The main benefit of this approach is that square markers provide enough correspondences (for corners) to obtain camera poses, and their binary codification provides robustness for error detection and correction[291]. In that regard, calculating the position and orientation of a camera and physical references becomes a straightforward task that requires simple python implementations and a dedicated static camera. Using markers allows for calculating points of 3D coordinates (world coordinates) from images (camera coordinates) in a more straightforward way. Using the camera's extrinsic (rotation R and translation T) and intrinsic parameters (focal length, optical center, and skew coefficient), it is possible to obtain a 3x4 projection matrix P. P is the result of the multiplication of the intrinsic matrix (K) and the extrinsic matrix ([R | t]) (figure 71). The goal is to use the camera calibration matrix to translate points with (u,v) parameters to 3D transforms (position and rotation) from detected objects.

4.13.2.2 Marker-less approach

A marker-less system based on machine learning models is implemented alongside the marker-based system. Whereas the marker-based system is efficient for getting fast information about the general setup, using machine learning models for object detection, segmentation, and point cloud classification allows having more information available for calculating orientations and performing machine operations such as grasping. In that regard, current techniques for object detection from real-time video have improved considerably in the past four years with the development of more efficient algorithms that can take full advantage of GPU's

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[290] Developed by Rafael Muñoz and Sergio Garrido, more information can be found here https://www.uco.es/investiga/grupos/ava/portfolio/aruco/

[291] As explained in https://docs.opencv.org/4.x/d5/dae/tutorial_aruco_detection.html

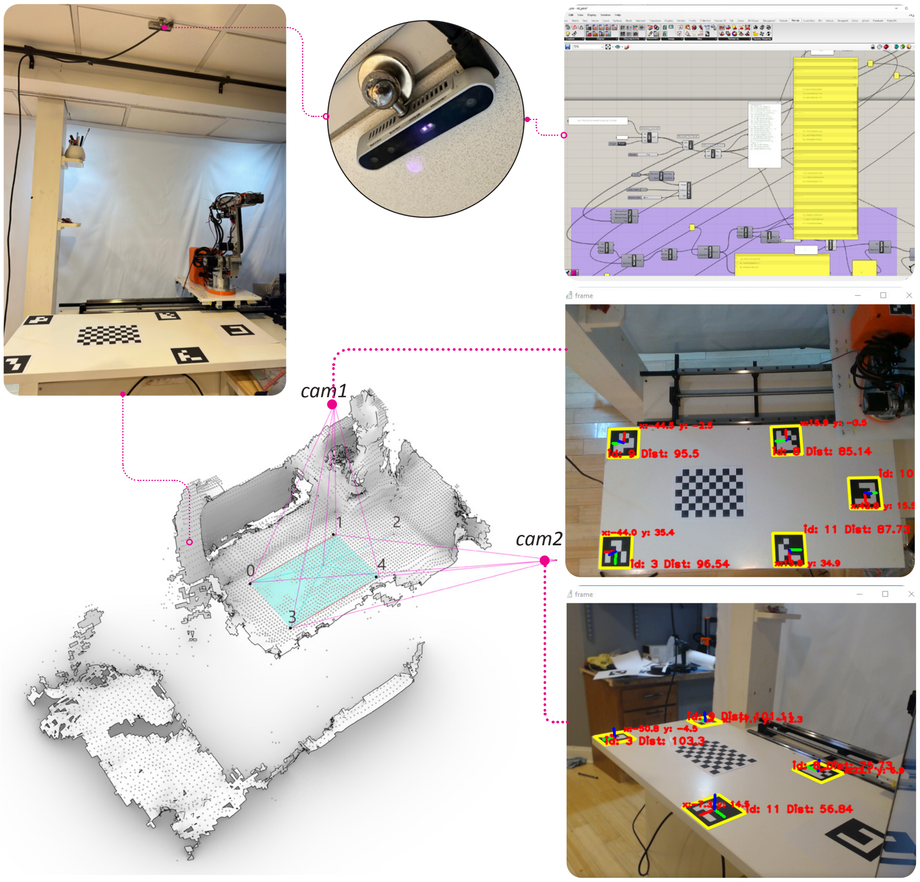
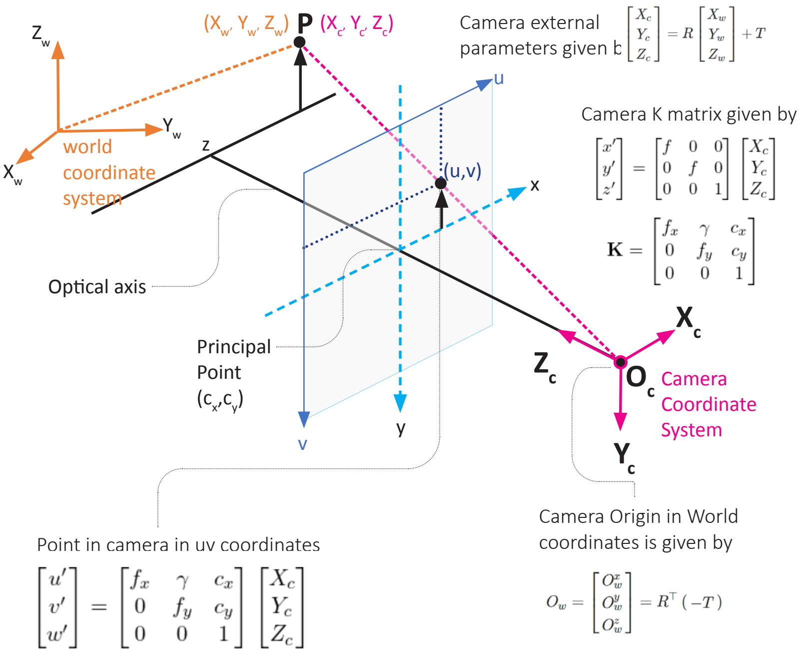


Figure 70
Marker-based system for pose estimation. The information is sent over a local server to any plattform for visualization including point cloud and mesh from the scene
Source: author



Camera external parameters given b

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = R \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} + T$$

Camera K matrix given by

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} f_x & \gamma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

Camera Origin in World coordinates is given by

$$O_w = \begin{bmatrix} O_w^x \\ O_w^y \\ O_w^z \end{bmatrix} = R^\top (-T)$$

Point in camera in uv coordinates

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} f_x & \gamma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix}$$

Figure 71
2D to 3D calculation diagram and equations
Source: author

computing power. Algorithms such as Fast RCNN[292], Faster RCNN[293], YOLO[294], or SSD[295] emerged as robust object detectors achieving great speed either in pictures or videos to output, for example, bounding boxes and segmentation masks. However, processing 3D information from objects requires alternative methods to deal with volumetric information. In that regard, new algorithms for fast object recognition and segmentation can help to improve better point cloud segmentation do to their capacity to calculate faster and generate masked representations that can eliminate intermediate steps in cleaning point clouds.

The main problem for implementing object detection and segmentation in point clouds using a real-time video feed from RGBD cameras is using powerful yet slow algorithms such as FAST RCNN that can perform very accurate detections but at an average of 5fps. Therefore, a new pipeline is proposed for real-time point cloud segmentation using YOLACT[296] as an alternative to Faster RCNN for object detection. YOLACT (figure 72) is a proven One-shot Convolutional Neural Network (CNN) for object detection capable of achieving over 30 fps and over 29.8m AP while returning high accuracy segmentation masks on MS COCO using a single GPU. Moreover, YOLACT produces high-quality masks (instead of simple bounding boxes) that are useful for translating to 3D coordinates and filter point clouds. Furthermore, this characteristic of YOLACT is the one that generates a fast and straightforward implementation for point cloud segmentation, reducing unnecessary computationally intensive steps.

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[292] Ross B. Girshick. Fast R-CNN. CoRR, abs/1504.08083, 2015. URL http://arxiv.org/abs/ 1504.08083.

[293] Shaoqing Ren, Kaiming He, Ross B. Girshick, and Jian Sun. Faster R-CNN: towards realtime object detection with region proposal networks. CoRR, abs/1506.01497, 2015. URL http://arxiv.org/abs/1506.01497.

[294] JosephRedmon, Santosh Kumar Divvala, Ross B. Girshick, and Ali Farhadi. You only look once: Unified,real-time object detection. CoRR, abs/1506.02640, 2015. URLhttp://arxiv.org/ abs/1506.02640.

[295] WeiLiu, Dragomir Anguelov, Dumitru Erhan, Christian Szegedy, Scott E. Reed, Cheng-Yang Fu, and Alexander C. Berg. SSD: single shot multibox detector. CoRR, abs/1512.02325, 2015. URL http://arxiv.org/abs/1512.02325.

[296] Daniel Bolya, Chong Zhou, Fanyi Xiao, and Yong Jae Lee. YOLACT: real-time instance segmentation. CoRR, bs/1904.02689, 2019. URLhttp://arxiv.org/abs/1904.02689.

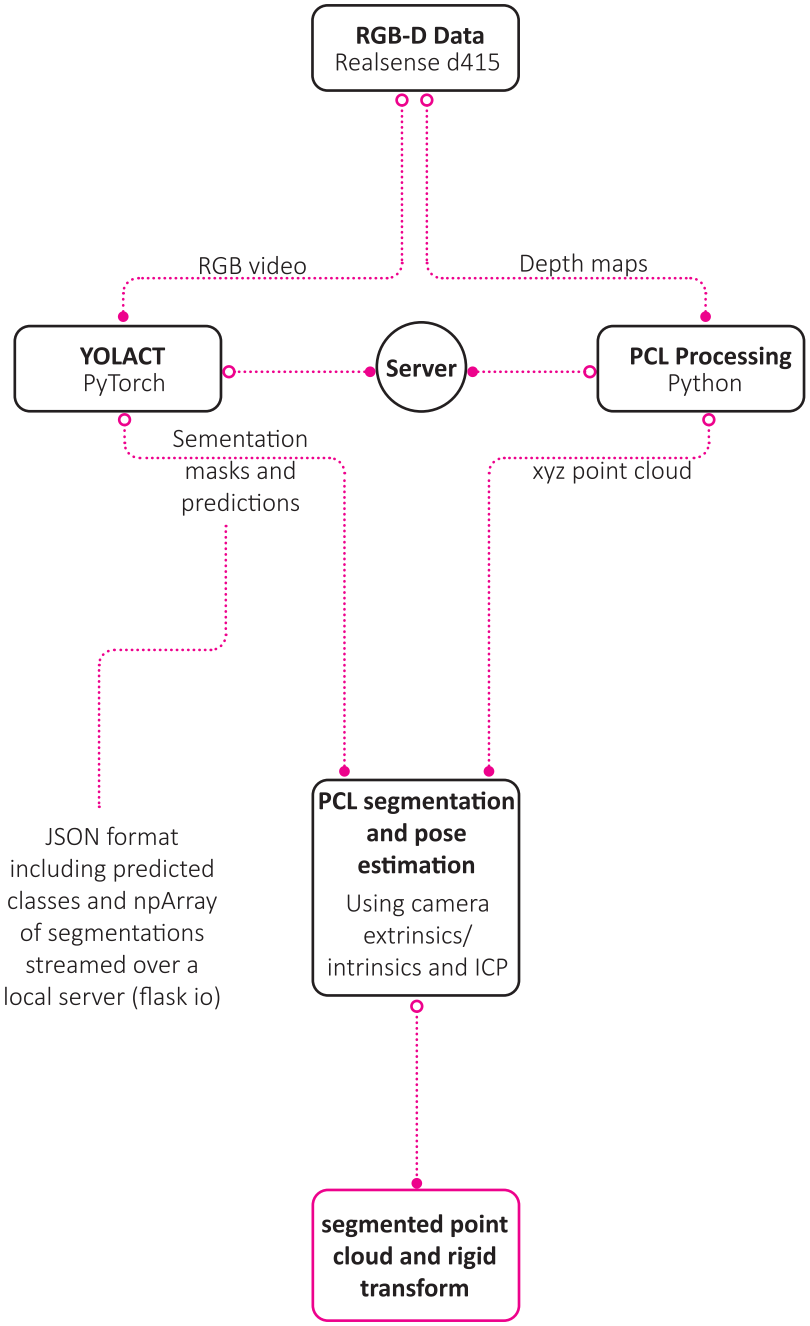


Figure 72
Yolact architecture and diagram implementation
Source: author

4.13.2.3 Hardware and software setup

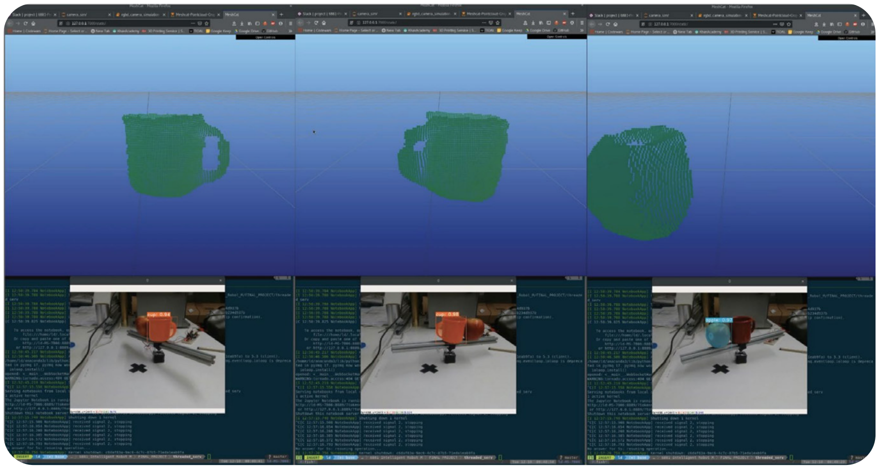
Using two intel d415 RealSense RGBD cameras, the system receives from each camera two data streams at 30 fps: A RGB image from the primary Full HD sensor and point cloud data from the stereoscopic depth sensor. Both data streams are separated as RGB data ([1920, 1080, 3] RGB pixel array) and point cloud data ([1280, 720, 3] np array XYZ) for individual processing. Video images are processed through YOLACT to generate segmented mask detections, and point cloud data is processed through a custom python program to get an oriented point cloud in space (figure 73). A significant challenge to producing a scalable pipeline was building a server that enabled simultaneous streaming of different components for multiple clients required for "real-time" point-cloud segmentation. Finally, a server was implemented to connect all the services and data channels. The server provides endpoints to the segmentation-Masks, as well as RGB and depth streams. Utility functions handle the calculation of the point cloud vectors and pair them with the correct masks. The server provides data for multiple clients and handles streams and requests asynchronously.

4.13.2.4 Integrating systems.

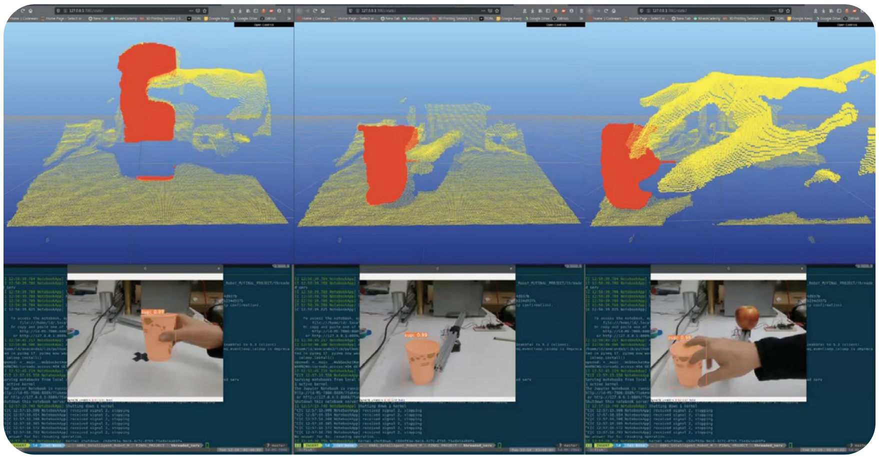
Marker-based and marker-less systems were integrated into one single pipeline that can retrieve position, rigid transform, and volumetric information from objects. Although combining computer vision and machine learning models for object recognition and pose estimation is possible, more work is needed for its utilization in non-ideal scenarios. Specialized hardware and better models need to be trained and deployed to work under the constraints derived from off-site deployment where nonideal light conditions and setups like the ones used in this project are not possible to implement.

4.13.3 Robotic motion system

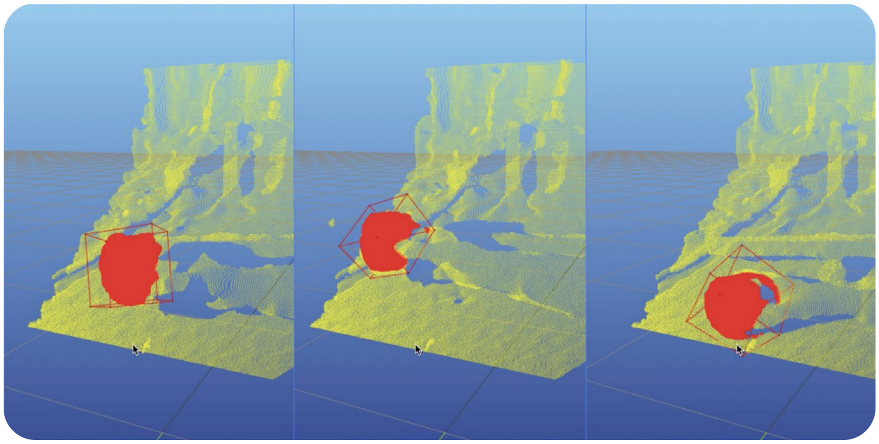
Finally, the last component of this project is a system that takes user inputs and determines machine actions. Pairing human gestures with machine action requires the development of systems that can receive inputs and calculate an output in the form of robotic movement in response. The implementation of this part of the project aims to develop a system to generate machine actions from



Point cloud segmentation in real time



Point cloud segmentation in occluded scenarios



Segmentation and transform calculation with bounding Volume

Figure 73
System detecting and filtering objects in 3D.
Source: Pinochet and Lesina-Debiasi, 2019

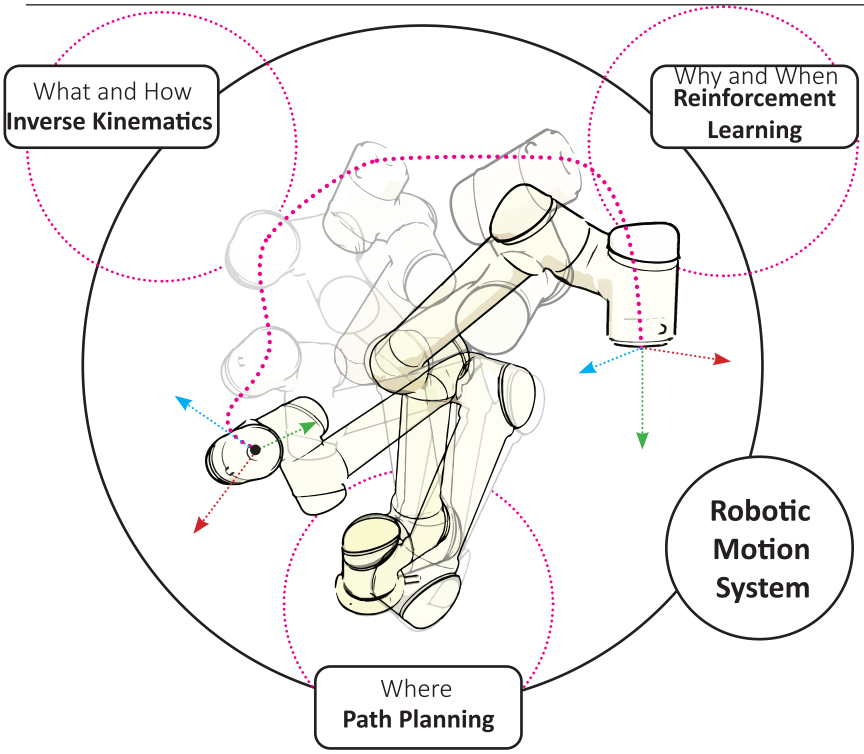


Figure 74
Robotic motion system
Source: author

real-time input instead of a predefined program. The goal is to complete a framework that moves from an operational paradigm to one based on interaction as a system capable of auto-regulating its actions based on a bidirectional exchange of information between agents. In this research, a 6DOF robotic arm motion system is developed, considering that a robotic arm is a generic-purpose model that can serve the purpose of implementing several proof-of-concept projects from a single platform. Enabling an exchange between agents (humans and machines) involves the generation of sub-components in a system capable of sensing, calculating, and performing a set of actions in response to the contingency of an interaction. Therefore, a system for robotic motion combining modules for inverse kinematics calculation (What and How to move), Reinforcement Learning (Why and When to move), and path planning (Where to move) was implemented (figure 74).

4.13.3.1 What and How to move: calculating Inverse kinematics

The use of 6 DOF robotic arms, in the same way as most computer numerically controlled machines (CNC), requires the calculation of movement according to predefined programs to achieve specific

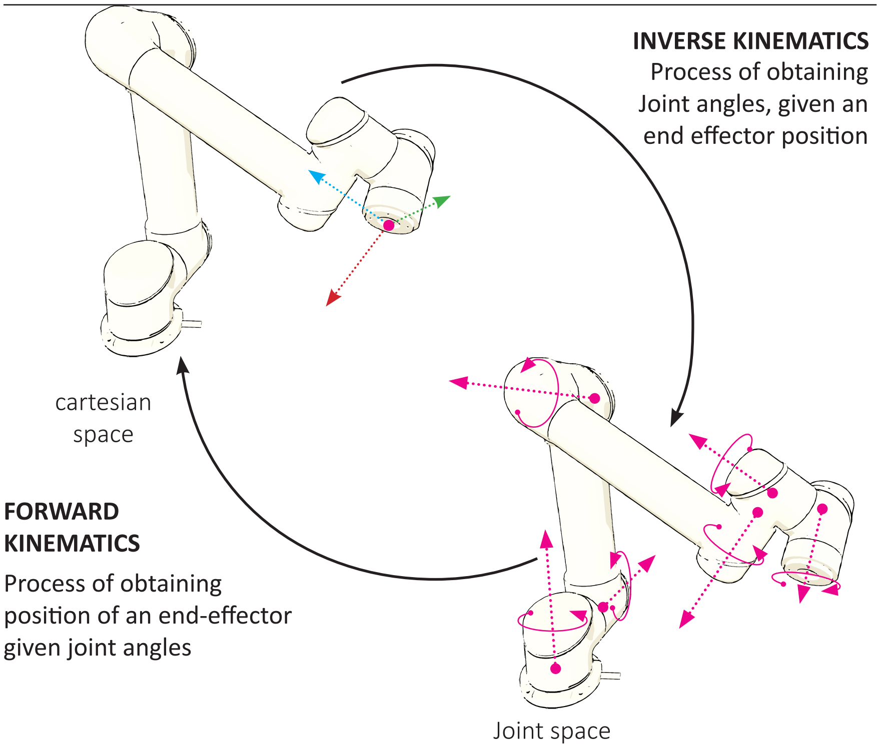


Figure 75
Inverse kinematics vs
forward diagram
Source: author

movements. Whereas most 3D printers or CNC milling machines are built as three-axis machines (XYZ movement) in which movement is a relatively simple task to compute as they usually move parallel to one plane of work. Working with machines with more degrees of freedom requires more complex calculations to perform efficient movements. Whereas Forward kinematics (FK) provides the means to calculate the equations to compute the position of the end-effector from a set of joint parameter values, in the case of articulated machines, such as industrial robots with three or more degrees of freedom, their movement can be calculated using what is known as Inverse Kinematics (IK). Moreover, as articulated robot arms are general-purpose positioning tools that have the ability to move freely in space, IK calculation plays a crucial part in determining the position, precision, and calculation time of an end-effector oriented according to a target (figure 75). As articulated robot arms are general-purpose positioning tools that have the ability to move freely in space, the solution strategies to solve efficient and collision-free trajectories are generally split into two classes: numerical or analytical (including trigonometry and algebraic methods) solutions[297].

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[297] For a complete overview of Robotic mechanical control see Craig, J. J. (2004) Introduction to Robotics: Mechanics and Manipulations, 3rd ed. Pearson Education.

Numerical methods perform iterative calculations generally using methods such as the Newton-Raphson, the Gauss-Newton, or the Inverse Jacobian technique. The main characteristic of numerical solutions to IK problems is that due to the difficulty of inverting kinematics equations in configurations with more than 6 DOF, an approximate solution is, in most cases, found. Other characteristics and advantages of numerical methods are avoiding deadlock[298] caused by joint limits and providing solutions for robot configurations that don't have analytical solutions. A disadvantage of numerical methods is that finding the solution for the IK problem is computationally more expensive due to the iterative optimization that is performed, making them more time-consuming when real-time tasks are required.

In analytical methods for IK calculation, each joint angle is calculated from the pose of the end effector based on mathematical formulas. Especially suitable for small DOF configurations due to the nonlinearity of the kinematic equations, the solutions can be calculated using algebraic, geometrical, or hybrid approaches combining both methods. For example, for a typical industrial robot with 6-DOF the general approach is solving the equations using algebraic methods[299]. One of the main disadvantages of analytical methods is that defining the kinetic diagram and trigonometric equations is time-consuming to derive. Another disadvantage is that the solutions for one kinetic configuration don't generalize to other robots (requiring the elaboration of new equations). However, the main advantage of analytical methods is that once the kinetic configuration has been determined and the corresponding equations have been derived, the calculation is fast and with a low computational cost. This characteristic makes analytical IK calculations highly suitable for real-time calculations.

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[298] When working in setups with two or more robots, joint limits can lead to potential collisions in coordinated path calculation. See O'Donnell, Patrick A., and Tomas Lozano-Perez. "Deadlock-free and collision-free coordination of two robot manipulators." In 1989 IEEE International Conference on Robotics and Automation, pp. 484-489. IEEE Computer Society, 1989.

[299] See Wang, Kesheng and Terje K. Lien. "Structure design and kinematics of a robot manipulator." ***Robotica*** 6 (1988): 299 – 309, or Tsai, L-W, and A. P. Morgan. Solving the Kinematics of the Most General Six- and Five-Degree-of-Freedom Manipulators by Continuation Methods. Journal of Mechanisms, Transmissions, and Automation in Design 107, no. 2 (06 1985): 189–200. https://doi.org/10.1115/1.3258708, and Lloyd, John, and Vincent Hayward. Kinematics of Common Industrial Robots. Robotics and Autonomous Systems 4,

no. 2 (1988): 169–91. https://doi.org/10.1016/0921-8890(88)90024-3

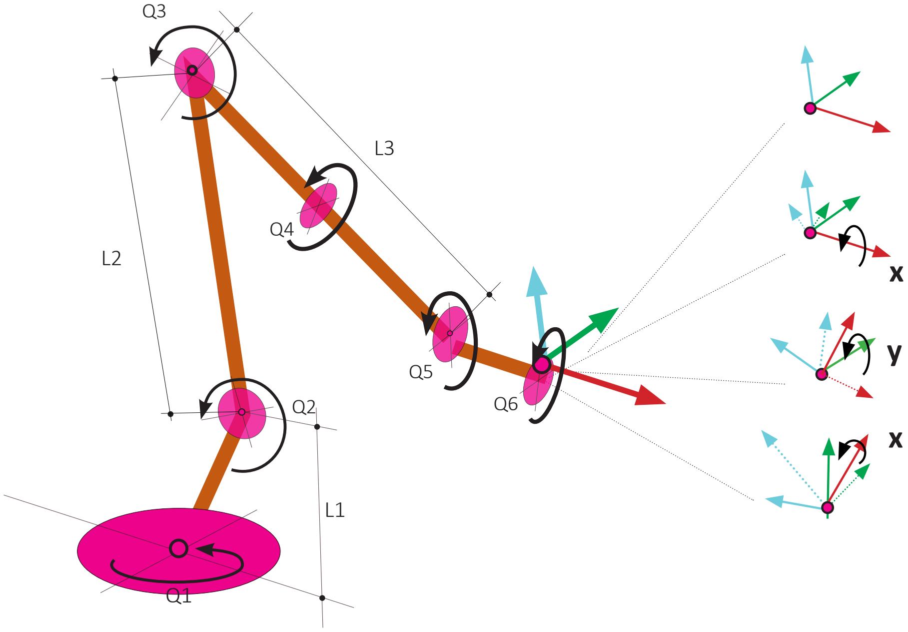

Figure 76
Kinematic diagram of a 6DOF robot arm
Source: author

$$
{}^{0}_{6}T = \begin{bmatrix} {}^{0}_{6}R & {}^{0}_{6}P_{ORG} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} {}^{0}_{6}R_{11} & {}^{0}_{6}R_{12} & {}^{0}_{6}R_{13} & {}^{0}_{6}P_{ORGx} \\ {}^{0}_{6}R_{21} & {}^{0}_{6}R_{22} & {}^{0}_{6}R_{23} & {}^{0}_{6}P_{ORGy} \\ {}^{0}_{6}R_{31} & {}^{0}_{6}R_{32} & {}^{0}_{6}R_{33} & {}^{0}_{6}P_{ORGz} \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Figure 77
transformation matrix
source: author

Joint i	θ_i (deg)	α_i (deg)	r_i (cm)	d_i (cm)
1	θ_1	90	0	a_1
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0
4	$\theta_4 + 90$	90	a_5	0
5	θ_5	0	0	$a_4 + a_6$

For the work here, using a traditional industrial 6-DOF configuration makes elaborating the proper software for kinematic calculations a more straightforward process. In traditional 6-DOF configurations, the calculation of IK can be solved by breaking down the problem into two smaller ones. In the presence of a spherical twist manipulator, kinematic decoupling allows determining the inverse position and the inverse orientation separately. Moreover, because the position of the wrist is affected by the first three joints of the manipulator (figure 76), even if the rest of the joints are actuated, the position of the wrist doesn't change. Hence, the transformation matrix of the system can be decomposed into a translation and rotation matrix with three unknown parameters (figure 77). Following a geometric approach and once the Denavit-Hartenberg parameters (DH parameters) have been established, the calculation of the Inverse position is determined by the first three joints in the system (q1, q2, q3) that corresponds to the wrist center point (o_c). After obtaining the first three joint angles from a given wrist position, finding the orientation is possible using Euler angles. The orientation of the wrist is given by the angles Φ, θ, and Ψ, also known as Roll, Pitch, and Yaw, respectively (figure 78). The analytical approach for solving IK in a 6-DOF system is straightforward, returning eight possible joint configurations.

A C# implementation was programmed using the analytical method[300] to calculate a typical 6-DOF IK configuration that works both in UNITY 3D and Grasshopper for Rhinoceros 3D. Also, tools for plane interpolation were written to perform and calculate path trajectories and test IK simulations (figure 79).

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[300] Other algorithms were implemented such as FABRIK and CCD, however, a simple geometric approach to IK was faster and more efficient for real time calculations.

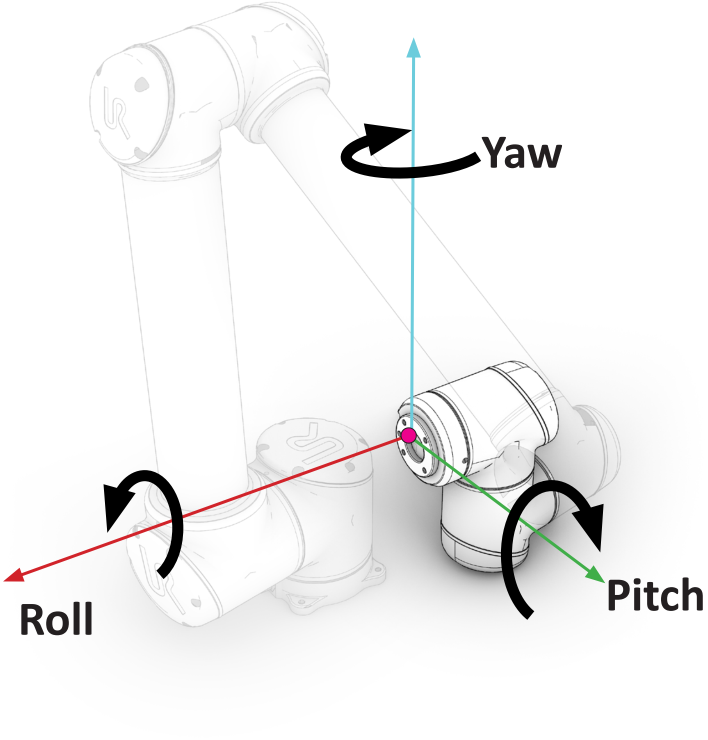

Figure 78
End effector Roll, pitch and yaw diagram
Source: author

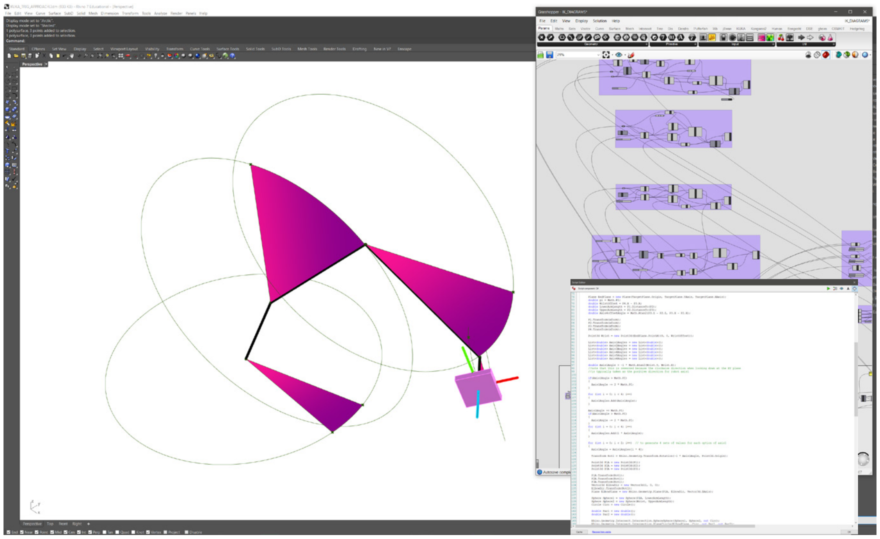

Figure 79
Inverse kinematics working in GH and Unity
Source: author

4.13.3.2 Why and When to move: Reinforcement learning for intelligent robotic motion.

After implementing an IK calculation method that dictates what and how to move, the next step was developing a system that can give autonomy to a robotic system to perform a movement. Furthermore, giving a computational system the means to discern why and how to move given a particular set of inputs (i.e., a human gesture) needs implementing more sophisticated systems that can learn new skills and adapt to their environment. In that regard, Reinforcement Learning (RL), a subfield of machine learning, provides the methods for training machines to make sequences of decisions in complex environments. Starting from a fundamental question: How to learn a new skill? RL provides a model based on how humans learn to develop intelligent machine behavior. Whereas most popular machine learning techniques are in the domain of supervised[301] or unsupervised[302] learning, reinforcement learning introduces a third type of paradigm for learning based on the interaction of agents within an environment.

Reinforcement Learning has roots in psychological theories of trial-error learning, optimal control theories, and temporal-difference methods[303]. However, the connectionism theory developed by Edward Thorndike[304] focused on how animals learn tasks through imitation and observation and served as the theoretical base to develop a model for modern reinforcement learning. After early research conducted in the late 50s[305] and early 60s[306], reinforcement learning largely dissapeared from the artificial intelligence field until the early 1980s when new theories on

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[301] Performing a classification or regression based on curated/labeled trained data.

[302] Understanding and clustering data based on unlabeled, non-curated data.

[303] As indicated in “Introduction: The Challenge of reinforcement learning” in Sutton, Richard S. Reinforcement Learning. Boston: Kluwer Academic Publishers, 1992.

[304] See Thorndike, Edward. Educational Psychology: By Edward L. Thorndike. The History of Education: Psychology. New York: The Science Press, 1903.

[305] See Samuel, A.L. (1959). Some studies in machine learning using the game of checkers. IBM Journal on Research and Development, 3, 210-229. Reprinted in E.A. Feigenbaum & 1. Feldman (Eds.), Computers and Thought, 71-105, New York: McGraw-Hili, 1963.

[306] See Minsky, M.L. (1961). Steps toward artificial intelligence. Proceedings IRE, 49.8-30. Reprinted in E.A. Feigenbaum & J. Feldman (Eds.), Computers and Thought., ·406-450, New York: McGraw-Hili, 1963. Available at https://courses.csail.mit.edu/6.803/pdf/steps.pdf

genetic classifier systems[307][308], learning automata theory[309], and new links to optimal control and dynamic programming theory pushed the development of new research[310][311]. The modern conception of reinforcement learning was built around the work compiled by Barto and Sutton in "reinforcement learning: an introduction,"[312] where popular algorithms such as Q-learning, or actor-critic, are discussed extensively, locating RL as one of the three main paradigms of ML.

As discussed previously, in this research, intelligence is understood as a process of showing intelligent behavior from the interaction between agents within an environment. Moreover, it was discussed how, from a cybernetic perspective, design is inherently computational as it involves calculation between different entities. Also, it was discussed how Design intelligence is the ability to acquire, generate and apply design knowledge. Along the same lines, the notion of intelligence used here is understood as an intelligent interaction between agents and objects within an environment. Moreover, similarly to how humans learn and adapt to the contingencies of a computational process, the development of machines that can show intelligent behavior by learning from the interactions in which they are participants is needed. In that regard, Reinforcement learning provides the means – as its definition asserts – to map from situations to actions in a similar fashion as humans do. Hence, the learning agent is not programmed with a sequence beforehand but learns which actions to take given a situation based on a numerical reward function. In this project, learning why and when to take action is crucial to enable a proper conversation and computational exchange between humans and machines.

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[307] See Holland, J.H. (1975). Adaptation in natural and artificial systems. Ann Arbor, MI: Univ. of Michigan Press.

[308] Holland, 1.H. (1986). Escaping brittleness: The possibilities of general-purpose learning algorithms applied to parallel rule-based systems. In: R.S. Michalski, 1.G. Carbonell, & T.M. Mitchell (Eds.), Machine learning, An artificial intelligence approach, Volume II, 593-623, Los Altos, CA: Morgan Kaufman

[309] Narendra, K.S. & Thathachar, M.A.L. (1974). Learning automata-a survey. IEEE Transactions on Systems, Man, and Cybernetics, 4, 323-334. (Or see their textbook, Learning Automata: An Introduction, Englewood Cliffs, NJ: Prentice Hall, 1989.)

[310] Werbos, P.1. (1987). Building and understanding adaptive systems: A statistical/numerical approach to factory automation and brain research. IEEE Transactions on Systems, Man and Cybernetics, Jan-Feb.

[311] Werbos, P.1. (1987). Building and understanding adaptive systems: A statistical/numerical approach to factory automation and brain research. IEEE Transactions on Systems, Man and Cybernetics, Jan-Feb.

[312] Sutton, Richard S. Reinforcement Learning. Boston: Kluwer Academic Publishers, 1992.

Implementing reinforcement learning requires learning what to do and establishing a model to map situations to actions. In that regard, if we take as an example how a baby learns how to walk, it is possible to extrapolate the general framework to establish the components of that model. In the case of a baby learning how to walk, a conceptual model for learning can be formalized in the following way:

a- The problem: learning to walk
b- The agent: a child
c- The environment: A surface to walk on
d- The set of actions: taking steps.
e- The set of states: walking, standing, sitting.
f- The reward: A hug from the mom or dad, a piece of candy, etc.
g- The policy: the sequence of actions that lead to a state change.

In the scenario of a child (agent) learning to walk (the problem), a child tries to manipulate its environment (a floor or surface to walk on) by performing actions (walking) by changing from one state to another (laying on the floor, standing, taking a step). At every step of the process (following a sequence of actions or policy), a reward (love from the parents) is at stake according to how well sub-modules of the task are accomplished (changes of state). Getting closer to the parents following a sequence of actions (a policy or function that returns an action to change the agent's state) represents a positive reward. In contrast, in the opposite case, falling and staying on the floor will result in a negative reward (figure 80 and figure 81).

A mathematical framework for defining one standard reinforcement learning model is based on what is called a Markov Decision Process (MDP), which can be designed similarly to the previous example. To design an MDP, we need the following:

a. A set of states, S
b. A set of Actions, A
c. A reward function, R
d. A policy,
e. A Value, V

In short, we have to take an action "A" to transition from our original state "S_0" to our final state "$S_{n.}$" In return, we get a reward "R" for each action we take, which can lead to a positive or negative reward. The actions we

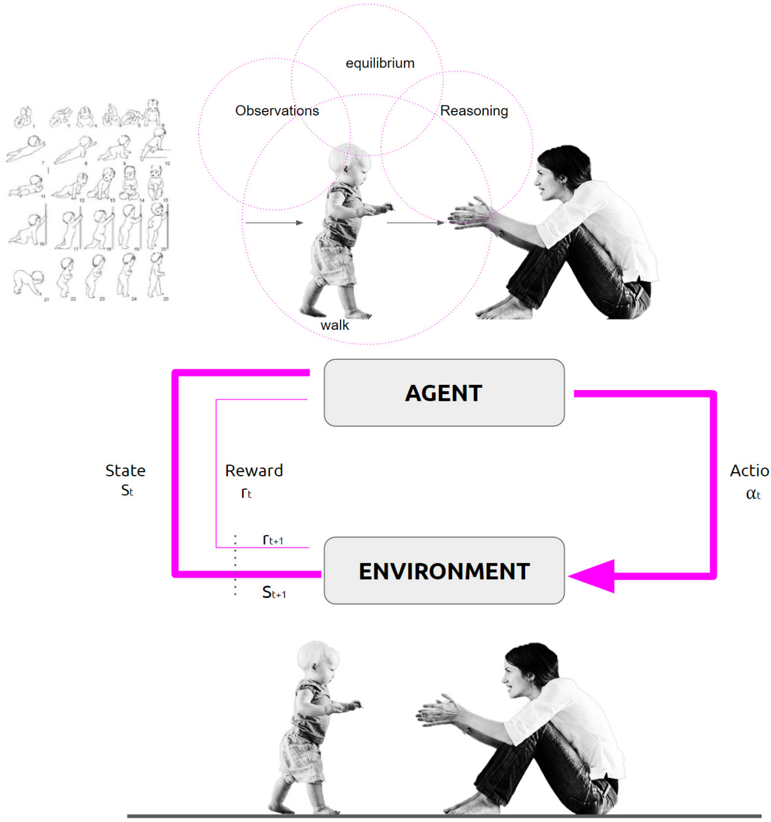

Figure 80
Source: author

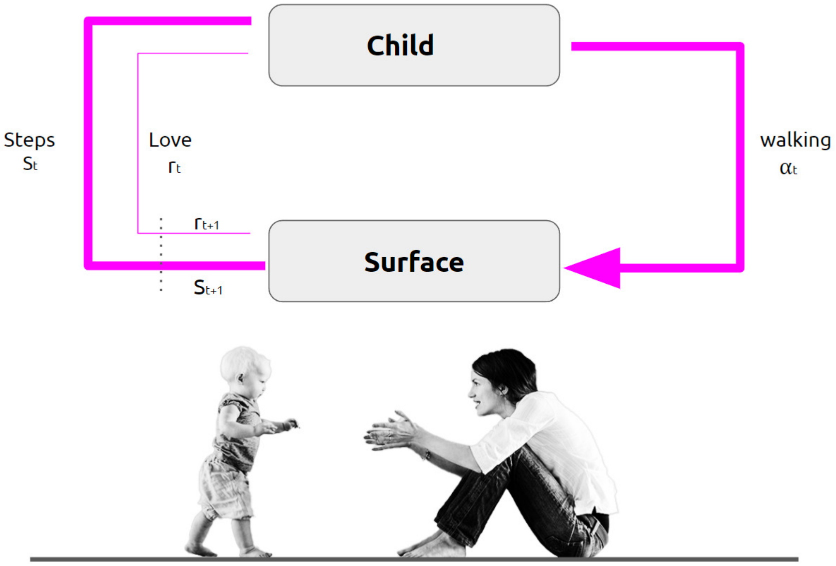

Figure 81
Source: author

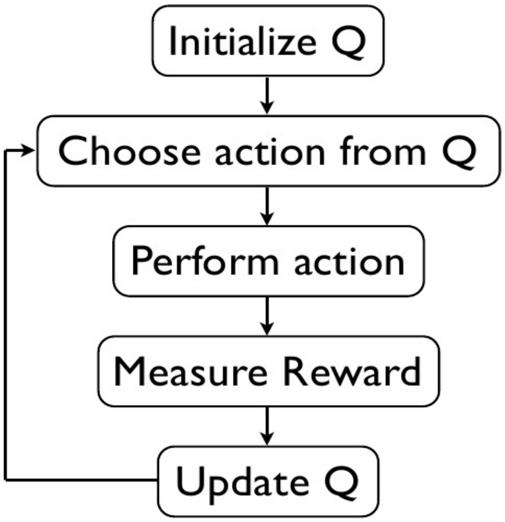

Figure 82
Q-learning diagram
Source: author

take over time define a policy “” while the rewards we get in return for such actions define a value “V” representing the cumulative reward over time. Hence, the task is to maximize the rewards by choosing over time the right policy. The way this optimization happens is by maximizing E(r_t | π, S_t) for all possible values of S for a time t[313.]

Another method is known as Q-Learning. It is a value-based, off-policy approach of supplying information to indicate to an agent which action should take. It is known as a model-free algorithm because it does not need an environmental model and can handle solutions by assessing the qualities of the actions taken at a particular time. The difference with MDPs is that instead of implementing a pure stochastic search, it aims to find the best course of action given the current state.

A typical pseudo-code implementation for Q-learning can be determined like this (figure 82):

a. Initialize (declare) a Values table ‘Q(s,a)’
b. Observe the current state ‘s’
c. Choose an action ‘a’ for the current state based on one of the action selection policies.
d. Take the selected action, and observe both the reward ‘r’ and the new state ‘s’
e. Update the state Value using the observed reward and the

---

[313] Taken from http://www.mshahriarinia.com/home/ai/machine-learning/reinforcement-learning

maximum reward possible for the next state.

f. Update the current state to the new state, and repeat until episodes in the optimization are finished, or the terminal state is reached.

In reinforcement learning, there are three categories of algorithms:

a. Policy-based: where the goal is to find an optimal policy. There are two main policy-based methods: deterministic and stochastic.
b. Value-based: where the goal is to find the optimal value. For example, the cumulative reward.
c. Model-based: Where different environments are created to train an agent.

In recent years, reinforcement learning has had significant breakthroughs with the emergence of new algorithms that are being applied in real-life scenarios such as self-driving cars[314], health care[315], the video game industry[316], and so on. The field of robotics, in particular, has implemented reinforcement learning[317] to deploy machines on-site that can learn, adapt and respond to environmental changes. Implementations such as Trust Region Policy Optimization (TRPO)[318], Proximal Policy Optimization (PPO)[319], or Asynchronous Actor-Critic Agents (a3C) have become highly popular as the models were capable of learning and performing highly complex tasks. Nevertheless, these On-Policy algorithms presented some drawbacks

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[314] https://www.wayve.ai/

[315] Yu, Chao, Jiming Liu, Shamim Nemati, and Guosheng Yin. 'Reinforcement Learning in Healthcare: A Survey'. ACM Comput. Surv. 55, no. 1 (November 2021). https://doi.org/10.1145/3477600.

[316] Juliani, Arthur, Vincent-Pierre Berges, Ervin Teng, Andrew Cohen, Jonathan Harper, Chris Elion, Chris Goy et al. "Unity: A general platform for intelligent agents." arXiv preprint arXiv:1809.02627 (2018).

[317] Kormushev, Petar, Sylvain Calinon, and Darwin G. Caldwell. 2013. "Reinforcement Learning in Robotics: Applications and Real-World Challenges" ***Robotics*** 2, no. 3: 122-148.

[318] Schulman, John, Sergey Levine, Pieter Abbeel, Michael Jordan, and Philipp Moritz. "Trust region policy optimization." In International conference on machine learning, pp. 1889-1897. PMLR, 2015.

[319] Schulman, John, Filip Wolski, Prafulla Dhariwal, Alec Radford, and Oleg Klimov. "Proximal policy optimization algorithms." arXiv preprint arXiv:1707.06347 (2017).

in relation to their need to collect new samples after each policy update. In contrast, although off-policy algorithms such as Q-learning[320], Deep Deterministic Policy Gradient (DDPG),[321] or Twin Delayed Deterministic Policy Gradient (TD3PG)[322] can learn from past samples using experience replay buffers, the high sensitivity to parameter configurations makes them brittle and require significant hyperparameter tunning to converge.

In this project, a reinforcement learning algorithm called Soft-Actor-Critic (SAC)[323] was used because it introduced mechanisms to solve the problems of the methods previously mentioned, requiring fewer samples while combating convergence brittleness. SAC introduced a modified RL objective function that maximizes both the reward and the policy's entropy. In the case of SAC, a high entropy (related to how unpredictable a variable is) of the policy means that the algorithm will encourage exploration. With a high entropy, the policy will assign equal probabilities to actions with similar Q-Values, ensuring that the model won't collapse by repeatedly choosing a particular action that can exploit the Q function.

Along with the actor-critic model, the modified objective function introduced by SAC makes it highly suitable for the inquiries of this research as it learns to generalize to conditions the agent didn't see during training. The structure behind SAC is explained in figure 83, in which two networks, an actor and a critic, interact to learn the best policy for action (figure 84). The Actor model has to learn what actions to take under a particular observed state of the environment. It does so by taking observations from a simulation as input and giving a particular action as output. In the case of the Critic model, it takes as input the action returned by the Actor model and observes what happens in

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[320] See Watkins, C.J.C.H., Dayan, P. Q-learning. Mach Learn 8, 279–292 (1992). https://doi.org/10.1007/BF00992698

[321] Lillicrap, Timothy P., Jonathan J. Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. "Continuous control with deep reinforcement learning." arXiv preprint arXiv:1509.02971 (2015).

[322] Cui, Q.; Kim, G.; Weng, Y. Twin-Delayed Deep Deterministic Policy Gradient for Low-Frequency Oscillation Damping Control. Energies 2021, 14, 6695. https:// doi.org/10.3390/en1420669

[323] See Haarnoja, Tuomas, Aurick Zhou, Pieter Abbeel, and Sergey Levine. "Soft actor-critic: Off-policy maximum entropy deep reinforcement learning with a stochastic actor." In International conference on machine learning, pp. 1861-1870. PMLR, 2018. And also Haarnoja, Tuomas, Aurick Zhou, Kristian Hartikainen, George Tucker, Sehoon Ha, Jie Tan, Vikash Kumar et al. "Soft actor-critic algorithms and applications." arXiv preprint arXiv:1812.05905 (2018).

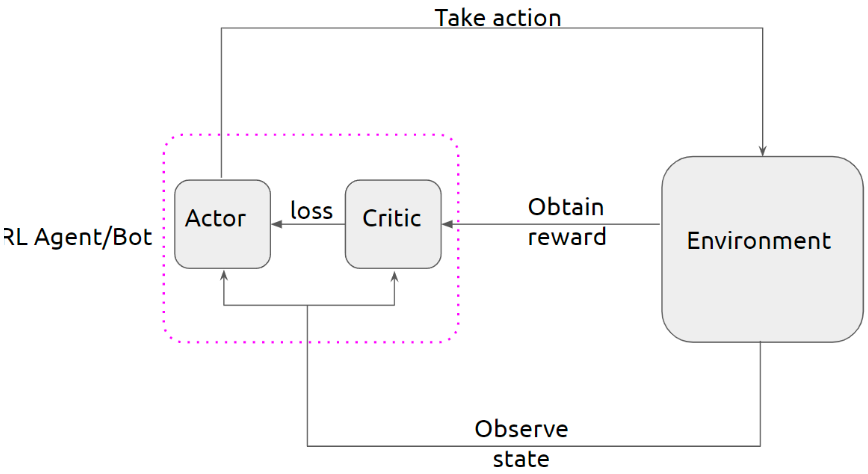

Figure 83
The SAC model
Source: author

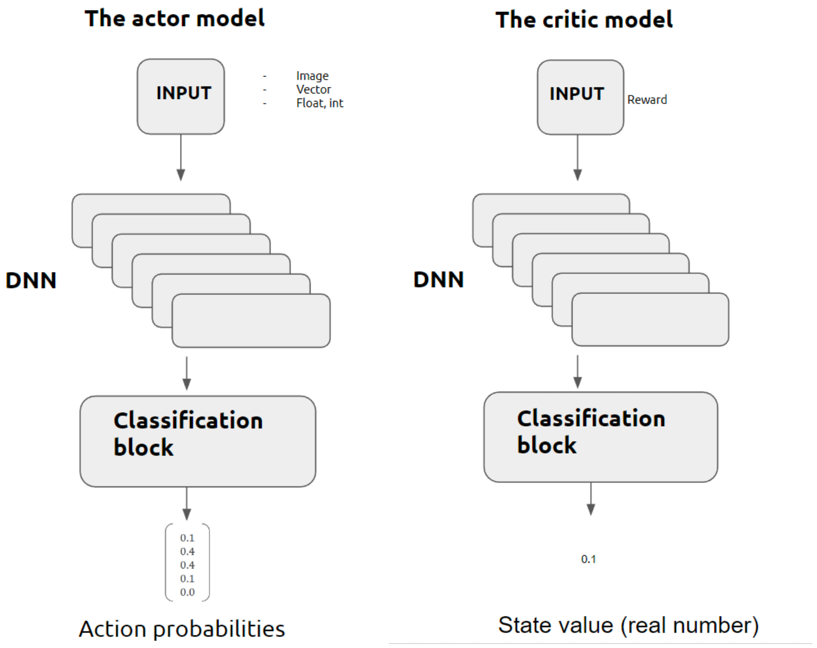

Figure 84
The actor and critic models
Source: author

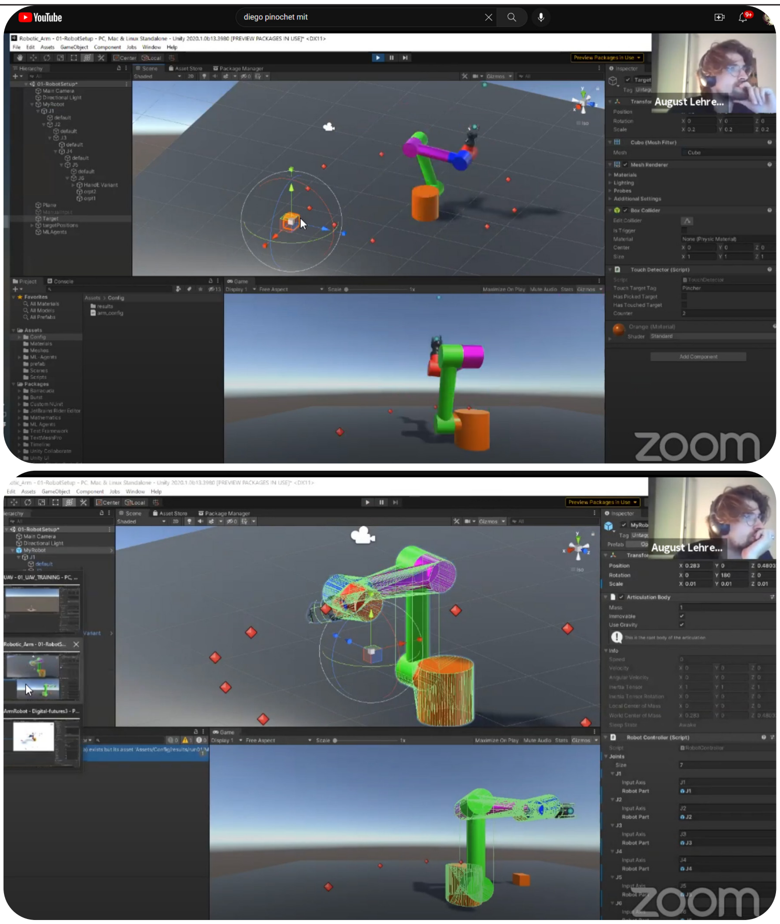

Figure 85
Smart collaborative agents
Source: author

the simulation. The Critic model takes the reward from the actions (negative or positive) to evaluate if the action taken by the Actor led the environment to be in a better state according to the goal. The Critic gives feedback to the Actor in the form of a Q-value indicating the quality of the action taken in the previous state. Finally, the actor can compare its current policy with a new one and decide how to improve itself to take better actions.

An implementation of SAC for 6-DOF robot was implemented in the 'smart collaborative agents' workshop taught at the international; conference Digital Futures 2020[324]. In the course of four eight-hour sessions, I taught students from different parts of the world to implement SAC in robotics, starting from 2-DOF agents up to the application in 6-DOF industrial robots. Combining theoretical and practical coding sessions, a

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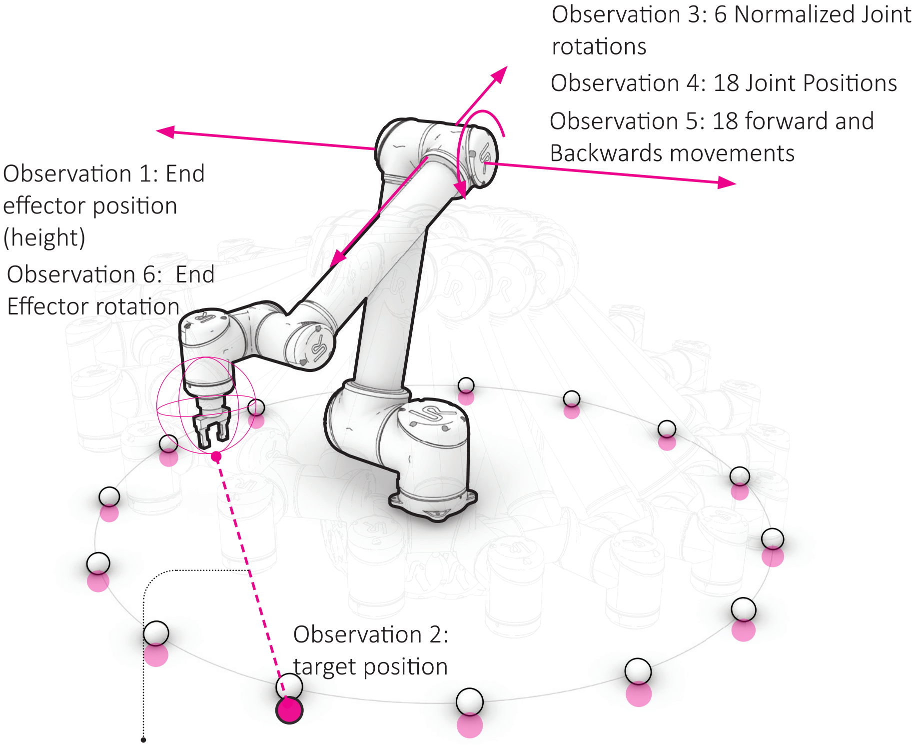
[324] https://www.youtube.com/watch?v=v2-0X_y5nvc&list=PLtXrWmW3nY-TrkqT-kReseehW72HwA8u7z



The reward is calculated according to the distance between End Effector and Target, the End Effector orientation (as vertical as possible), and also the height of the End Effector (Z value). The purpose of the training is to teach the robot to move towards a target maintaining a desired orientation and a position that is as vertical as possible

Figure 86
Reinforcement learning setup diagram
Source: author

complete pipeline for training and deploying collaborative robotics was implemented (figure 85). The algorithms implemented in the workshop were used to generate robotic movement according to environmental inputs such as human gestures. The training setup was implemented according to figure .

To train the robot, the SAC model takes 69 vector observations (figure 86):

- 6 normalized rotation values per joint (float)
- 18 values for each joint position (x,y,z float array)
- 18 values for forward and backward movements of each joint (x,y,z float array)
- 18 values for lateral movements (x,y,z float array)
- 3 values for end effector position (x,y,z float array)
- 3 values for the target position (x,y,z float array)
- 3 values for End effector rotation (x,y,z rotation array values)

The reward function is calculated according to how close the end effector is in relation to the target position, how vertical the end effector orientation is, and if the end effector touches the target. Based on the calculation of the reward at each step, the network propagates the values to each joint. On average training the model for satisfactory movement takes around 1.3 hrs. and 500.000 steps. (figure 87)

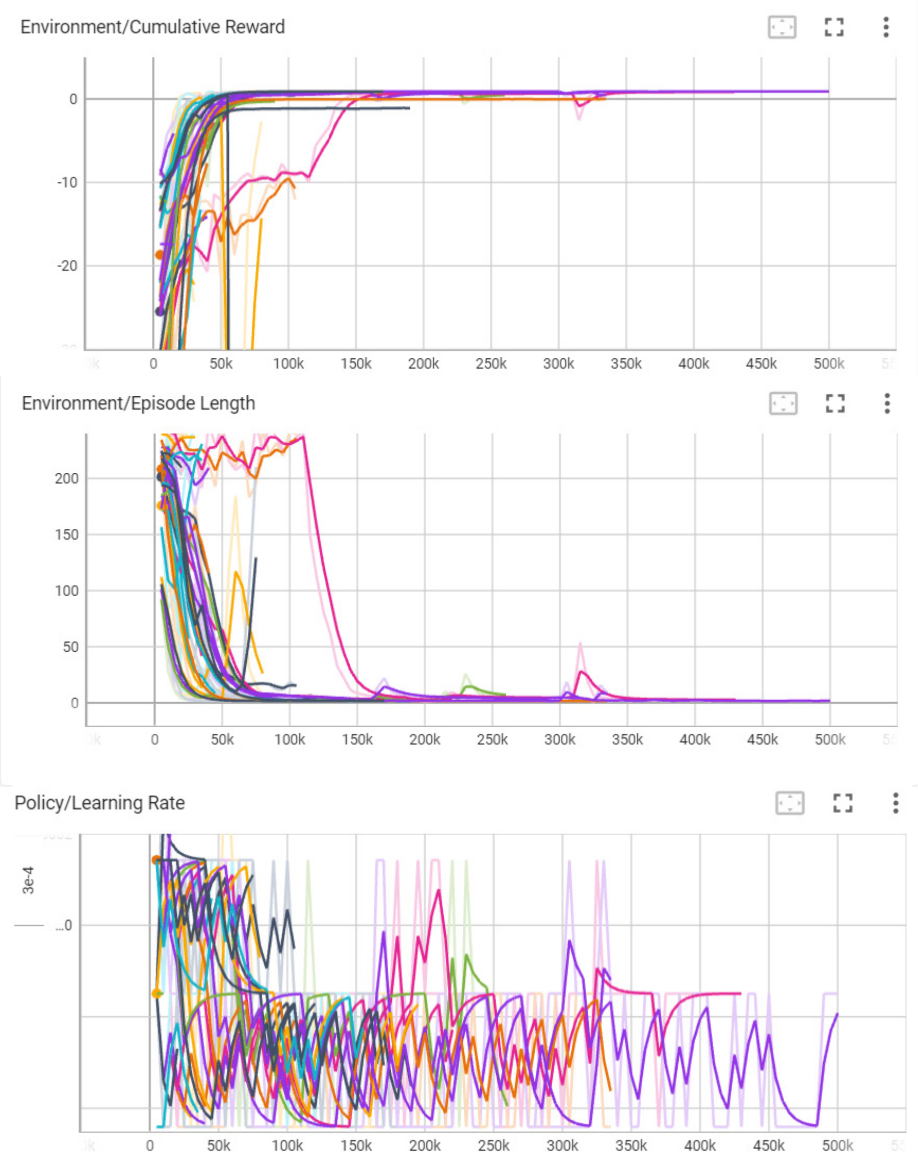
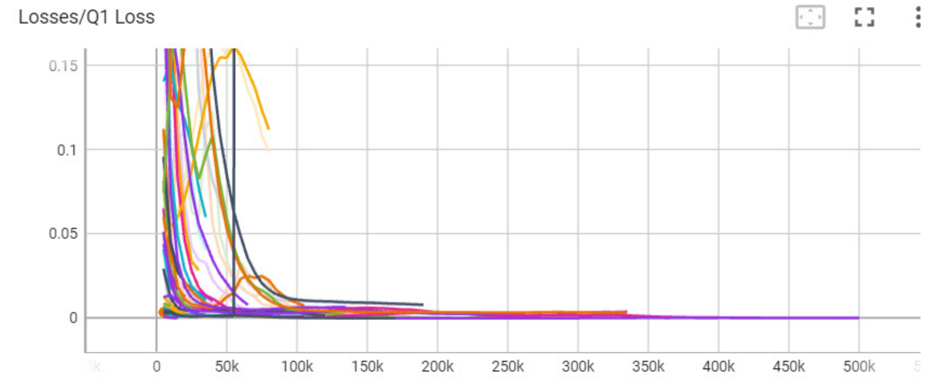
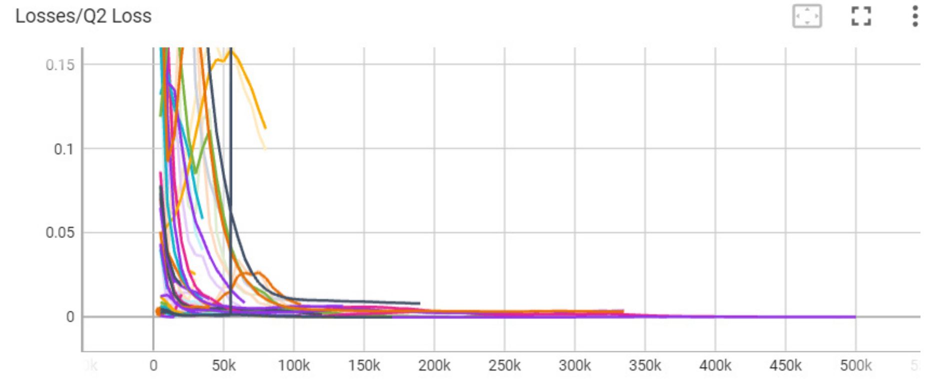
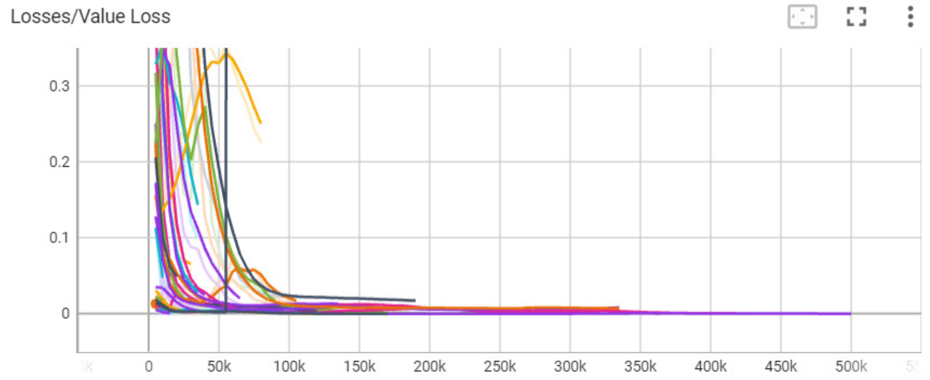
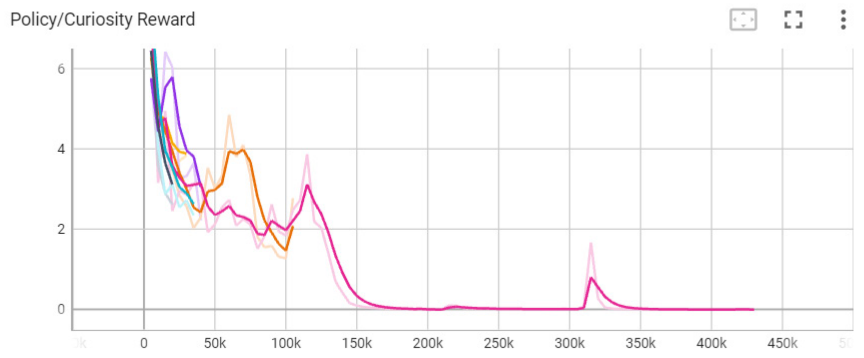


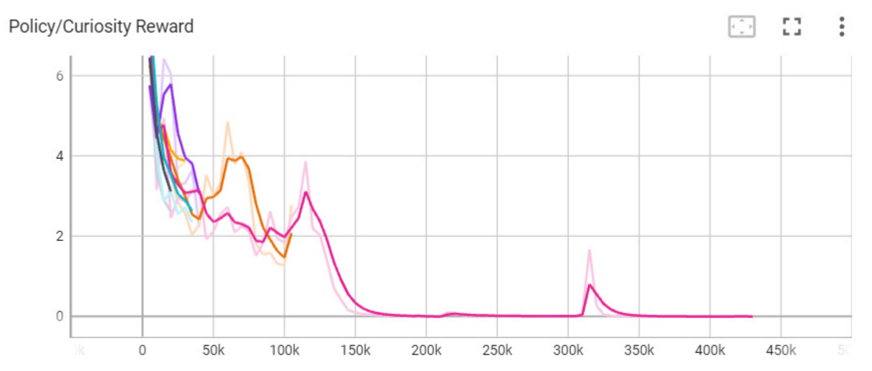
Figure 87
Training performance
Source: author

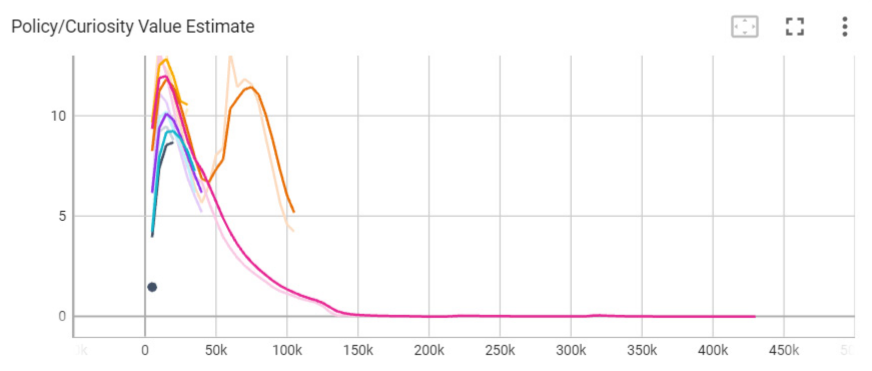

Losses/Q1 Loss
0.15
0.1
0.05
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k
500k

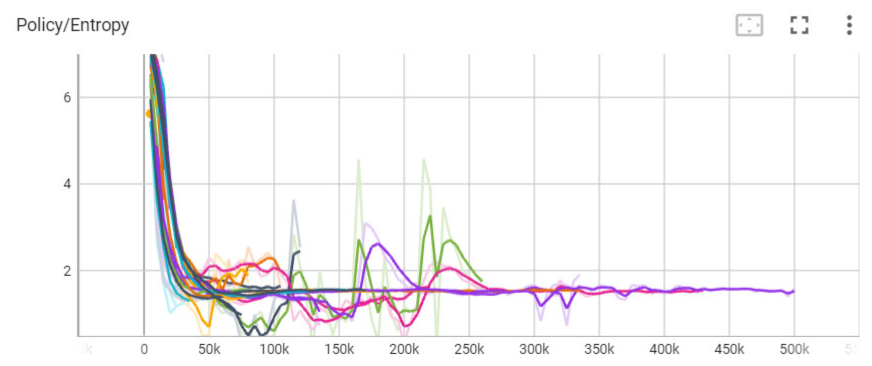

Losses/Q2 Loss
0.15
0.1
0.05
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k
500k

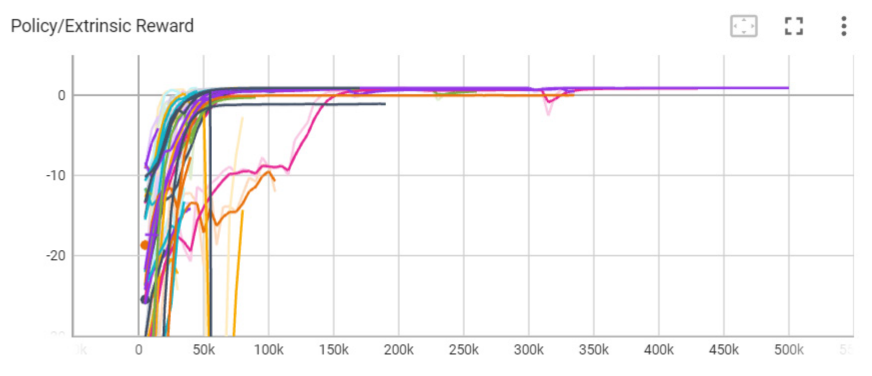

Losses/Value Loss
0.3
0.2
0.1
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k
500k


Policy/Curiosity Reward
6
4
2
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k


Policy/Curiosity Reward
6
4
2
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k


Policy/Curiosity Value Estimate
10
5
0
0
50k
100k
150k
200k
250k
300k
350k
400k
450k


Policy/Entropy
6
4
2
0
50k
100k
150k
200k
250k
300k
350k
400k
450k
500k


Policy/Extrinsic Reward
0
-10
-20
0
50k
100k
150k
200k
250k
300k
350k
400k
450k
500k

4.13.3.3 Where to move: Path planning and robot trajectory based on object pose calculation.

Finally, the third component of the project is the implementation of algorithms that instruct a robotic arm not only what, how, why, and when to move but also where to move without clashing with other objects or itself. Implementing path planning is a task that seeks to add a layer of environmental awareness to a 6-DOF robot configuration. Adding the capacity to compute efficient collision-free trajectories from specific environmental configurations opens the door to more complex interactions between humans-machines and the objects involved in the interaction with significant potential for design and fabrication tasks. Whereas implementing deep reinforcement learning adds the capacity to make informed decisions and learn how to perform coherent actions towards a goal, path planning gives context awareness to a robot to locate itself in space.

The field of autonomous robots has extensive applications in the industry ranging from developing autonomous vacuum cleaners, autonomous self-driving vehicles, unmanned aerial vehicles, and humanoid robots to swarm robotics for package sorting. For most of these applications, planning an efficient collision-free trajectory is essential. Developing robotic systems performing autonomously in the wild has been a fertile research topic for decades. The problem of moving in space is a complex task that requires the application of algorithms that can solve efficiently in terms of time and computation a required translation task. The main characteristics of a path planning problem can be summarized like this[325]:

a- Given a start position, deliver a set of states as positions or velocities that a robot should perform to reach a goal position.
b- The set of trajectories computed should avoid collision with obstacles of the environment (or with itself in the case of articulated configurations)
c- Generally, the computed path should be optimized based on some heuristic or parameter.
d- The computed path should be traversable by the robot, given its dynamics.

---

[325] Information taken from https://erc-pgc.github.io/handbook/automation/Path-Planners/intro/

The most general approaches for path planning calculations are graph-based or sampling-based algorithms. In the case of graph-based algorithms, the search for an optimal path is calculated from a topological graph overlayed on configurational space indicating positions, states, etc. Examples of these algorithms are Dijkstra's algorithm[326], A-Star (A*)[327], or D-Star (D*)[328]. Sampling-based algorithms, on the other hand, represent the configuration space with a roadmap by generating random sample states and searching the most efficient path from the built tree. Examples of these algorithms are Rapidly exploring Random Trees (RRT)[329], RRT Star (RRT*)[330], Informed RRT Star (iRRT*)[331], Batch Informed Trees Star (BIT*)[332]. In this project, a three-dimensional version of RRT is implemented (figure 88) in python and simulated in PyBullet[333]. To implement RRT, helper functions for Random Sampling, Nearest point search, and functions for distance metrics were developed. For this RRT implementation, Inverse Kinematic calculation and collision detection methods from PyBullet were used. RRT is simulated using a maximum of 12000 iterations to find a possible navigation path from a starting position to a goal target. In this case, the joint angles are calculated automatically in PyBullet according to the position of the end effector that follows the planned path (figure 89).

---

[326] Dijkstra, E.W. A note on two problems in connexion with graphs. Numer. Math. 1, 269–271 (1959). https://doi.org/10.1007/BF01386390

[327] Nilsson, Nils J. (2009-10-30). The Quest for Artificial Intelligence (https://ai.stanford.edu/~nilsson/QAI/qai.pdf) (PDF). Cambridge: Cambridge University Press. ISBN 9780521122931.

[328] A. Stentz, "Optimal and efficient path planning for partially-known environments," Proceedings of the 1994 IEEE International Conference on Robotics and Automation, San Diego, CA, USA, 1994, pp. 3310-3317 vol.4, doi: 10.1109/ROBOT.1994.351061.

[329] LaValle, Steven M.. "Rapidly-exploring random trees : a new tool for path planning." ***The annual research report*** (1998): n. pag.

[330] Karaman, Sertac, and Emilio Frazzoli. "Incremental sampling-based algorithms for optimal motion planning." Robotics Science and Systems VI 104, no. 2 (2010).

[331] J. D. Gammell, S. S. Srinivasa and T. D. Barfoot, "Informed RRT*: Optimal sampling-based path planning focused via direct sampling of an admissible ellipsoidal heuristic," 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, USA, 2014, pp. 2997-3004, doi: 10.1109/IROS.2014.6942976.

[332] Gammell, Jonathan D., Siddhartha S. Srinivasa, and Timothy D. Barfoot. "Batch Informed Trees (BIT): Sampling-based optimal planning via the heuristically guided search of implicit random geometric graphs." In 2015 IEEE international conference on robotics and automation (ICRA), pp. 3067-3074. IEEE, 2015.

[333] PyBullet is a framework for physics simulation for games VFX, robotics and Reinforcement Learning. Coumans, E., Bai, Y.: Pybullet, a python module for physics simulation for games, robotics and machine learning. http://pybullet.org (2016–2019)

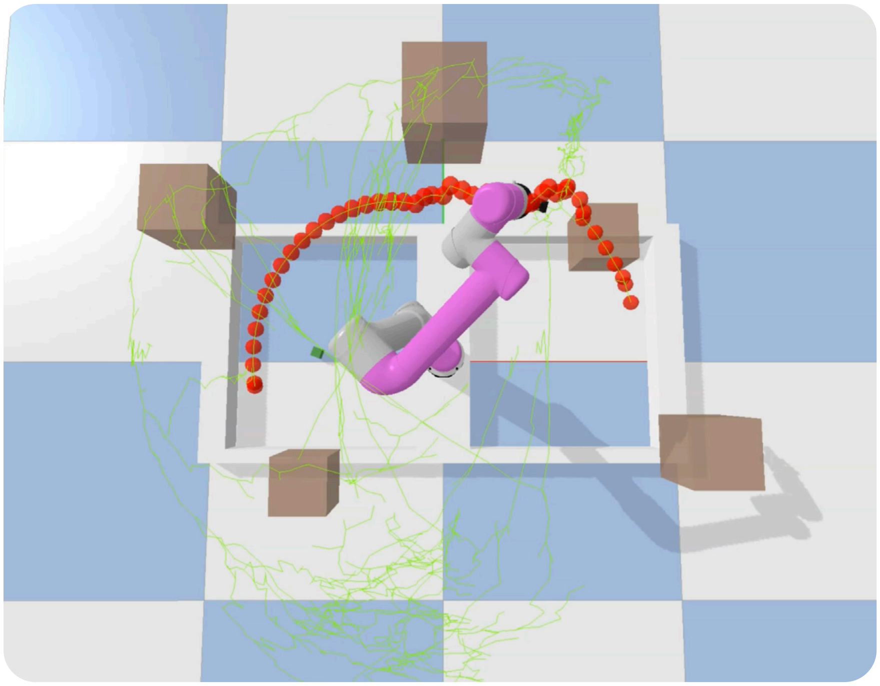


Figure 88
Robotic path planning in PyBullet given a complex environment with random obstacles
Source: author

To test the implementation of RRT, a pick-and-place program was developed[334]. For such purpose, a computer vision program to recognize shapes and orientation was written in python. The system consists of the simulation of a depth camera system and an object segmentation algorithm. A simplified version of UNET[335], an Image segmentation algorithm, was written in PyTorch[336] (figure 90 and figure 91). Using a virtual camera pointing downwards to a set of randomly positioned objects, a dataset of 300 sample images (RGB

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[334] Although there are ready-made solutions to calculate path planning (such as https://github.com/caelan/pybullet-planning developed by Caelan Garret) or algorithms for point cloud registration http://www.open3d.org/docs/latest/tutorial/Basic/icp_registration.html), the author of this thesis developed the methods presented here as part of class work at MIT. The work was written as part of the final project for 6.4212 Intelligent Robotic manipulation class taken by the author in the fall of 2019. This class is an Advanced Graduate Subject (AGS) from course 6 at MIT, and for its 2019 version was taught by professor Russ Tedrake (Robot locomotion group) and Tomas Lozano-Perez (Learning & Intelligent Systems Group).

[335] Ronneberger, Olaf, Philipp Fischer, and Thomas Brox. “U-net: Convolutional networks for biomedical image segmentation.” In International Conference on Medical image computing and computer-assisted intervention, pp. 234-241. Springer, Cham, 2015.

[336] Paszke A, Gross S, Massa F, Lerer A, Bradbury J, Chanan G, et al. PyTorch: An Imperative Style, High-Performance Deep Learning Library. In: Advances in Neural Information Processing Systems 32 [Internet]. Curran Associates, Inc.; 2019. p. 8024–35. Available from: http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf

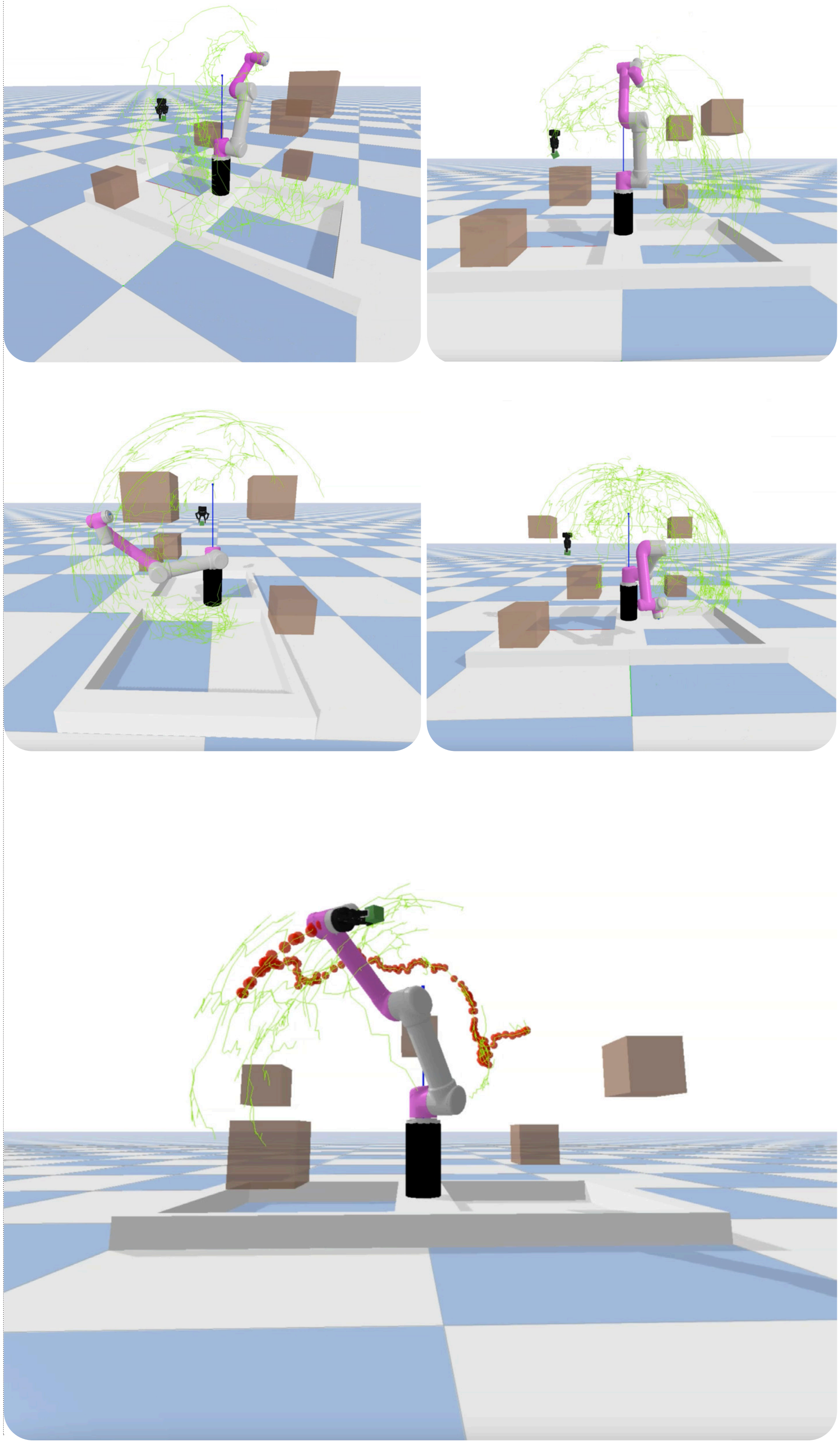
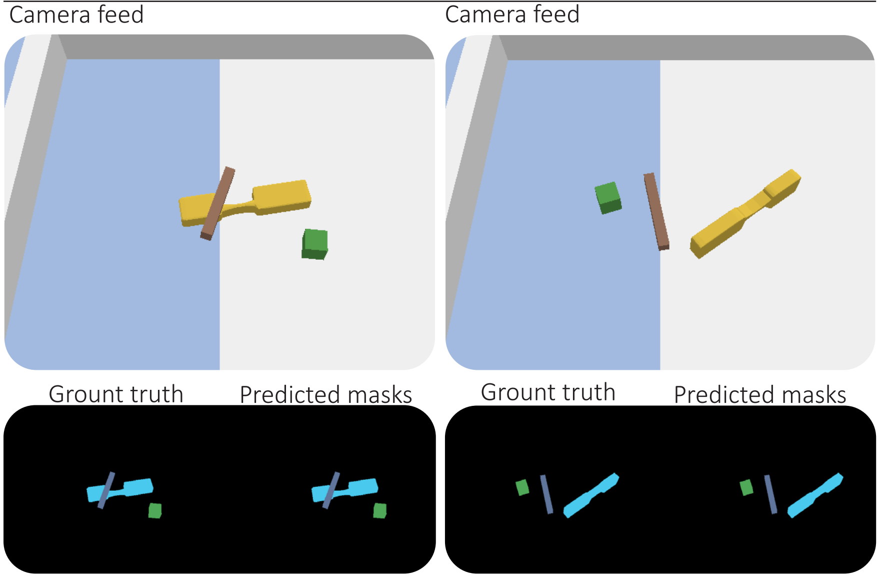


Figure 89
Path planning in py bullet
Source Author



Camera feed

Camera feed

Grount truth

Predicted masks

Grount truth

Predicted masks

Figure 90
UNET for object segmentation from virtual camera feed in PyBullet
Source: author

```
===============================================================
=======
Layer (type:depth-idx)                    Param #
===============================================================
=======
miniUNet                                  --
–DoubleConv: 1-1                          --
|    └Sequential: 2-1                     --
|    |    └Conv2d: 3-1                    1,792
|    |    └BatchNorm2d: 3-2               128
|    |    └ReLU: 3-3                      --
|    |    └Conv2d: 3-4                    36,928
|    |    └BatchNorm2d: 3-5               128
|    |    └ReLU: 3-6                      --
–Down: 1-2                                --
|    └Sequential: 2-2                     --
|    |    └MaxPool2d: 3-7                 --
|    |    └DoubleConv: 3-8                221,952
–Down: 1-3                                --
|    └Sequential: 2-3                     --
|    |    └MaxPool2d: 3-9                 --
|    |    └DoubleConv: 3-10               886,272
–Down: 1-4                                --
|    └Sequential: 2-4                     --
|    |    └MaxPool2d: 3-11                --
|    |    └DoubleConv: 3-12               3,542,016
–Down: 1-5                                --
|    └Sequential: 2-5                     --
|    |    └MaxPool2d: 3-13                --
|    |    └DoubleConv: 3-14               4,721,664
–Up: 1-6                                  --
|    └Upsample: 2-6                       --
|    └DoubleConv: 2-7                     --
|    |    └Sequential: 3-15               5,900,544
–Up: 1-7                                  --
|    └Upsample: 2-8                       --
|    └DoubleConv: 2-9                     --
|    |    └Sequential: 3-16               1,475,712
–Up: 1-8                                  --
|    └Upsample: 2-10                      --
|    └DoubleConv: 2-11                    --
|    |    └Sequential: 3-17               369,216
–Up: 1-9                                  --
|    └Upsample: 2-12                      --
|    └DoubleConv: 2-13                    --
|    |    └Sequential: 3-18               110,976
–OutConv: 1-10                            --
|    └Conv2d: 2-14                        260
===============================================================
=======
Total params: 17,267,588
Trainable params: 17,267,588
Non-trainable params: 0
===============================================================
=======
```

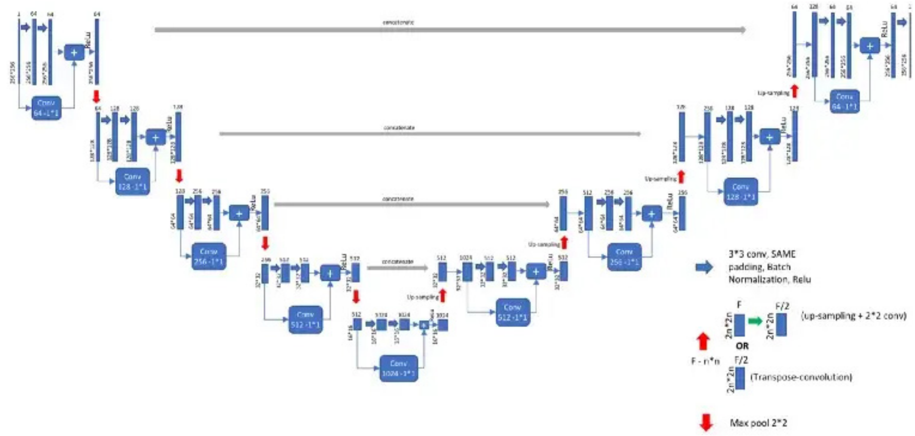


Figure 91
Modified UNET model architecture
Source: author

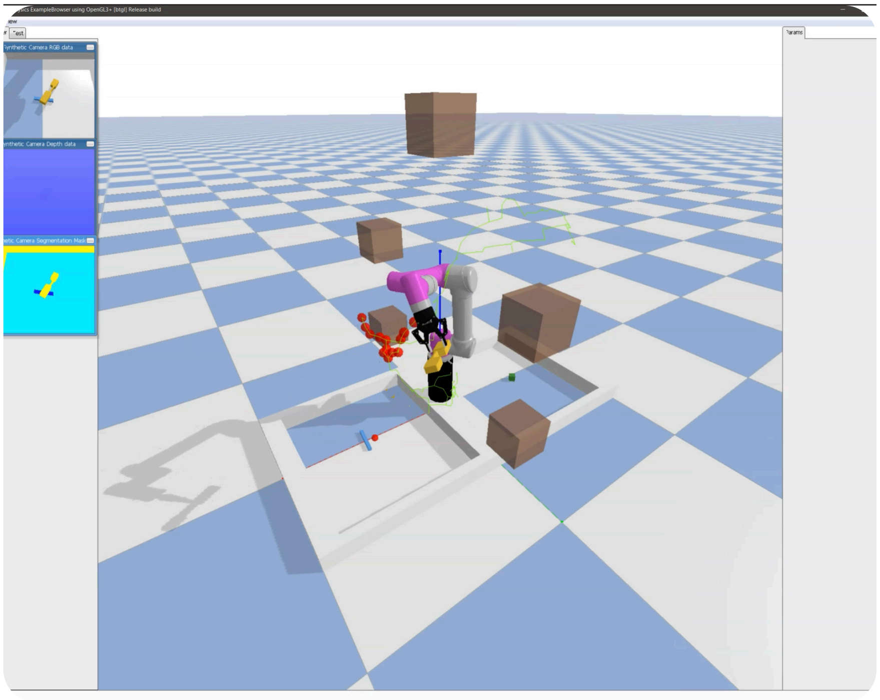


Figure 92
Path Planning from estimated grasp position using UNET and ICP
Source: author

and Grayscale depth) is collected. The network was trained over ten epochs using a dual NVIDIA RTX 3090 configuration, achieving a mean Intersection over Union (mIoU)[337] score of 1.0 (perfect score). To perform pose detection and calculate the starting point for RRT, two 3D point clouds are generated. The first one is generated using the predicted masks from UNET that filter the points (a similar and less computationally expensive version of the implementation in 3.7.2.2) generated from depth images (calculated based on the fixed intrinsic camera parameters). The second point cloud is sampled from the objects in the simulation. Subsequently, an implementation of the Iterative Closest Point algorithm (ICP)[338] is used to align the ground truth point cloud to the filtered point cloud and find the object's rigid transformation (position and orientation) in world space to perform the RRT calculation (figure 92).

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[337] The Intersection over Union is a metric used in deep learning to estimate how well a predicted mask or bounding box matches the ground truth. It is measured by dividing the Area of Overlap by the Area of union between the mask and the ground truth image.

[338] P. J. Besl and N. D. McKay, "A method for registration of 3-d shapes," IEEE Trans. Pattern Anal. Mach. Intell., vol. 14, no. 2, pp. 239–256, 1992.

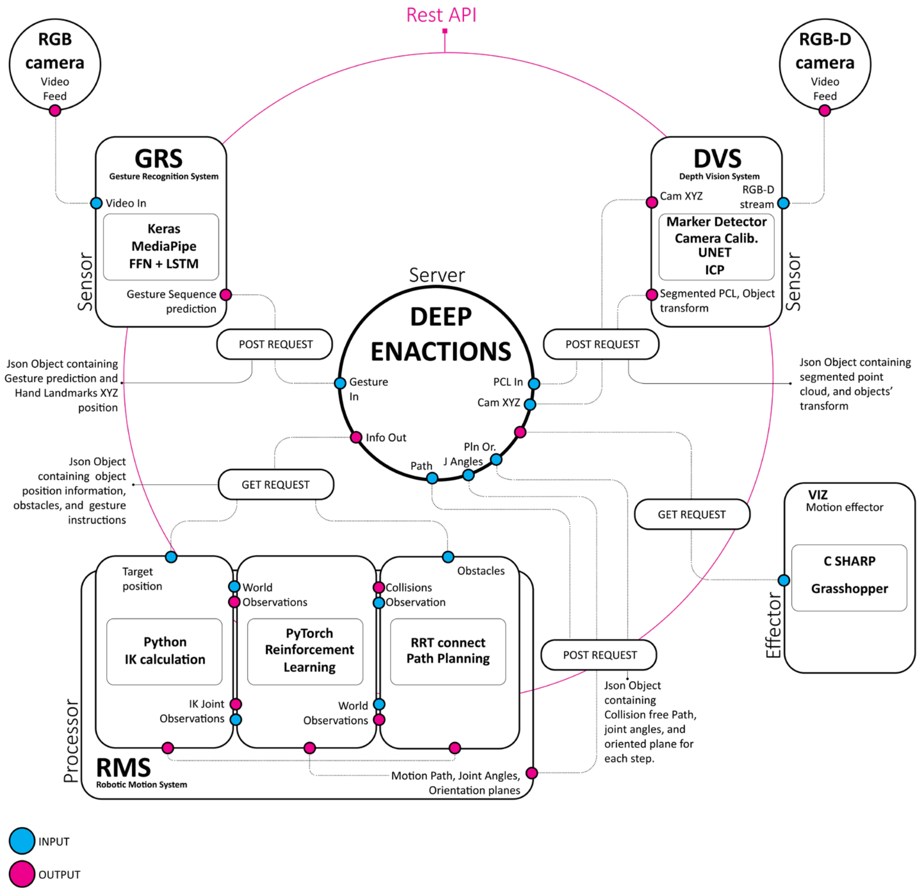


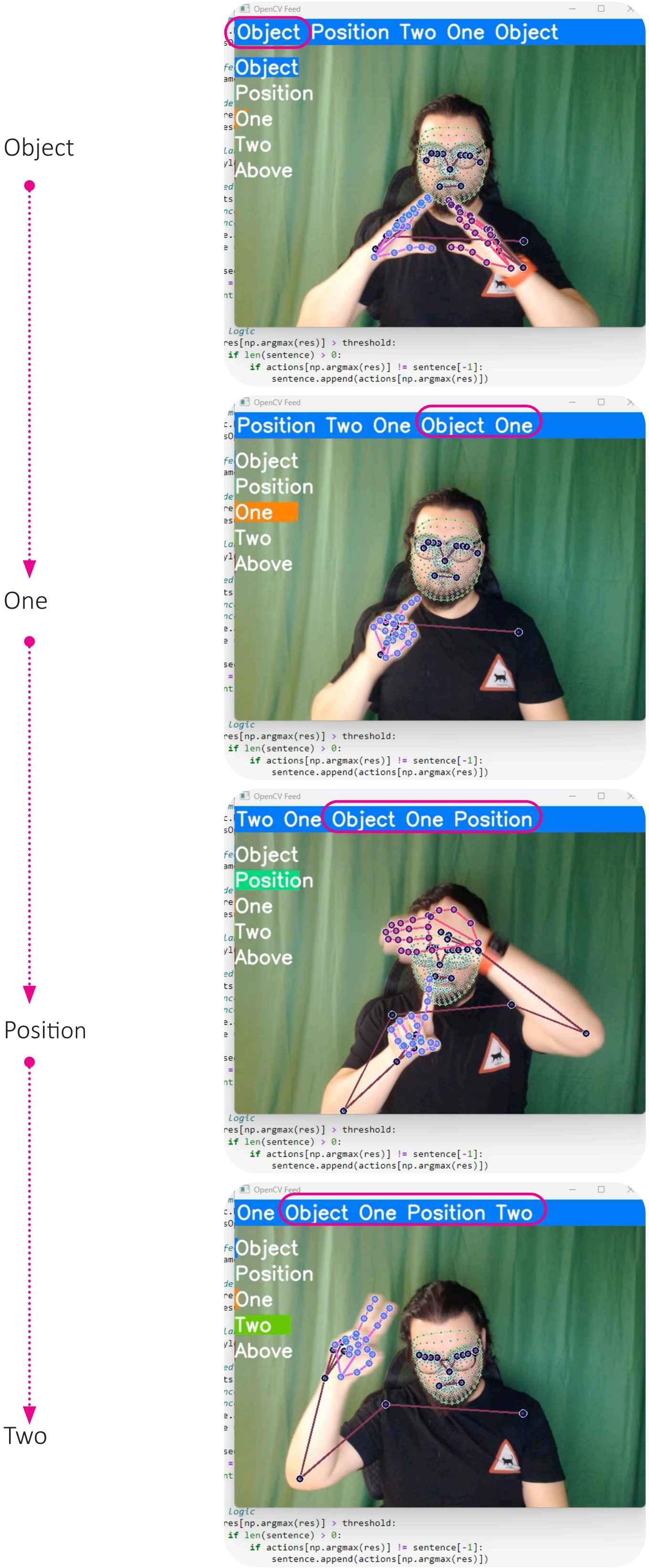
Figure 93
REST API Implementation Diagram
Source: author

4.13.4 Closing the loop: Integrating gesture detection, machine vision and robotic action.

Integrating all the systems into one closed-loop system for interaction requires the development of tools to bridge the different modules and perform efficient information delivery among them in real-time. For this purpose, a Representational State Transfer Application Programming Interface (REST API) was implemented in python. Using a RESTful API allows the implementation of specific endpoints for each request from clients to the server in a dynamic way. In that way, each project module is implemented as a client with specific inputs and outputs, and the server can transmit and manage the flow of information between modules on-demand. As shown in the diagram (figure 93), each module communicates with a central server posting or requesting information.

As an example, the gesture detection module acts as a sensor that is constantly sending information to the central server as new gestures are predicted. Moreover, the central server takes the information from the sensor module and, according to the prediction, sends a request to a processor such as the Path planning or the Reinforcement Learning modules. The processor modules take information from the environment sensor module and calculate a motion plan that is sent back to the server, which transmits the information to the effector module that performs the intended motion. Thus, modularizing and decoupling the components of the project and connecting them through a central server allows efficient management of computational resources, isolating each function and software implementation in their environments. Finally, although the system involved a graphical module implemented in Unity 3D for visualization, in this specific implementation, the effector module has been deployed in Grasshopper for Rhino3D, as it provides ready-made graphical and geometric components to test the system effectively.

Once connected, the system allows direct motion generation from gestures. As explained in 3.7.1.3, the system can detect different types of gestures (sequence of movements, static symbolic gestures, and sequence of symbolic gestures) that can be trained and assigned to specific tasks. For example, in a design case scenario, symbolic gestures can be assigned to specific discrete operations dedicated to manipulating objects such as tools or materials. Discrete actions such as ‘grabbing,’ ‘releasing,’ ‘going to the robot’s rest position,’ or switching between different detection modes (i.e. switching from symbolic gesture detection to free movement sequences) can be triggered using symbolic gestures. Moreover, symbolic gesture sequence detection can be associated with more complex tasks involving positions, orientations, and temporal sequences of discrete actions such as ‘moving X object to <position>’ (figure 94 and figure 95) or ‘put object X in <position><orientation> to Z object.’ (figure 96 and figure 97). Finally, and taking environmental information from the DVS module, the software can calculate sequences of movements based on the RMS in the form of collision-free paths. Connecting the Deep Enaction System to software such as Grasshopper allows for prototyping and testing in a fast way the interactive capabilities of a conversational tool that can be extended for design and making purposes. In the case of this tool used for design, the system is intended to bypass fixed representations and act as a facilitator for an on-the-fly thinking computational tool by engaging designers with a responsive machine.



```
Object Position Two One Object

Object
Position
One
Two
Above
```

```
 logic
res[np.argmax(res)] > threshold:
 if len(sentence) > 0:
     if actions[np.argmax(res)] != sentence[-1]:
         sentence.append(actions[np.argmax(res)])
```

```
Position Two One Object One

Object
Position
One
Two
Above
```

```
 logic
res[np.argmax(res)] > threshold:
 if len(sentence) > 0:
     if actions[np.argmax(res)] != sentence[-1]:
         sentence.append(actions[np.argmax(res)])
```

```
Two One Object One Position

Object
Position
One
Two
Above
```

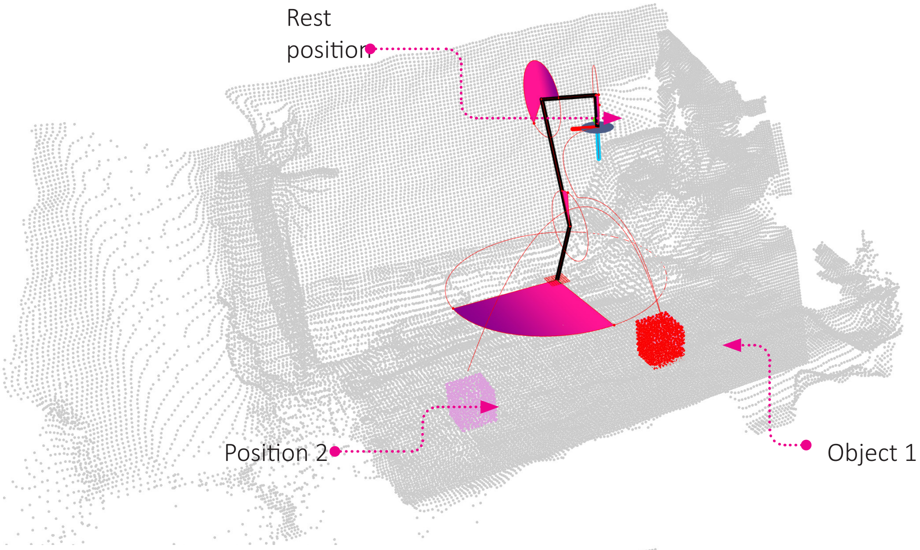
```
 logic
res[np.argmax(res)] > threshold:
 if len(sentence) > 0:
     if actions[np.argmax(res)] != sentence[-1]:
         sentence.append(actions[np.argmax(res)])
```

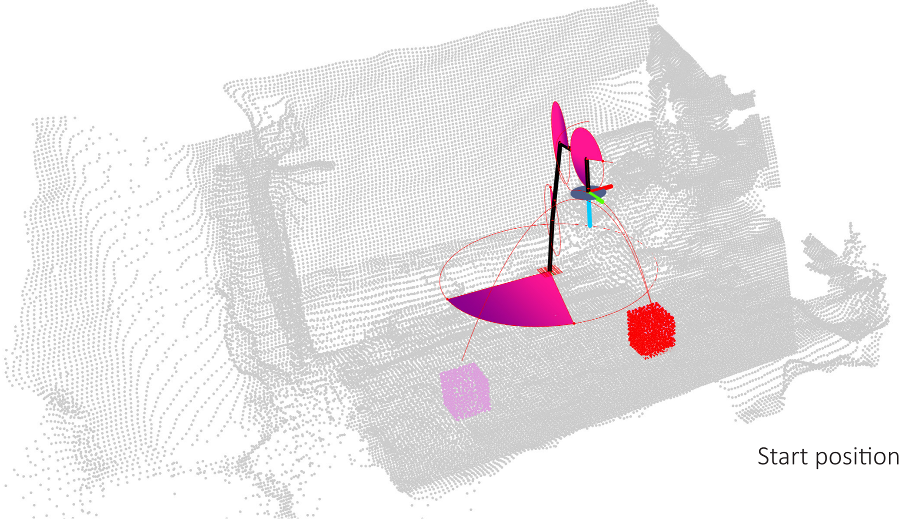
```
One Object One Position Two

Object
Position
One
Two
Above
```

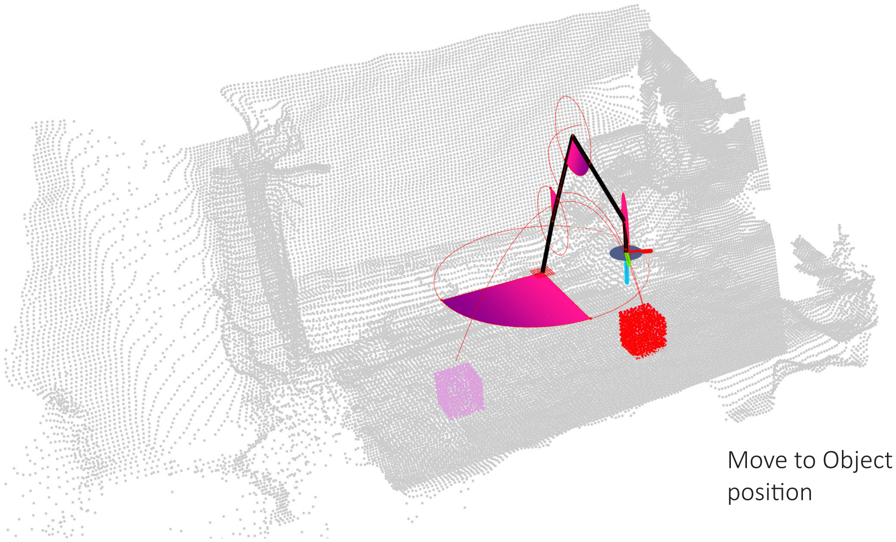
```
 logic
res[np.argmax(res)] > threshold:
 if len(sentence) > 0:
     if actions[np.argmax(res)] != sentence[-1]:
         sentence.append(actions[np.argmax(res)])
```

Figure 94
Testing the system with simple pick and place operations
Source: author



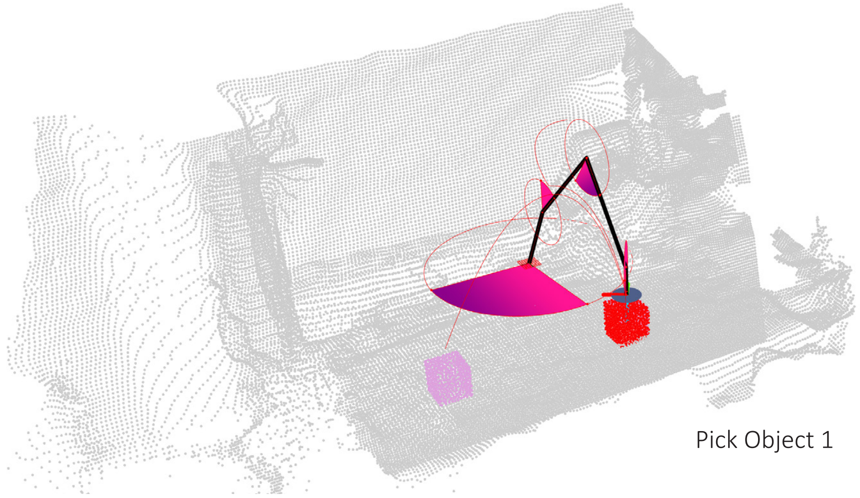


Start position

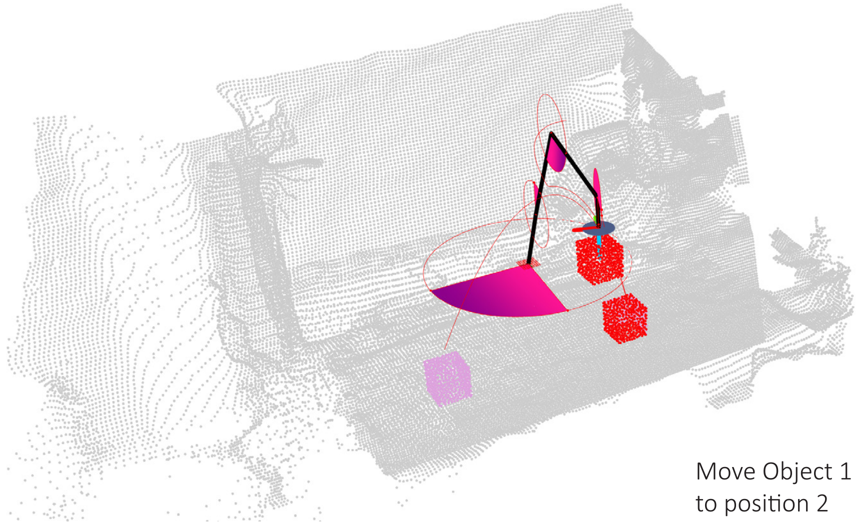


Move to Object 1 position

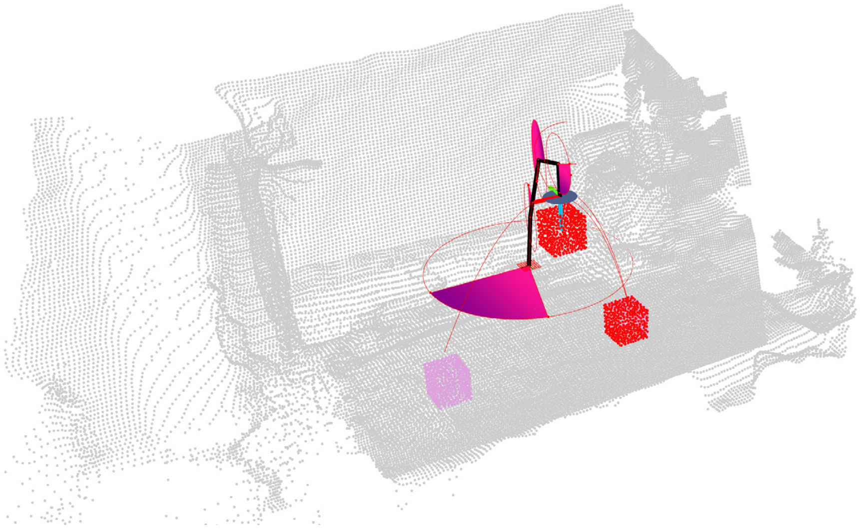
Figure 95
Simple robot movement according to action
Source: author

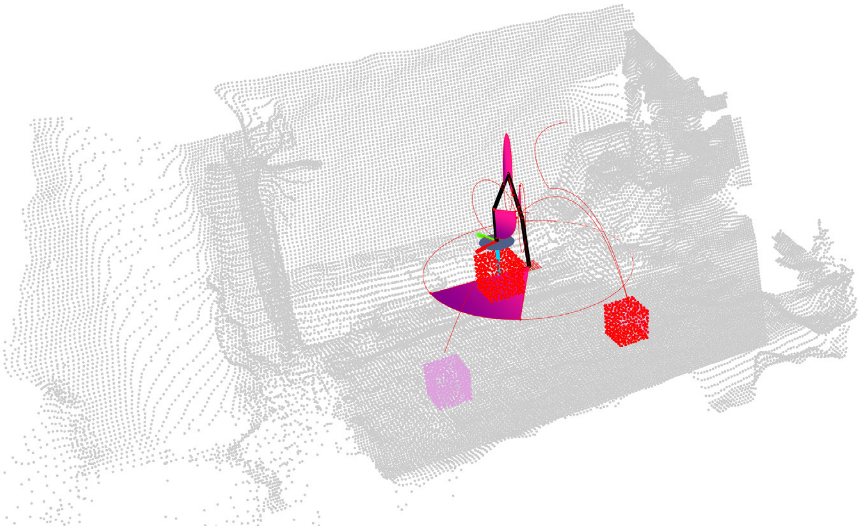


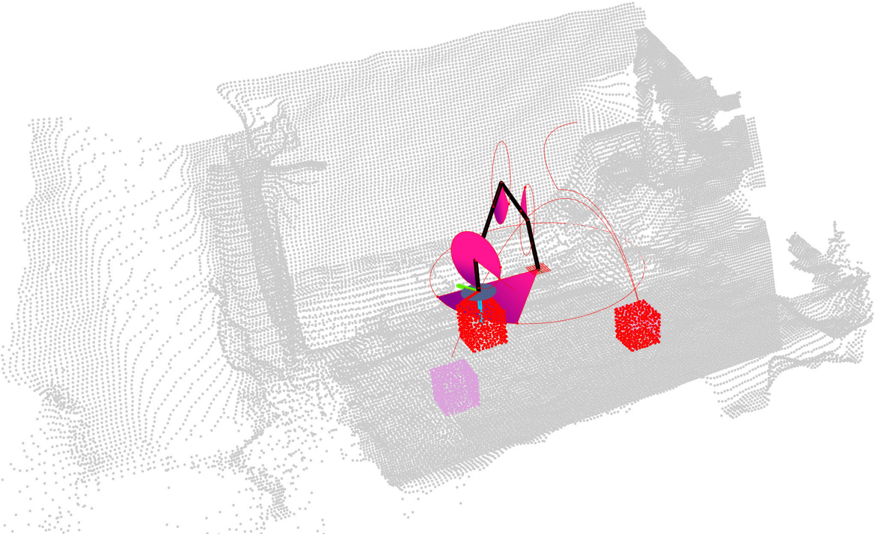
Pick Object 1

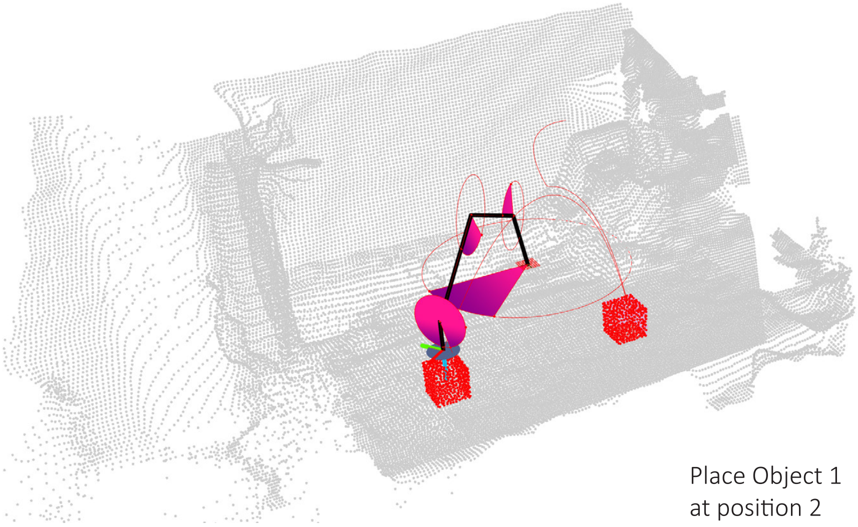


Move Object 1
to position 2









Place Object 1
at position 2

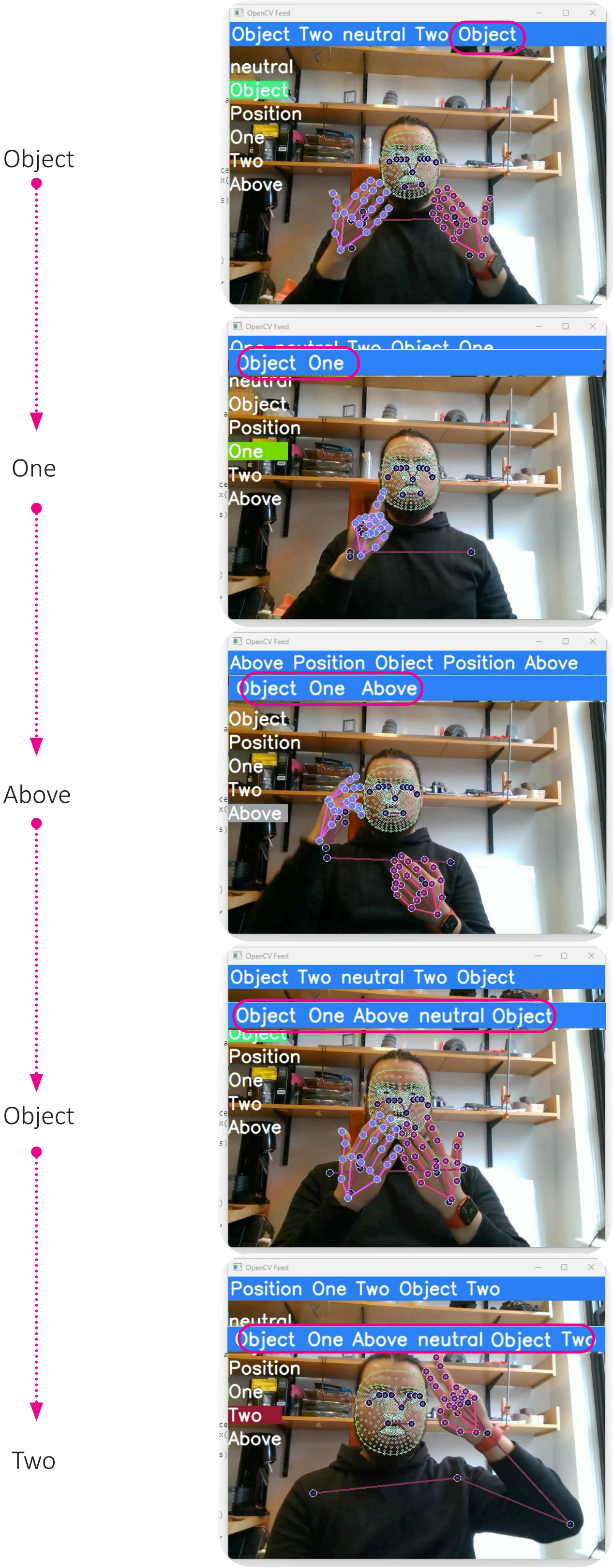


Figure 96
Object 1 on top of object 2
Source: author

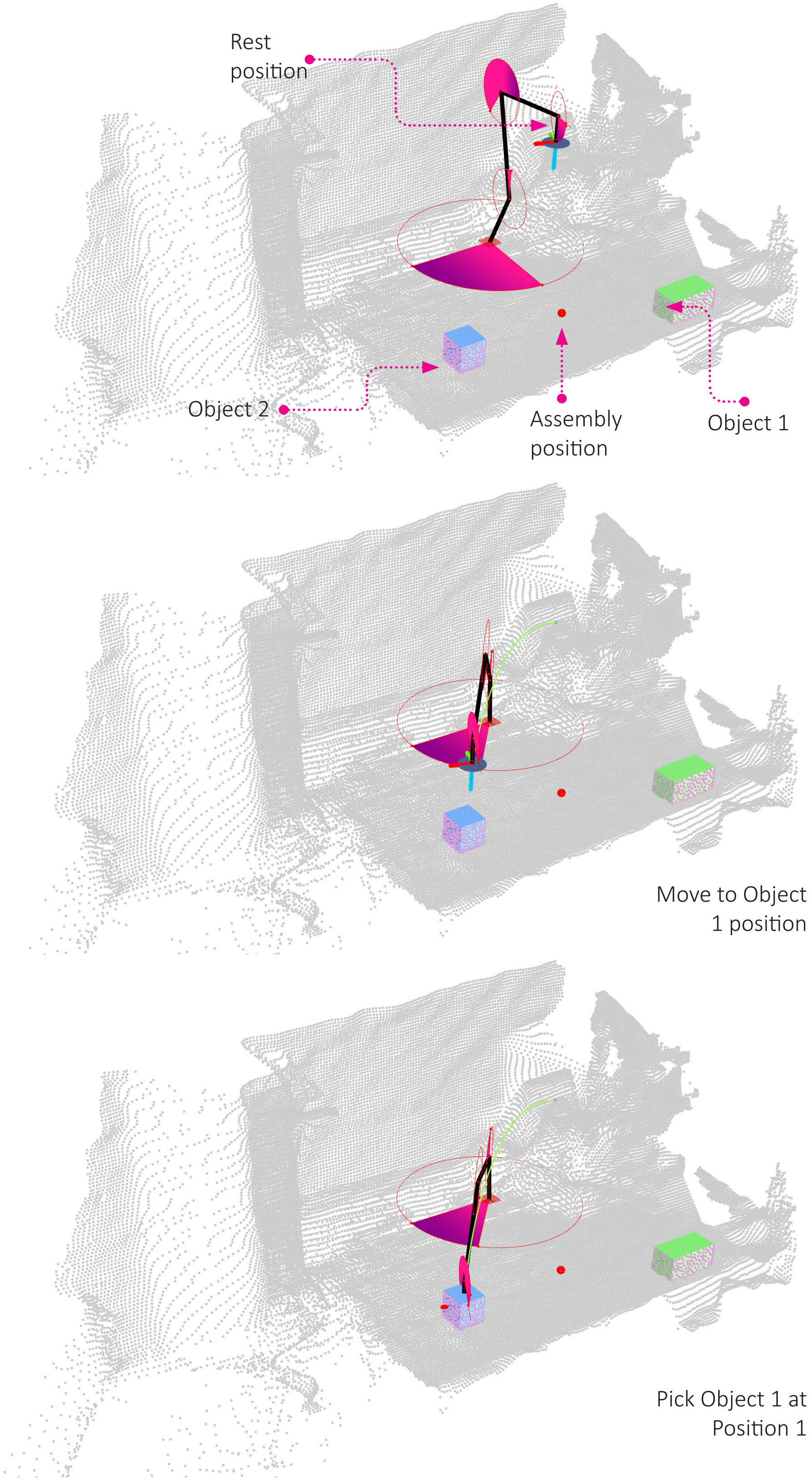
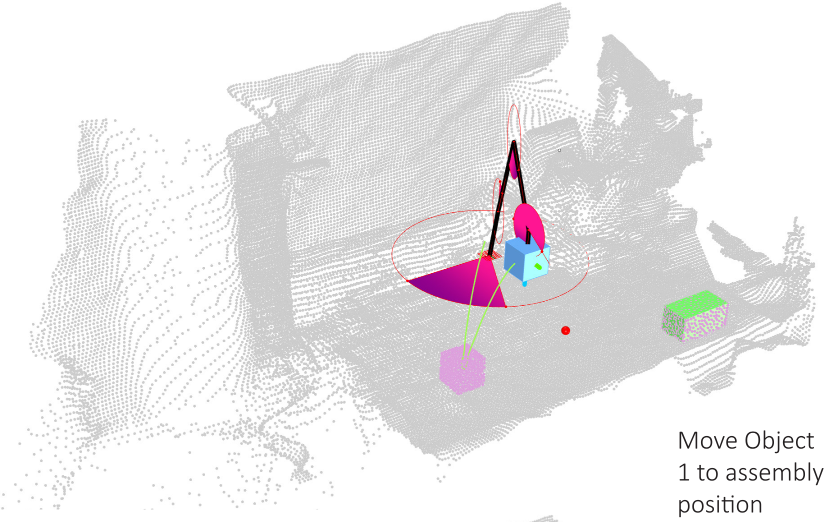
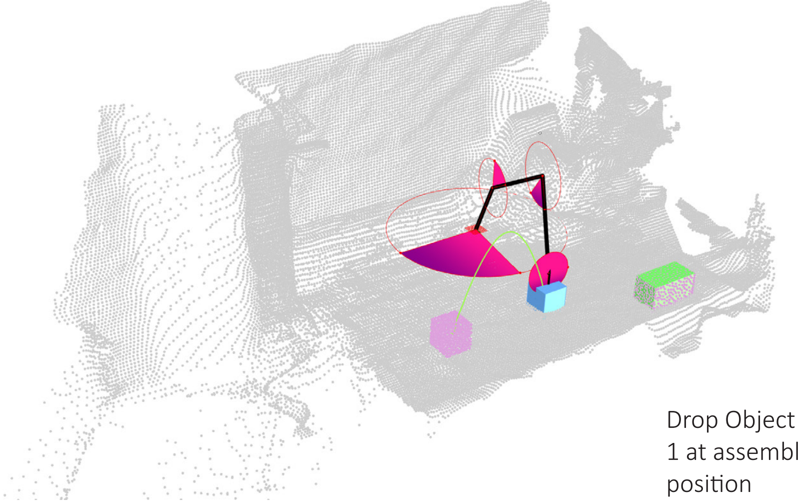


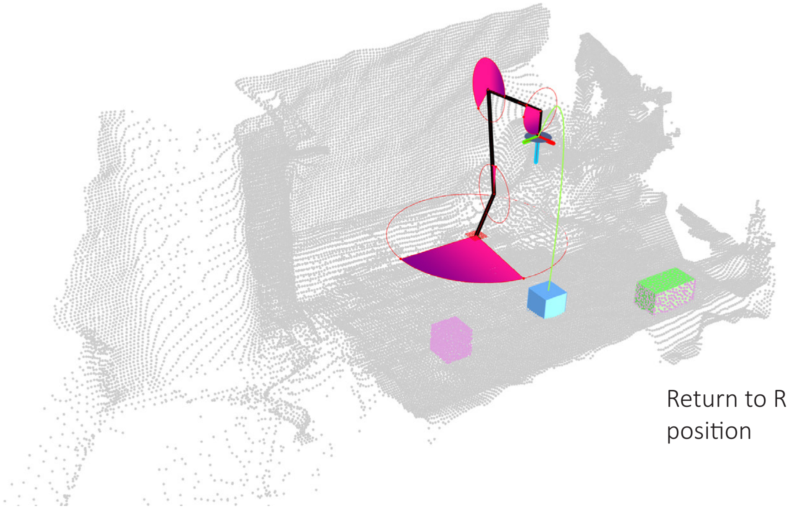
Figure 97
Robot Action sequence
Source: author



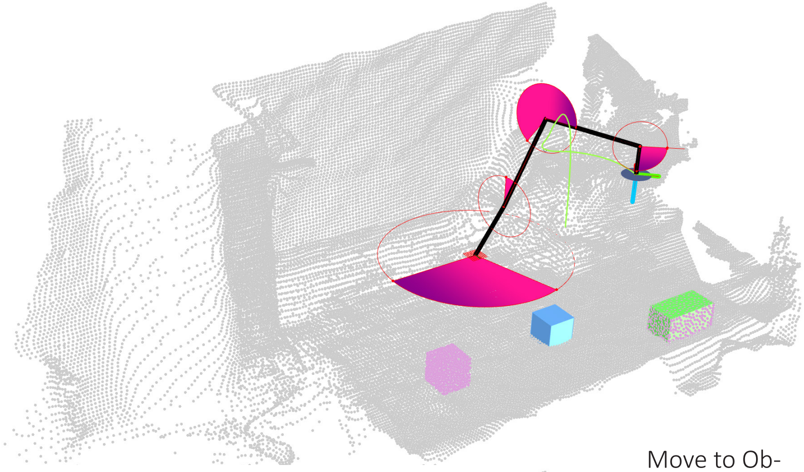
Move Object 1 to assembly position



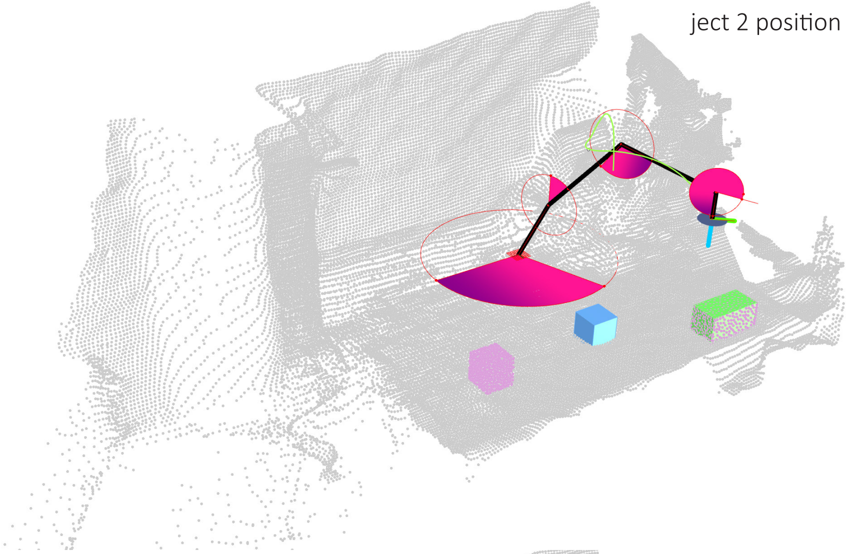
Drop Object 1 at assembly position

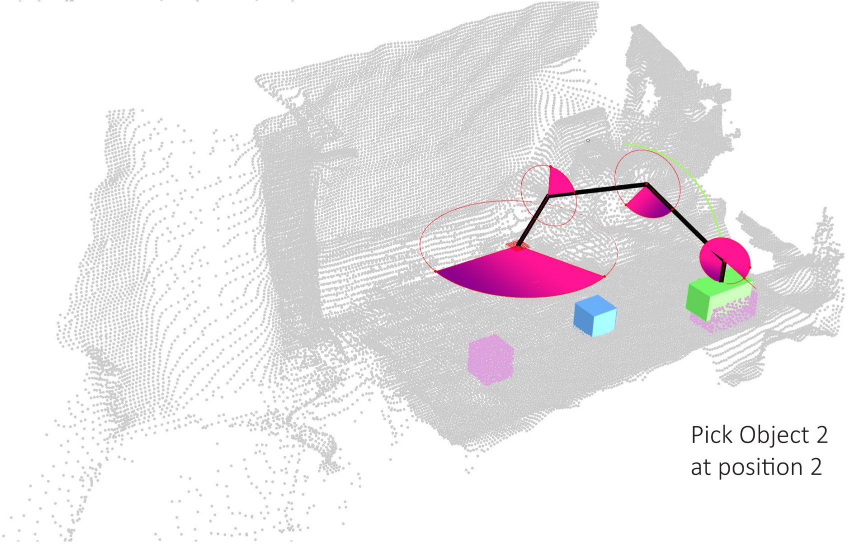


Return to Rest position

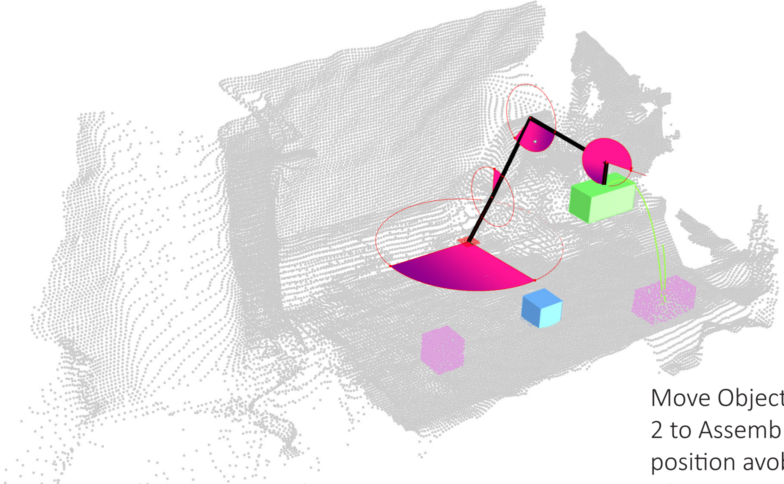


Move to Object 2 position

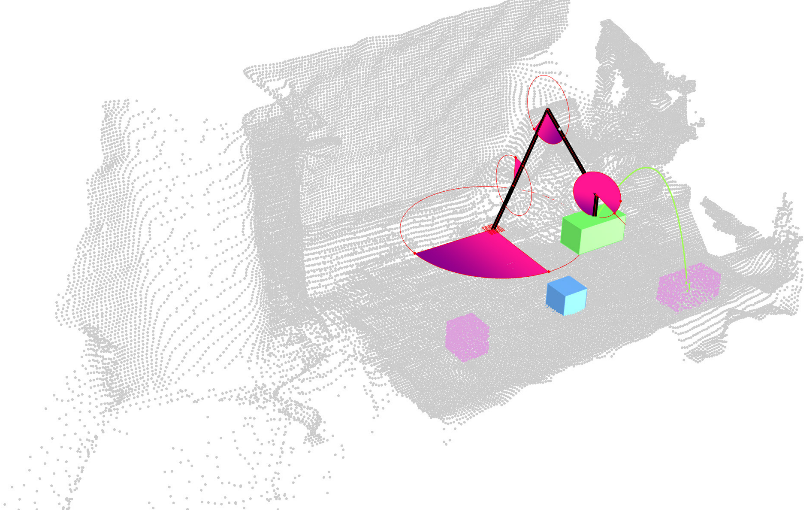


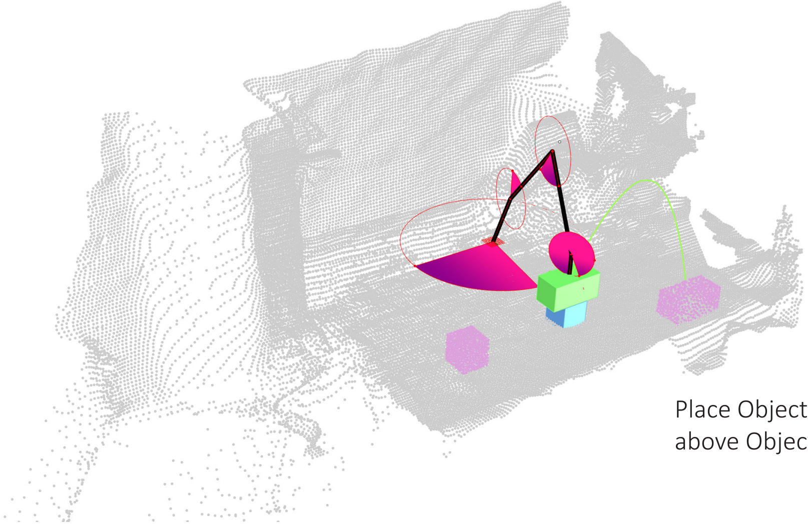


Pick Object 2 at position 2



Move Object
2 to Assembly
position avobe
Object 1





Place Object 2
above Object 1

4.14 Discussion and future implementations

This chapter explores the role of representations and the limitations posed by the computational design trichotomy in enhancing and extending creativity throughout the design and making process. While technological advancements in design have primarily focused on representing and streamlining the process of rationalizing design concepts, considering design as a problem-setting exercise rather than a problem-solving one opens the door to a new conception of creation through technology, breaking down the boundaries imposed by the trichotomy and favoring a situated approach to design and making. Adopting a cybernetic approach to design, which focuses on the multiple interactions and exchanges between the designer, tools, and environment, this chapter presented a closed-loop system for interaction between humans and machines. The system is based on a conversational model that emphasizes the importance of action and demonstrates how meaning-making is related to the ways in which we make sense of things interacting with our environment generating stable perceptions that can be determined as different designs.

The development of a gesture recognition system in conjunction with a robotic motion system creates a model for Computational Design that embraces the interactive and open-ended nature of creation, enabling multiple stable states to emerge as design outcomes. Throughout the discussion, it has been possible to identify the components necessary to enable such interactions and reframe computational design tools to embrace computation as an active endeavor. Overcoming the dualism between plans and actions, it is possible to reframe how we use technology to open different courses of action considering the ever-changing characteristics of the surrounding environment. As Suchman argues: 'every course of action depends in essential ways to its own material and social circumstances to achieve intelligent action'[339]. Hence, by embracing the idea of design as a situated action endeavor, it is possible to determine the necessary components to achieve such interactions.

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[339] Suchman, Lucy. Human-Machine Reconfigurations: Plans and Situated Actions. 2nd ed. Learning in Doing: Social, Cognitive and Computational Perspectives. Cambridge: Cambridge University Press, 2006. doi:10.1017/CBO9780511808418. p.70

The integration of sensing, computing, and actuating capabilities to a system to perform in response to human behavior allowed the development of an interactive cybernetic system for action with the potential of becoming an interactive design and making system. With the aid of different algorithms, Deep learning models, and sensors, it has been possible to implement an interaction system that can be adapted and trained to engage in a conversation and mutual intelligibility between a designer and a computer. The implementation of ‘Deep enactions’ sets the foundations for implementing a ‘Computational Gestural Making’ framework that could be applied in the physical world.

Computational Gestural MAKING

5

In this chapter, I probe into physical-making processes. I present an approach to Design as Making focusing on the elaboration of plans for action as 'recipes' and the use of materials as 'Design ingredients.'

I start by moving the discussion from representation to making as a way to consider the contingency of making and the interaction provided by computation as defining factors in the creative process. I start by asserting that elaborating plans for action, goes beyond a representational endeavor to describe an object but, and instead relates more to the description of open-ended procedures that, although highly specific in terms of instructions, are broadly open to embrace free performance and the emergence of new things.

I then draw upon Lucy Suchman's ethnomethodological approach to situated action to build my own approach to making as a way of designing, highlighting the theoretical implications of considering the act of making as situated design, and the role of language, interaction, communication, and tools in the process. From these considerations, I discuss the theory behind computational making and making grammars as an inspiration and foundation for Interactive Making processes in the light of technology. Based on this discussion, I introduce two academic experiences, ‘Discrete Heuristics’ and ‘Making Ingredients,’ as examples of practical pedagogical applications of the theoretical concerns that lie at the foundations of this research in relation to Making as Designing using gestures. I discuss the methodologies developed in both examples for developing frameworks and workflows for designing and making as one integrated process.

Finally, I implement the Computational Gestural Making framework, building on top of the developments presented in the previous chapter, adding a physical and material component. By applying the Computational Gestural Making Framework, I answer the questions presented at the beginning of this dissertation and present a novel approach that could potentially leverage the use of technology to produce novel things, novel processes, and new knowledge about the things we design. For this purpose, I present a final project implementation through the use of a custom general-purpose robotic arm controlled by a multimodal system composed of different machine and deep learning modules capable of sensing and acting according to contextual characteristics such as material context and gestures. I present and explain different applications to interactive fabrication that constitute a ‘mind to factory’ approach to design in which the computational design trichotomy is reformulated into a new paradigm for thinking and making with machines.

5.1 From representing to making

According to Flusser, our society is was experiencing a creativity crisis[400]. In his view, the automation of industrial manufacturing has led not only to a physical separation between creators and the objects they create but has also eliminated observation as a collaborative effort of the eye and hand, a critical factor in the creative development of our society[401]. One may argue that the use of technology in design is constrained by the imposition of a hylomorphic model, where form takes precedence over matter, resulting in a constant imposition of preconceived ideas onto the material world, and "a violent assault on a material prepared 'ad-hoc' to be informed with Stereotypes"[402]. Consequently, the designer is compelled to pause the creative process, i.e., the development of an idea, form, or concept, and instead focus on the representation and execution of the idea, disregarding the vital interaction between perception and action that is present in analog processes involving manual creation.

As presented in the previous chapter, this thesis proposes a cybernetic and multimodal approach to Design based on conversation. Rather than representing a course of action, the development of systems for mutual intelligibility between humans and machines aims to set a foundation to establish the rules and mechanisms to compute as a collective endeavor. To do so, it is paramount to implement the mechanisms by which a machine can access the world, sensing and acting according to environmental variables. In that regard, it was argued that it is possible to generate intelligent machine behavior by giving machines the capacity to see, infer, and act according to contingencies of different scenarios. It was argued that a computational design trichotomy emerged from using technology primarily for representational and productive endeavors instead of as a vessel for design's intellectual and constant development.

It was stated that by focusing on new ways of interacting with tools, it is possible to reframe the role of representation in design and unleash the potential of technology to think and compute as

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[400] Flusser, Vilém, and John Cullars. "On the Word Design: An Etymological Essay." Design Issues 11, no. 3 (1995)

[401] Ibid pp 43.

[402] Ibid pp43

a collective endeavor. A modular approach focused on assembling different models into one system capable of recognizing gestures, detecting objects, and inferring actions, emerges not only as a novel system implementation with potential for creation but also as a framework to think about how to implement such systems. The proposition of flexible, interactive systems based on the assembly of different modalities for communication, perception, inference, and action addressed the concerns expressed in this dissertation related to how interactivity is key to keeping creativity alive as we make new things. Nevertheless, in the construal of considering design as an open-ended activity, in the proposition of interactive systems, the challenges come in the form of establishing the nature, purpose, and relevance of such systems in the design field.

5.2 A note on Human–Computer interaction and its relevance in Design and Making.

The theoretical foundations presented more than 35 years ago by Suchman[403] in relation to the interaction between humans and machines resonate vibramntly in the development of this dissertation. Suchman coined the term ‘situated action’ to tackle the issue of purposeful action and shared understanding. These concepts were fundamental to understanding and framing the nature of human-machine interactions in an increasingly computer-driven society. From the standpoint of the social sciences, Suchman presented a new perspective on mutual intelligibility[404] in the presence of new developments in machine intelligence that can be extrapolated to the current explosion in artificial intelligence deployments at a consumer level and that are reflected in the consequences of adding technology for design purposes. Sharply stating that the goal of much of the research around computational models of intelligent behavior was oriented toward ad-hoc goal-oriented solutions in particular scenarios, Suchman advocated for a complete reframing of the theory of human-machine interaction from an ethnomethodological perspective, focusing on communication and

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[403] Suchman, Lucille Alice. Plans and Situated Actions : the Problem of Human-Machine Communication. Cambridge [Cambridgeshire]: Cambridge University Press, 1987.

[404] The relation between observable behavior and the processes not available to direct observation. Ibid, pp 2.

how actors use resources to accommodate to particular situations. Departing from the planning model proposed by computer sciences paradigm for developing goal-oriented/problem-solving machines, the theory behind situated action proposed a way to contribute to the understanding of human intelligence and interaction. In Suchman's words, her proposition was aimed toward understanding *"how people produce and find evidence for plans rather than subsumed the details of action under the study of plans."*[405] To Suchman, *"plans are subsumed by the larger problem of situated action"*[406]. Suchman's ethnomethodological view of purposeful action was framed by five propositions that this dissertation takes and extrapolates to the problem of interaction in design:

a- Plans are representations of situated actions: Drawing on Mead's theory of the disjunction between our actions and our understanding of them, Suchman raises concerns about the connection between projected or reconstructed actions and those taking place in situ. In lieu of this, she posits an alternative perspective whereby plans serve as resources, akin to templates, for situated action, but they do not dictate the course of action[407].

This viewpoint asserts that individuals typically do not anticipate alternative courses of action or their outcomes until the execution of an action is already underway. Isn't this what designing is about -up to some extent? If we consider the discussion in previous chapters, when we design through sketches or physical models, we are faced with a dimension that is inaccessible to us inside a computer. The natural world, with its environmental components and intricate features, exerts a profound influence on our internal mechanisms, influencing the way we perceive and communicate our intentions in a myriad of ways. In the face of the material dimension, we are compelled to distinguish and choose our actions according to parameters and characteristics that are not always present in the digital realm. It is during these moments - when we encounter imprecise gestures, varying material consistencies, or unexpected stimuli perceived through our senses- that our plans are

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[405] Ibid pp 50.

[406] Ibid. pp 50.

[407] Suchman, Lucille Alice. Human-Machine Reconfigurations : Plans and Situated Actions. 2nd ed. Cambridge ;: Cambridge University Press, 2007.p71.

subtly altered. Perceiving the material world in varied ways, which is contingent upon circumstances, is a vital element in the act of creation and the development of novel concepts.

As I discussed in the preceding chapter, the individual nature of our gestures, coupled with the boundless array of actions we undertake each time we interact with the material world, as well as the constantly shifting conditions that arise from working with tangible objects, extend the potential outcomes of a design process towards an infinite number of stable configurations, all in response to a given design challenge. According to Suchman, post hoc analysis and representation of our actions reveal more about the character of our analyses than the nature of our situated actions. Nevertheless, both future planning and retrospective analysis can serve as valuable tools for formalizing newly acquired knowledge, skills, and overall learning that can emerge from situated action. Reflection on past experiences and knowledge encoding can retroactively improve how we create by modifying and enriching our prospective planning toward situated action, thus enhancing our abilities to produce increasingly refined and sophisticated works.

b- In the course of situated action, representations occur when otherwise transparent activity becomes in some way problematic: In her work, Suchman acknowledges that plans can be formulated both before and after the fact. To expand on this idea, she references Heidegger's concept of "readiness" in relation to the manipulation of objects. Heidegger argues that when we manipulate an object, it tends to disappear from our conscious awareness and become seamlessly integrated into our practical activities, almost as if it were an extension of our own body. This phenomenon, which he calls "ready-to-hand," renders the object transparent and indistinguishable from ourselves[408].

On the other hand, if an object proves to be uncooperative or "unready-to-hand," our activities become more goal-oriented, requiring us to develop explicit rules and procedures to overcome any obstacles. This shift in focus from the object to the activity highlights the fact that rules and procedures are not self-contained or foundational but instead contingent on and derived from the

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[408] Ibid, pp 73

particular context in which they are enacted[409]. In other words, rules and procedures are mechanisms for deliberation, and the situated action that they represent shapes their ultimate form and function. Therefore, the accountability of action to these rules and procedures is not based on procedural or rule-based compliance alone but rather on the specific circumstances and context in which the action occurs.

The previous argument relates to design and technology in several ways. According to Idhe[410], the relationship between humans and technology can only be understood in terms of 'intentionality' and the 'middle ground', 'area of interaction' or 'performance' that arises between the two. Furthermore, Idhe posits that it is only through specific, time-bound actions that the relationship between humans and non-humans can be defined or comprehended. In contrast to Latour's position, Idhe argues that this relationship is asymmetrical as the non-human actant is never fully transparentand therefore, only human agency has intentionality[411]. Nevertheless, to both Idhe and Latour, the concept of performance speaks to the real-time interaction in which both humans and objects - referred to as 'non-humans' by Idhe and Latour - are transformed into a new entity, a 'Sociotechnical Assemblage' according to Latour[412]. In this sense, both humans and objects engage in a dance of agencies, as the human with-intentions confronts the resistance and accommodation of mechanical agency provided by the object[413].

The resulting actions and products are made possible not solely by the human or the object, but by the relationship and actions enacted through their interaction. This underscores the notion that in analog design processes, tools often become almost invisible, acting as mediated objects through which the designer focuses on the specific act of 'making something.' Clark's[414] interpretation of the relationship between humans and technologies in terms of degrees of transparency provides a valuable perspective for understanding

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[409] Ibid. pp. 52

[410] Ihde, Don. Bodies in Technology. Minneapolis: University of Minnesota Press, 2002. pp 91.

[411] Ibid. pp. 96

[412] Latour, Bruno. 1994. "On Technical Mediation." Common Knowledge 3. pp.64

[413] Ihde. pp. 94

[414] Clark, Andy. Natural-Born Cyborgs : Minds, Technologies, and the Future of Human Intelligence. New York: Oxford University Press, 2003.pp.37

why the problems identified in my “Making Gestures” Master’s thesis - the generic, the creative gap, and black-box - are relevant to contemporary design practices involving digital technology[415].

Similarly to Heidegger and Merleau Ponty, Clark[416] argues that the difference between ‘opaque’ and ‘transparent’ technologies depends on the degree to which they fit our individual human characteristics. The more intricate and challenging technology is to use, the more opaque it becomes in terms of diverting the user from its intended purpose. However, the current model imperative in digital design practice is based purely on tool operation, neglecting the idea of real-time interaction and leaving out essential parts of the cognitive processes of design. The many intricacies of digital tools - the black-box - lead designers to focus on the elaboration of plans for representation - the creative gap - which can often result in the reliance on software to solve a particular design problem - the generic - relegating the act of making to an initial effort that is later rationalized by a fixed structure and fabricated - for example, through a 3D printer[417].

The adaptability and modular nature of the Computational Gestural Making framework proposed in this dissertation provides an effective means of addressing concerns surrounding the development of plans for interaction as recipes. It is imperative to acknowledge that these recipes are prone to alteration in response to dynamic contextual shifts or inadequate communication between participants. It is essential to recognize that the fragility of machine learning models under suboptimal conditions necessitates a reassessment of the underlying mechanisms that govern interaction. For example, when conditions are not ideal, it is crucial to revise the mechanisms that guide the interaction. Troubleshooting, therefore, involves re-training the model, altering hyperparameters, modifying lighting conditions, adjusting camera positions for optimal viewing angles, and so on. Such measures can be documented and presented as a

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[415] Making Gestures: Design and fabrication through real time Human Computer Interaction (Master of Science Thesis), Massachusetts Institute of Technology, 2015. pp.38

[416] Clark, pp 38.

[417] Pinochet, Diego. 2016. Making- Gestures: Continuous design through real time Human Machine interaction. In Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016). Melbourne.

troubleshooting guide to restore the desired[418] harmonious interplay between humans and non-humans that may have been disrupted due to contextual factors. By incorporating these solutions into the framework, it is possible to create an adaptive and resilient system that can facilitate seamless interactions between humans and non-humans, even under challenging circumstances.

c- The objectivity of the situations of our action is achieved rather than given: Returning to the work of Mead, Suchman challenges the perspective held by the social sciences that the objective world is an inherently given construct[419] as a normative sociological view. Instead, she draws upon Mead's concept of a "reversal" which suggests that human interaction precedes the establishment of a common-sense world as an objective reality. Mead's ideas-according to Suchman- acknowledge the existence of a natural world that is inherently constrained but also emphasize that this world is subject to interpretation through human interaction. In this view, the objective world becomes a necessary condition for intentional action, just as intentional action becomes a necessary condition for constructing the objective world. Suchman adopts an ethnomethodological framework, which posits that our world is rendered publicly available and mutually comprehensible through our everyday practices[420]. The underlying assumption of this approach is that objectivity emerges as a result of systematic practices or methods that enable us to communicate our individual experiences and circumstances to one another. Hence, the focus of this approach is on the mechanisms by which the mutual intelligibility and objectivity of our shared world are achieved through our daily actions, such that our common-sense understanding of the social world is not a precondition for interaction, but rather, its outcome.

Suchman's consideration can be extrapolated to the context of digital design and fabrication. The idea that the digital is an adequate representation of the real ignores the phenomenological dimension of meaning[421]. This dimension involves aspects of materiality and human intervention as active decision-making agents. Therefore,

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[418] By the designer

[419] Suchman, pp74

[420] Suchman, pp76.

[421] Perez-Gomez, Alberto "The historical context of contemporary architectural representation" in Ayres, Phil. Persistent Modelling : Extending the Role of Architectural Representation. Abingdon, Oxon ;: Routledge, 2012. pp 13.

the linear process of creating a physical object through digital design and fabrication tools entails a "creative gap"[422] in the reasoning process of developing an idea in order to create a plan for its physical manifestation that freezes and objectifies a design before it is produced. In that regard, Gürsoy and Özkar[423] distinguish between "making of" and "making for" processes, where the former does not consider materialization as a mechanism for reasoning about the design itself, whereas in the latter, materialization and design are indistinguishable.

This cause-effect relationship between idea and prototype relies on evaluating results to modify the structure that originated the output. The process of translating an idea into a digital model, to G-code, to material, to prototype, and so on, involves a series of translations and black-boxed operations that happen either with minimal human intervention (clicking and typing) or without human intervention-3D printing the designed object-. Furthermore, these operations depend on formal or codified knowledge about 'ways of representing' that do not account for perceptual and phenomenological contingencies and interactions of the agents involved, including the eyes, hands, gestures, mind, materials, and tools. This black-boxed world, or what Perez-Gómez calls "the between dimensions"[424] - from idea to prototype- is not an issue in analog-making processes since they do not rely on predefined structures of codified knowledge. Instead, these processes are based on "ways of making" that consider a constant unfolding and evolving process of applying tacit knowledge as situated action to create something.

Designers -within a digital environment- bring their ideas to life through a series of actions involving clicking and typing, which translate their intentions into various visual representations, such as rendered images, technical drawings, and interactive visualizations, to name a few. However, If the purpose of design is to produce a physical output, digital fabrication techniques enable designers to generate prototypes through design iterations. However, the one-way visual communication established between human and machine

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[422] Pinochet, pp 283

[423] Gürsoy, Benay, and Mine Özkar. 2015. "Visualizing Making: Shapes, Materials, and Actions." Design Studies 41: 29–50. https://doi.org/10.1016/j.destud.2015.08.007.

[424] Pérez-Gómez,pp 13.

throughout the process, from the mind to software, from software to code, and from code to material, appears to be insufficient, at least in terms of material and tool feedback, to reason about the development of different ideas and emergence of new things. For example, shape grammars are an effective way for designers to develop their ideas as a step-by-step process and communicate them using visual reasoning in which the concept of emergence represents a foundational characteristic. In her paper "computing with emergence,"[425] Knight argues that emergent phenomena in most computational systems are the output of computations, and are not used as input [426]. In that regard, Knight distinguishes different sorts of emergence: anticipated, possible and unanticipated, addressing the diferent ways not only shapes emerge but also rules can emerge from a computational process[427]. Similarly, Gürsoy and Özkar propose a distinction between accidental emergence, which arises from the execution of a scripted algorithm, and anticipated emergence, where shapes and rules are clear and recognizable throughout the process[428]. If digital fabrication tools are used beyond their representational purposes, by considering the opportunities that human-machine interaction systems present to compute and reason in real-time through various steps of the manufacturing process, it could be possible to enable anticipated emergence and increase the designer's awareness of the entire process[429].

d- A central resource for achieving objectivity of situations is language, **indexically relating the circumstances it presupposes, produces, and describes:** Adopting an ethnomethodological approach, Suchman highlights the indexical nature of language, which implies that the communicative value of a linguistic expression is inherently tied to the situational context of its use[430]. Suchman's apporach holds similarity with Wittgestein's theory of language[431]. Wittgenstein posits that language games offer a means of comprehending the various ways in which language is employed

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[425] Knight, T. (2003). Computing with Emergence. Environment and Planning B: Planning and Design, 30(1), 125–155. https://doi.org/10.1068/b12914

[426] Although Knight provides some exceptions, see Ibid pp 130.

[427] Ibid pp 136.

[428] Gürsoy and Özkar, pp.33

[429] Ibid, pp 34.

[430] Suchman, p77.

[431] See Wittgenstein, L. (1953). The philosophical investigations. Oxford: Blackwell.

within diverse contexts and for diverse purposes. He contends that language is not a rigid assemblage of unchanging principles and definitions, but rather an adaptable and dynamic activity that is fashioned by the specific scenarios in which it is utilized. Wittgenstein's view is that each language game has a distinct collection of principles, which are not fixed or universal but rather dependent on the specific context in which they are employed. These principles are not arbitrary, however, as they are determined by the customs and conventions of the community that utilizes the language game. The idea of language games serves as a tool for Wittgenstein to illustrate his more comprehensive philosophical notions concerning the essence of language, meaning, and comprehension. He argues that meaning does not exist autonomously from language but rather emerges from language usage within specific contexts and practices. In essence, Wittgenstein's theory of language games underscores the significance of comprehending how language is used in practice, as opposed to theory. It highlights the importance of context, custom, and the context-specific application of language use, and has had a substantial impact on disciplines such as linguistics, anthropology, and philosophy of language. In a similar way to Wittgestein, Suchman argues that providing a comprehensive and precise description of the meaning intended by a language user in relation to a given context requires a detailed account of the situational and contextual factors that inform the utterance. Consequently, the situational dimensions of a linguistic expression encompass a diverse and indeterminate range of potentially relevant features. Moreover, Suchman emphasizes that all language has an essentially indexical relationship to the embedding world and that mutual understanding does not rely on a fixed stock of knowledge associated with specific words or actions that machines could process and understand[432].

Suchman highlights the significance of situational context in shaping the meaning of language in communication, conversation, interaction, and mutual understanding. Specifically, she argues that adhering to an instruction requires more than a simple prescription of ad hoc instructions based on preconceived descriptions. Instead, it necessitates a sensitivity to the situatedness of those instructions and the potential for new descriptions to emerge in response to the unique features of each particular context. In essence, Suchman underscores the importance of viewing language not as a static

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[432] Ibid, pp 80.

system of fixed meanings, but rather as a dynamic and contextually-dependent phenomenon that is constantly being shaped and re-shaped through use. This observation has significant implications for the realm of artificial intelligence, which must process vast amounts of data to achieve efficient generalization, and, if applied to Design, falls short in expanding concepts, ideas, or the formulation of novel questions and solutions given a design problem. Nonetheless, efforts to include background assumptions of a statement as part of its semantic content contradict the fact that there is no fixed set of assumptions underlying a given statement. Each elaboration of assumptions introduces further assumptions, ad infinitum. Expanding these ideas to the concept of Design as a conversation between humans, tools, and materials within a particular context, we can interpret the central proposition of this dissertation as a means of blurring the boundaries of the trichotomy through real-time human-machine interaction.

e- The mutual intelligibility of action: Suchman posits that the structural framework of rules, plans, and other elements is not the fundamental basis of situated action but rather an emergent byproduct of it[433]. Accordingly, the social world, as Garfinkel suggests, is not the outcome of a ‘cognitive consensus’ but rather a manifestation of our implicit application of the ‘documentary method.’ This method delineates a search for patterns that underlie unique appearances by observing how actions are regarded as indications of underlying intentions or plans. It is a capability that is tantamount to identifying rationality, as much as the ability to act rationally itself. In that regard, while in concrete situations, the conduct of actors must be identifiable as a category of appropriate actions, there are no universal rules for interpreting actions that are independent of context. Suchman contends that the constancy of the social world is achieved by situated actions that foster and maintain shared understanding in specific instances of interaction[434]. This enables actors to utilize normative conduct guidelines to produce significant actions effectively. In some ways, the point Suchman suggests about the normative guidelines we use when confronted with any situation and context is close to the general theory of habitus.

Habitus is a concept within the discipline of sociology that pertains

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[433] Idib, pp 80.

[434] Ibid, pp 81.

to how individuals perceive and respond to the social environment in which they exist based on their idiosyncratic routines, proficiencies, and predispositions. Those who share a mutual cultural heritage (such as social class, religion, nationality, ethnicity, education, and profession) also share a habitus, which encapsulates how group culture and personal history interweave to shape the physical and mental constitution of an individual. As such, one's habitus exerts a substantial impact on and configures their social actions. Bourdieu introduced the concept of habitus as a theoretical construct to explain how social structures influence individual behavior[435]. In Bourdieu's theory, habitus refers to the set of dispositions, habits, and attitudes that are shaped by an individual's social and cultural background, guiding their thoughts and actions in the world. Bourdieu believed that habitus is not fixed or predetermined but, rather, is constantly evolving in response to changing circumstances and experiences. Design, like other skillful practices, works similarly. Through repetition and interaction with other people, materials, tools, and so on, we internalize daily practices and tacitly learn how to devise ways of making based on whatever problem or task we have in front of us. When we attend to a Design problem, we recognize features, parameters, and the constituent 'ingredients', as we go, to find by trial and error the action sequences-acquired over time and tacit- that allow us to develop a solution or expand the problem through new questions derived from the evidence of our actions. We constantly adapt to a physical, mechanical, or chemical aim, through a series of assembled actions, not in isolation but in the presence of a cultural and historical context[436].

The relevance of this discussion when extrapolated to the act of creating new things goes back to the discussion of knowledge and its production. According to Forsythe[437], a great deal of knowledge is tacit, meaning that individuals may not be aware of what they know or what they are doing when performing a task. As a result, what they say they are doing, what

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[435] See Bourdieu, Pierre. *Outline of a Theory of Practice*. Translated by Richard Nice. Cambridge Studies in Social and Cultural Anthropology. Cambridge: Cambridge University Press, 1977. doi:10.1017/CBO9780511812507. Also, Bourdieu, P. (1984). Distinction: A Social Critique of the Judgment of Taste. Cambridge: Harvard University Press and also, Bourdieu, P. (1990). The Logic of Practice. Cambridge: Polity Press.

[436] Mauss, Marcel. (1935). "Techniques of the Body." In Sociology and Psychology: Essays. London: Routledge & Kegan Paul, pp. 95-123.

[437] Forsythe, D. E. (1993). Engineering knowledge: The construction of knowledge in expert and novice engineers. In G. C. Bowker & S. L. Star (Eds.), Social dimensions of science and technology: Understanding the work of science (pp. 49-84). Sage Publications.

they think they are doing, and what they are observed doing may not always align. Applying structure to this kind of knowledge would be a difficult task if it is even possible. Schön similarly argues that "problems of real world-practice do not present themselves to practitioners as well-formed structures."[438] Schön's ideas align with the view of knowledge in the social sciences[439], where problems are "messy" and not easily solved. When a designer approaches a problem, she selects and names the things she will notice. Although this naming and framing, she chooses details to bring to attention and organizes the information according to her personal objectives, giving coherence to the problem and establishing a direction to pursue. According to Schön, depending on disciplinary backgrounds, organizational roles, past histories, interests, and perspectives, individuals frame situations differently. Given the varying possibilities of each situation, the hypothesis enforced here is that knowledge is not static or concrete but shared and actively constructed.

Concerning context and the situatedness of design, it is possible to argue that designing, like other creative disciplines, is a material process that responds to many contingent factors. Keane, from his semiotic perspective on material things[440], challenges the use of semiotics as a means of communicating pure meaning through symbols, asserting that this approach creates significant problems in comprehending materiality[441]. He contends that treating objects merely as illustrations to convey meaning is misguided, as it prioritizes fixed meaning over actions. This perspective becomes relevant to design when any attempt to define, verbalize, and compartmentalize the design process into structured symbolic representations obstructs the emergence of new knowledge. Design, with its inherent materiality, is tied to the problem of indexicality, advocating for a more practical rather than a contemplative approach to activities.

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438 Schön, D. A. (1987). Educating the reflective practitioner. Jossey-Bass. Page 4

439 Forsythe, 49.

440 Keane, M. T. (2005). Semiotics and the philosophy of language. New York, NY: Athlone Press. Page 49.

441 Ibid. pp 137

5.3 Computing in the material world

If we conceive of design as a process of creation that emerges from our engagement with the world, then it follows that being in the world entails an encounter with material things that cannot be reduced to mere mental representations. In this sense, design is inherently indexical, where the notion of "bundling" refers to the co-presence of qualities that arise from materiality. The qualities that are bundled in any object vary in terms of their salience, value, utility, and relevance across different contexts. Consequently, every object possesses the potential to resemble something different each time we attend to it. As Keane notes, the semiotic character of material things implies that the outcome is not determined, but their semiotic orientation points towards their unrealized future potential[442]. The concept of bundling is central to every creative endeavor. Design, as something we do, is related to our unique human condition as creative individuals. In addition, making is a way of manifesting and impressing our uniqueness onto our environment, always attending to things as something different. Therefore, the indexical quality of design allows creators to generate new things and knowledge about how things emerge in the world.

Knowledge, as Bohm notes, is produced and transformed through thought, and thought is the way knowledge achieves its actual and concrete existence, making it essentially a material process[443]. Design is a process of situated knowledge that is inherently material, undetermined, and ambiguous, and, therefore, imprecise. Design becomes something concrete through the act of designing, by acting and impressing our unique perspective based on how things resemble something else each time we attend to them, learning new things. Heidegger's concept of "begegnen," or things showing up to us as we act in the world, is also relevant here[444]. Every decision is based on something that is not fully mastered, which reflects Heidegger's rejection of the "explicitness" of thought[445]. Therefore, design is a process of situated, embodied knowledge that arises from our encounter with the material world and reflects our

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[442] Ibid, page 188

[443] Bohm, David. Wholeness and the Implicate Order. London ;: Routledge, 1995. pp 50.

[444] as cited in Dreyfus, Hubert L. Being-in-the-World : a Commentary on Heidegger's Being and Time, Division I. Cambridge, Mass: MIT Press, 1991. pp x.

[445] As cited in Dreyfus, pp 4.

unique perspectives and interactions with the world around us. As developed in chapter 3, going beyond representation as fixed plans for designing and making allows moving to the determination of plans for actions that can embrace the ambiguity and non-deterministic characteristics of creation as a collective act.

As shown in chapter 3, the Computational Gestural Making framework developed in the deep enactions project establishes a path to embrace interactivity by establishing a language and a template for effective communication as a system enabling real-time interactions between a designer and a machine.

As I discussed extensively in this dissertation, how we learn and create things depends on how we constantly interact with our surroundings. In the same way, it has been discussed how, in this constant interaction, the elaboration of representations as strict plans for achieving something does not suffice when the purpose is to design and explore design problems. In that sense, the elaboration of templates or guidelines for action emerges as a path for enabling human-machine interaction and the use of technology beyond mere efficient production, and it engages a more integrated tool for thought and sets a fertile field for divergent thinking.

The proposition of a framework for designing and making based on gestures sets the foundations for creative processes as a conversation that can engender new knowledge about what we do. In that regard understanding how we use tools and how we address the unique aspects of materiality involved in making processes is crucial. In the previous chapter, most of the implementations were constrained to the digital world in which only a few physical characteristics were simulated toward integrating into all the parts of the system successfully. However, when confronted with reality, the aspects of materiality and how we engage with the material world present a new level of complexity that needs revision and further consideration.

5.4 Designing with discrete things… made of unpredictable stuff

Concerning materiality and our body's disposition towards material things, in the construal of the embodied mind, an interesting approach is the one made by the Material Engagement Theory. Malafouris argues that 'action' is a form of cognition and that human cognition is not situated in the head but in our entire body[446]. Furthermore, an interesting concept introduced by Clark is the 'leaky mind'[447] presented in the Extended Mind Theory (EMT). According to this concept, the local mechanisms of the mind are not exclusively in the head, instead 'cognition leaks out into body and world'[448]. Similarly, Malafouris explains from an enactive perspective how humans think and learn through things by engaging with our surrounding material environment[449] and how the mind extends form the head to the objects we touch and interact with. According to Robinson[450], the EMT 'is the notion that in specific kinds of mind-body-world interaction there emerges an extended mind or extended cognitive system that doesn't just use but incorporates the pencils, paper, computers, and other extra-cranial objects and environments we use to help overcome or work around our brain's klugey design flaws'[451]. The hand, gestures and the use of tools as mechanisms by which we learn and think are crucial to why the revision of the design process through technology is relevant.

Ingold suggests that creative endeavors involve not reproducing preconceived ideas, but rather the joining and following of the material forces and flows that bring the work into being[452]. Robinson describes this interaction between the mind and tool as "circulation," in which tools become an externalized mind and cognition becomes internalized tools[453]. Understanding this circulation is crucial in comprehending the role of digital tools - both software and hardware - in the creative aspects of Design, and in exploring the affinities and tensions that arise when using tools as both objects to sense and objects to think with. As Robinson suggests, the mind-tool interface is

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[446] Malafouris, Lambros. How Things Shape the Mind : a Theory of Material Engagement. Cambridge, Massachusetts: MIT Press, 2013.

[447] Clark, Andy. Natural-Born Cyborgs : Minds, Technologies, and the Future of Human Intelligence. New York: Oxford University Press, 2003.

[448] Ibid pp p.xxvii

449Ibid pp7.

[450] Robinson, Douglas. Feeling Extended : Sociality as Extended Body-Becoming-Mind. Cambridge, MA: MIT Press, 2013.

[451] Ibid pp1

[452] Ingold, T. (2008). Bringing Things Back to Life: Creative Entanglements in a World of Mate-rials (Working Paper). Realities / Morgan Centre, University of Manchester. Retrieved from http://www.manchester.ac.uk/realities/ publications/ workingpapers/ pp 17

[453] Robinson pp35.

not a static one but rather involves a bi-directionality where designers internalize tools as mind and externalize mind as tools through a proprioceptive circulation[454]; Thus, gestures and actions, as forms of sense and movement, play a vital role in this negotiation. The idea of circulation or interaction as a performance that constantly engages humans, tools, and the environment has revealed essential factors for formulating how this interaction should occur throughout this dissertation. This interaction, which is founded on unified action and perception, is fundamental to nurturing creativity and cognition in the design process that can lead to new knowledge about the things we think and do.

In developing systems aimed toward Design through technology, it is crucial to focus on real-time interaction, allowing designers to improvise and respond to the contingencies of the world around them, including material objects, tools, and their own bodies. Therefore, since Design is not a process of following pre-structured rules but rather a constant discovery where new rules and actions emerge as new things are encountered, developing interactive systems is imperative, especially when dealing with the unpredictability of material things. Thus, in the ubiquitous use of digital design and digital fabrication tools, how to use digital fabrication tools not as a ‘Making of’ process but as ‘Making for’ one, as Gürsoy and Özkar state? How to consider and incorporate materiality’s ambiguous and unpredictable aspects in design and making processes to produce new things and new knowledge about those things? In this section, I delve into the richness of shape and making grammars as a Design paradigm to explore Computational Gestural Making as a way to interact and collaborate in real-time with digital fabrication tools. It focuses on gestures and the choreography of making as critical process elements instead of merely fabricating an object.

5.5 From Computational Fabrication to Computational Making

Recently, a new area of inquiry emerged inside the Design and Computation Group at MIT known as Computational Making seeks to relate design and making under a computational perspective to the Design discipline[455]. As opposed to Computational fabrication – that is, manufacturing through the use of digital and physical computational

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[454] Ibid pp 60.

[455] Knight, Terry Design Studies, 41, Part A , pp. 1- 7, 2015, ISSN: 0142-694X, (Special Issue: Computational Making).

automated systems[456]- Computational making understands, on the one hand, 'making' as an activity that is time-based, dynamic, improvisational, contingent, situated, and embodied, that is tightly interrelated in numerous forms to designing[457]. On the other hand, Computational making understands computation as the use of mathematical systems, theories, methodologies, and so on, along with technologies and tools based on them[458]. Moreover, based on the intersection and relation of these two concepts – making and computing- it seeks to understand and formulate new questions and theories about the relationship between abstract computation and embodied making through their affinities and dissensions.

One foundational research paper about how computation and making relate to each other is Making Grammars: From computing with shapes to computing with things[459] which expands Stiny's computational theory of shapes and the algebra behind them, known as shape grammars. This paper proposes a computational theory of making based on the improvisational, perception, and action approach of shape grammars[460]. It proposes adapting shapes grammars that compute with shapes to make designs to making grammars that compute with stuff to make things[461]. In this paper, Knight and Stiny inquire into computational making developing implementations that go from drawing (á la Stiny) to knotting (á la Ingold) to painting with watercolors (á la Sargent) to frame making as a computational activity –that is, through an algebra and rules for its application- by capturing the prominent properties of stuff and things in the making, described computationally[462]. Through examples adapted from shape grammar rules and schemas, Knight and Stiny propose a set of time-based descriptions for making and identifying the elements involved in each one of the examples. For example, when it comes to knotting, Knight and Stiny extend a computation with lines –infinitely divisible abstract elements- to a

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[456] As an example, the computational fabrication group at CSAIL MIT (http://cfg.mit.edu) led by professor Wojciech Matusik, is a referent in the field investigating problems in digital manufacturing and computer graphics.

[457] Ibid. p2.

[458] Ibid. p3.

[459] Knight, Terry; Stiny, George. Design Studies, 41, Part A, pp. 8- 28, 2015, ISSN: 0142-694X, (Special Issue: Computational Making).

[460] Ibid. p8.

[461] Knight, p.3.

[462] Knight and Stiny, p26.

computation with strings –infinitely divisible material elements- to explain how the algebras behind shape grammars can be modified to apply to things in the material world. In this example, they describe Things (knotted strings in 3D), Stuff (strings), Doing (knotting by pulling, looping, etc.), and Sensing (touching by grasping, focusing attention, repositioning, and so on with hands) as the elements and actions involved in the computational making process.

Taking into account the transition from lines subject to the unique interpretation of a designer through visual perception, to the use of physical strings, subject to the unique interpretation by a maker through visual and tactile perception, abstraction is used to explicate a step-by-step computation with knots describing the process of doing and sensing[463] . Furthermore, another example -painting with watercolors- the authors describe the many possibilities of formalizing the painter John Singer Sargent´s grammar through the correspondent description of elements involved in making the paintings. Nonetheless, as they assert, describing rules for computational making processes that comprise different materials that behave differently not only in time but in interaction with other materials is a very complex task that may require further development[464]. But despite material considerations, also tools and the way the body interacts with them - as gestures- are a part of the process that needs to be considered when trying to formalize making as a set of rules. Furthermore, in the making process, the richness of shape grammars –and their extension as making grammars- as a methodology for designing using visual perception through observation and embedding is confronted with the particular nature of physical things. Finally, Knight and Stiny acknowledge the difficulties of translating the properties of shape elements to physical things and their differences and limitations when it comes to embedding, for example when the computation is made with discrete elements such as strings.

Before determining and explaining the development of interactive design and fabrication systems, I present the experiences using a pedagogical approach to Design inspired by shape and making grammars and the theory behind the area of Computational Making. These experiences represent the work developed during my last eight years as an academic instructor that helped me

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[463] Ibid. p23.

[464] Ibid. p25.

build the foundational characteristics behind the Computational Gesture-Making framework. Not necessarily digital but inherently computational, a pedagogical framework I developed called ‘Discrete Heuristics’ that gathers the concepts discussed in this dissertation and that was applied to educational scenarios, helped me shed light on how to tackle the development of interactive fabrication systems beyond the computational design trichotomy.

5.6 Discrete Heuristics: an exercise on plans for action, tools, and material computation.

Shape grammars offer a versatile educational paradigm for design, enabling designers to use rules perceptually to create diverse designs. However, when these designs are translated into the physical world, they must contend with the unpredictability of materials. This forces designers to consider material phenomena as a critical aspect of designing and expressing their uniqueness in the physical world. Computational making provides a basis for understanding the process of designing and making by developing rules and schemas computationally. At the Design School of Adolfo Ibañez University, the “Discrete Heuristics” third-year studio was an opportunity to leverage visual computation as the fundamental design methodology considering designing a perceptual reasoning process that applies three-dimensional geometrical rules in light of material phenomena. Students were encouraged to study different materials and techniques during the studio, developing material and formal rules for future application. This allowed them to abstract crafting processes and create rules that could be applied to various materials and designs.

During the studio, students were challenged to elucidate the phenomenological characteristics of the process, comprehending how specific tools and unique gestures can give rise to distinctive manifestations of discrete components according to the material employed (as depicted in 98). This concept served as the starting point for the studio, which aimed to reformulate the creative act by employing discrete shapes as “things” and design heuristics as rules (as illustrated in figure 99), harnessing the potential of computational making to make the thought process explicit. Moreover, by creating ‘making grammars’ and utilizing a 7-axis KUKA robot, students were encouraged to devise design methodologies where the robot -as a tool for thinking- acts as a collaborator or counterpart in crafting.

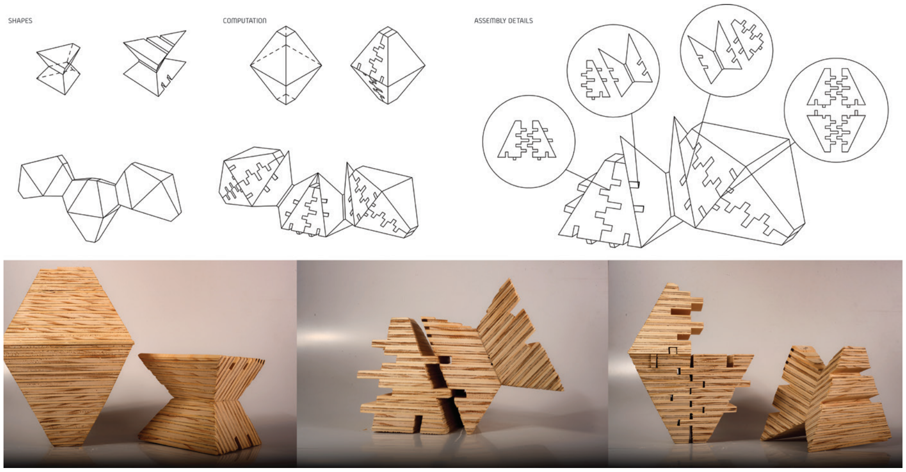

Figure 98
Computations of different assemblies with plywood components. Alvaro Riquelme, Discrete Heuristics Studio, DesignLab 2016.Taught by Diego Pinochet.
Source: author

Figure 99
Material computations of thin composite shells. Francisca Dominguez. Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet
Source: author

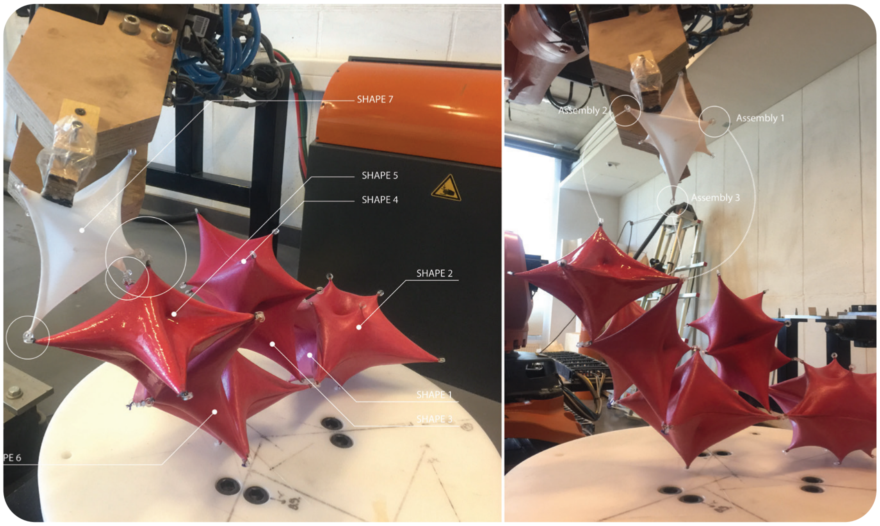

Figure 100
'Shaping' Material computations of Elastic Fabric with resins and digital assembly with a 7-axis Kuka Robotic Arm. Lucía Abarca, Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet
Source: author

Whether working with materials to fabricate discrete components or using robotic arms as a partner in the assembly of designs, students were prompted to develop a crafting process based on shape and material computation, utilizing rules to make the process of making explicit (as shown in figure 100).

The studio had a modular approach to Design. The pedagogy considered adding complexity layers incrementally in the quest to develop a "personal design process." In the beginning, the students were tasked with designing a process of making using visual computation of shapes to describe and learn about the emergence of their designs with 3D shapes. They first learned about shape grammars through exercises that generated rules computing different designs, similar to Terry Knight's Visual Computing class at MIT. Using discrete elements made of white paper, students analyzed their own and others' designs, learning visual computation as a methodology. Next, students focused on the assembly between components, adding a layer of complexity to the process. They designed rules for the aggregation of shapes and the details of the assembly between them, going beyond the use of double-sided tape (as illustrated in figure 101). After mastering visual computation through shapes and rules, the studio added another layer of complexity, incorporating material phenomena. In this stage, students chose two materials

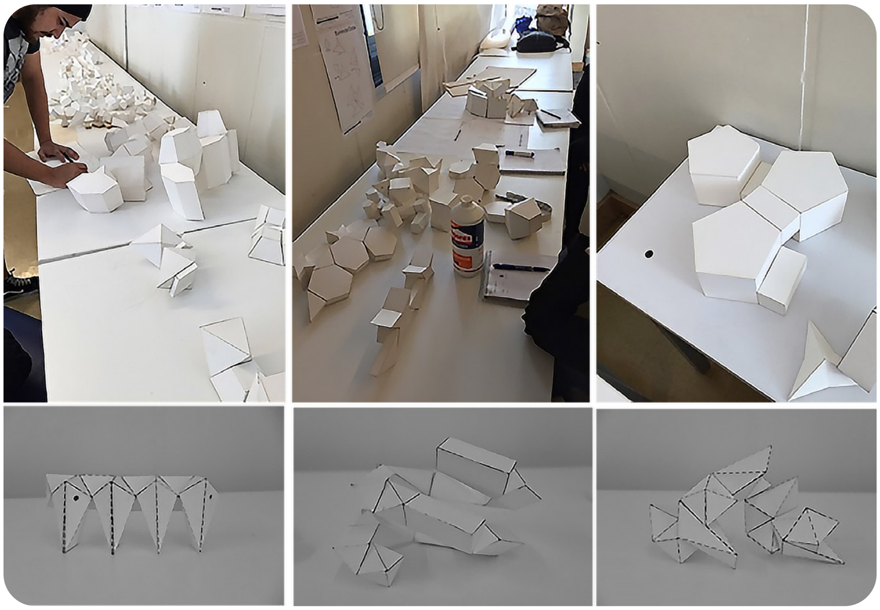

Figure 101
Shape computations using paper models. Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet

of different characteristics and described the techniques required to make any shape using them, including identifying tools -through knolling pictures- and the 'stuff' involved in the process as a recipe (figure 102). Students then described a step-by-step process by which the material 'stuff' is processed, focusing on detailed descriptions of body gestures and the phenomenological characteristics that emerged from the process of working with materials. The objective was to teach students to recognize specific moments where following a specific and "discrete" recipe proves insufficient while at the same time showing how their personal experience and knowledge play a fundamental role in how to cope with the unexpected situations of making processes.

Considering cooking as an analogy, students were asked to understand the process of making by realizing the difference between linear deterministic manufacturing processes such as 3D printing, and perceptual making processes, such as drawing, painting, or crafting. As an example, preparing food, involves a predefined generic structure in the form of a recipe/algorithm that indicates rules, procedures, and also quantities to be followed. Nonetheless, the act of preparing food involves sensing and acting of the 'moments' impossible to quantify or code beforehand. In a similar way to Stiny's and Knight's alchemic description of Sargent's paintings, thickness, smell, taste, consistency, color, and so on are

Figure 102
Knollin pictures of the design 'ingredients'. Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet
Source: Benito Gonzalez.

parameters often described with ambiguous sensorial instructions that are either visual – when meat reaches a specific color according to a desired cooking point- or physical –adding more flour to thicken a sauce preparation or olfactory. These moments are the ones that Stiny and Knight describe as the 'in between' moments that are susceptible to be broken up into finer and finer parts, not describable but only enacted[465]. The idea behind this was to formulate the act of making as a deictic 'discrete heuristic' process that proves to be highly specific according to the partial description of a process (the discrete) yet highly ambiguous when it comes to enacting those rules (the heuristic) according to context, material behavior and the gestures performed in the making (figure 103). By practicing other students' processes, students realized that original designs and the knowledge and techniques related to how to make those designs,

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[465] Ibid. p16

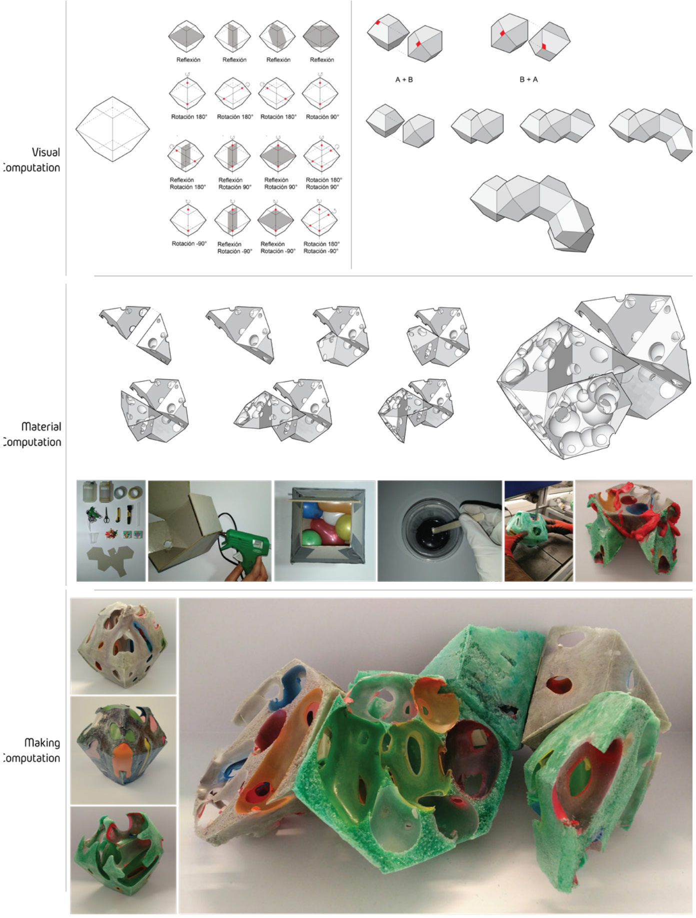

Figure 103
Discrete Heuristic process for the development of lightweight foam structures. Rosario Yañez. Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet
Source: Rosario Yañez

emerge because of their unique impression of gestures, ideas, and the way they interacted with tools in a specific environment. The studio reflected especially on materials and the body techniques that emerged from enacting design recipes. The studio focused on how the body learns, adapts, and internalizes processes culturally. As Mauss argues, the body is not a neutral vessel but is culturally and socially constructed through practices such as dance, sports, and other physical activities such as crafts. He identifies three types of techniques of the body: habitual, individual, and collective[466]. Through these techniques, Mauss argues that individuals internalize

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[466] Accordin to Mauss, Habitual techniques are those that are learned through repetition and become second nature, such as walking or breathing. Individual techniques are those that are unique to an individual's body, such as a particular way of throwing a ball. On the other hand, collective techniques are shared by a group or society, such as the gestures and movements associated with a particular cultural dance or even a craft.

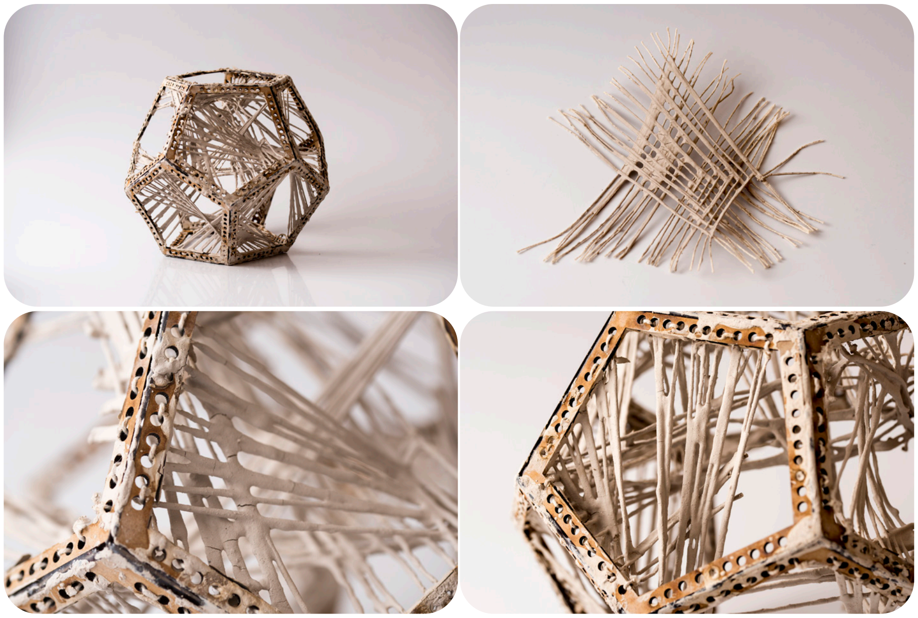

Figure 104
Material experiments by Katherine Dossow in Discrete Heuristics studio.
Source: Author

cultural norms and values, shaping not only their bodies but also their sense of self and identity. In the case of design and the Discrete Heuristics studio, the aim was to generate new ways of making by integrating those cultural and contextual conditions that determine our techniques as part of the design's computation and that, in time, are apprehended as new skills and new design knowledge (figure 104).

Ultimately, students came to the realization that the emergence of originality within their proposals stemmed not only from the interplay between historical precedents and the unpredictability of the present moment but also from the dynamic interplay between human expression and the inherent characteristics of the materials they employed, which imbued the physical world with the distinctiveness of the self. This realization was underscored by how the materials reacted during the creative process, and in accordance with specific actions. Programming a robotic arm to break stones in the work 'Reconciliation' is an example of the discrete heuristics applied in the design studio. In this project, a student worked an entire semester programming a KUKA robot to break -using similar

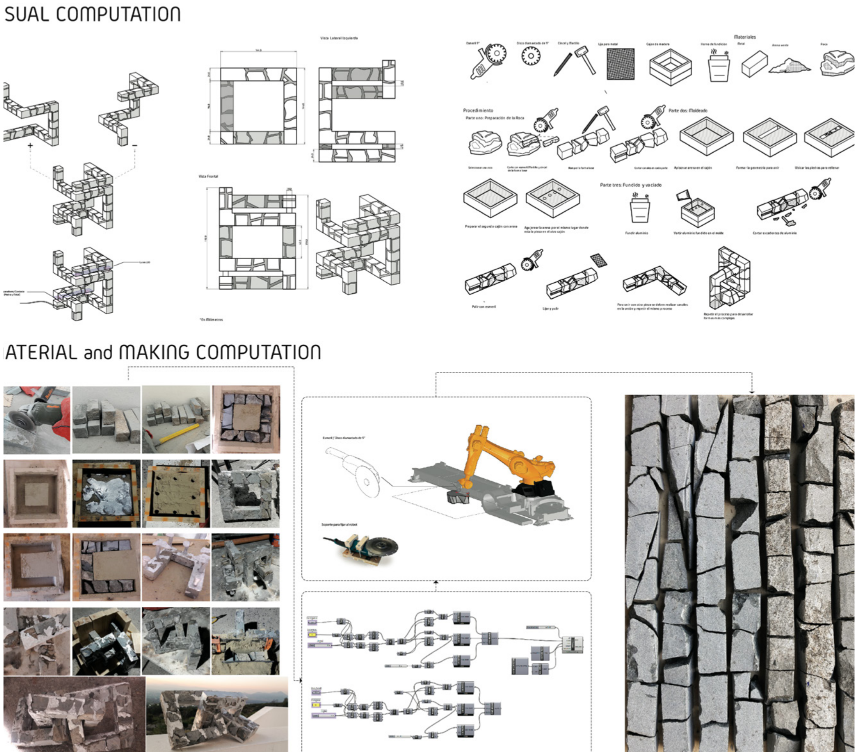

Figure 105
Development of a grammar for breaking stones with a robotic arm and for component assembly through molten aluminum. Lucas Helle. Discrete Heuristics Studio, DesignLab UAI 2016. Taught by Diego Pinochet
Source: Lucas Helle

routines- different types of rocks into smaller pieces (figure 105). The goal of his proposal was to understand the material behavior of the rocks breaking in unpredictable ways and how through the use of metal casting technique, he could reconcile two materials of different natures.

The algorithm's inherent discreteness, as a series of unyielding rules for fracturing stone, proved to be a remarkably fruitful and dynamic creative process. Indeed, the components derived from this process were always inherently unique, necessitating a constant reimagining of new formal methodologies to properly fuse them to molten metal, as evidenced in (figure 106). As they navigated the complexities and imperfections of the stone, the students experimented with an array of fixed procedures for working with molten aluminum, utilizing a diverse set of gestures to generate many different prototypes. Throughout this process, they developed an in-depth understanding of the mechanics behind Design principles, honing their ability to generate novel geometrical configurations and crafting personalized techniques for working with these two distinct materials.

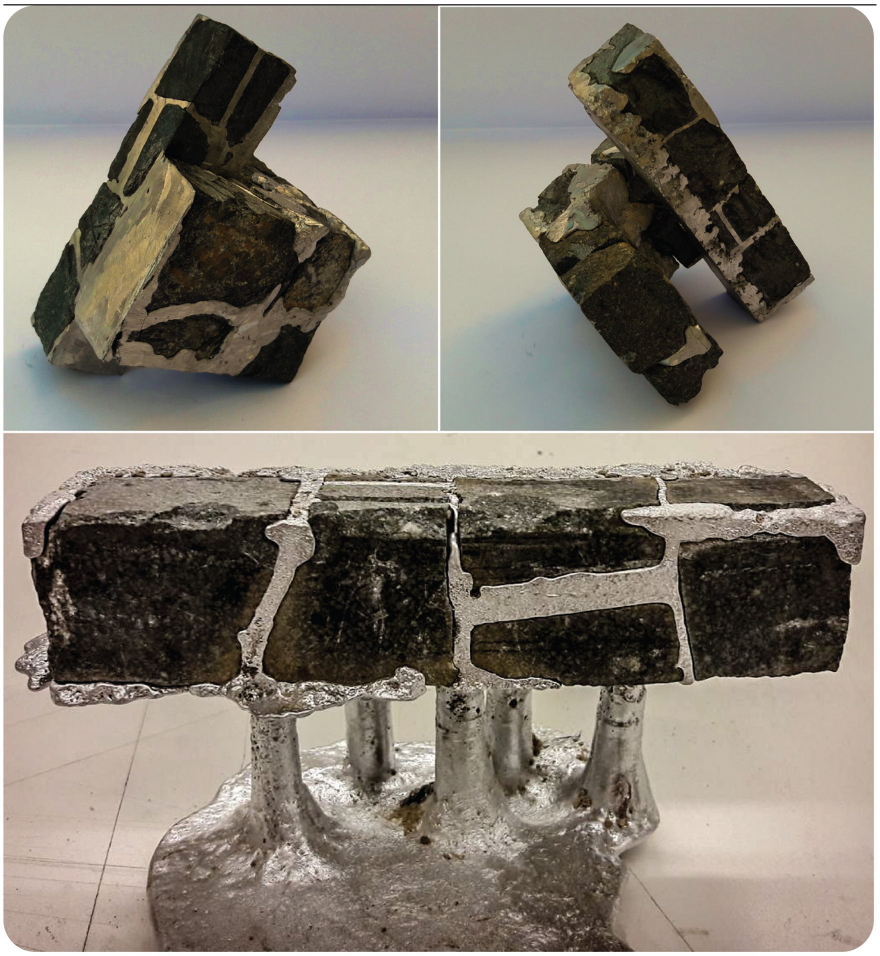

Figure 106
Work by Lucas Helle.
Discrete Heuristics Studio,
DesignLab UAI 2016. Taught
by Diego Pinochet
Source: Autor

The Discrete Heuristic Studio ultimately imparted a profound methodology to students, allowing them to freely explore the boundaries of design, tools, and materials techniques (figure 107). This approach went beyond the mere creation of prescriptive rules, instead emphasizing the critical importance of analyzing and describing sensorial instructions to fully comprehend and engage with the unexpected through the heuristic nature of interacting with physical objects. Through this innovative methodology, students realized that the emergence of originality within their proposals was not solely a result of the interplay between historical precedents and the unpredictable nature of the present moment. Instead, it was also a product of the dynamic tension between the human and the objects they engaged with, as their unique gestures imbued the physical world with their own distinctive essence. Furthermore, the materials themselves played a critical role in this process, reacting unexpectedly as the students worked to bring their creations to life.

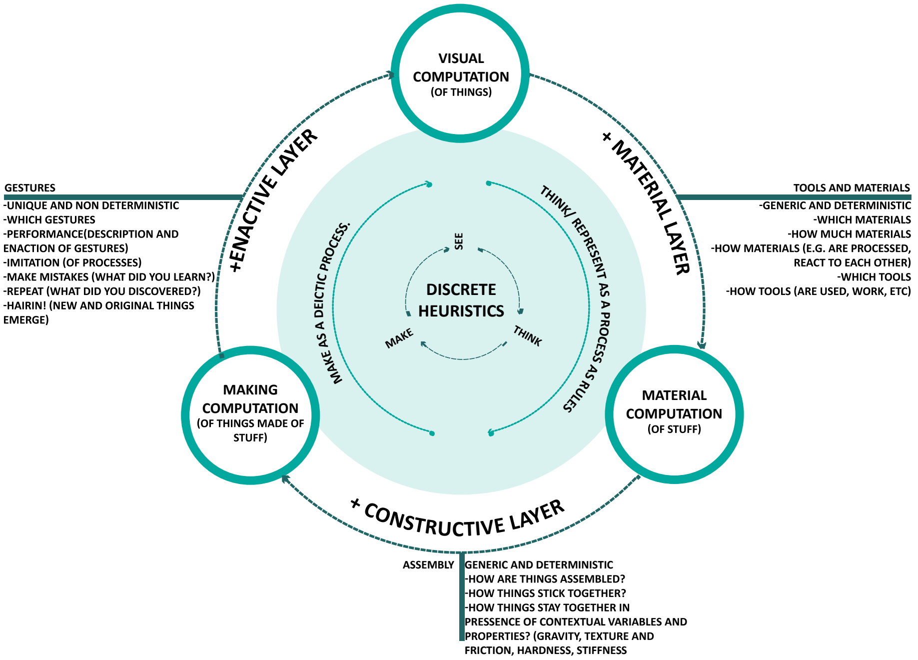

Figure 107
Discrete Heuristics Studio diagram. Based on Stiny´s and Knight´s Computational Making Paradigm, the studio teaches students about design, material computation and interactive digital fabrication in three stages adding layers of information to the creative process. Diego Pinochet, DesignLab UAI 2016. Source: author

5.7 Making ingredients: an exercise on Design context and the production of design knowledge

Another instance to test the theoretical and practical concerns of this dissertation in academic practice in relation to making, computation, and the production of knowledge through the development of novel design processes, was the Making Ingredients studio. Making Ingredients was an option studio in the Master in Architecture program at MIT’s School of Architecture and planning (figure 108). The studio was taught by a team conformed of Lavender Tessmer and me, invited guest lecturers Maya Hayuk, and Joseph Choma, and Teaching Assistant Gil Sunshine. Celebrating the return to campus after COVID-19 restrictions for in-person teaching were lifted, Making Ingredients was framed as an experimental fabrication studio committed to crafting vibrant and immersive installations that celebrated the reinvigoration of our physical space at MIT. The studio drew inspiration from diverse references that ranged from architectural fabrication research to street art and its ability to transform the built environment through colors, patterns, and light. The studio particularly emphasized the tangible aspects of design

Figure 108
Making Ingredients Studio at SA+P MIT. 2021
Source: author

Figure 109
Mapping the context.
Making Ingredients option studio, Fall 2021.
Source: author

and fabrication that were noticeably scarce at MIT for one and a half years.

Students worked collaborativelly around the MIT campus to evaluate the contextual, conceptual, and technical aspects of design and making. On the one hand, students documented and analyzed the immediate externalities of the built environment, highlighting the contextual elements of design and deployment, such as site constraints, material life cycles, and the metrics of time and labor (figure 109). On the other hand, students considered the distribution of skill, knowledge, and automation as drivers of design decisions. Furthermore, students considered the histories and contexts of digital fabrication machines and their impact on architectural design, considering their ubiquity in architectural education. Developing a critical standpoint, students were asked to evaluate the contrasting views of the maker movement and its relationship to how architects design for machines. Finally, students examined the process of design, representation, and fabrication through the lens of tacit versus explicit knowledge while considering the opportunities and shortcomings of digital computation for encapsulating knowledge of physical techniques.

The studio was structured into two modules: research and proposal. In the first module, students researched the ingredients of architectural production, analyzing and cataloging materials, resources, tools, and skills. In the second module, students proposed strategies and workflows as recipes to go from design to production, deploying physical prototypes and contextualizing projects within areas of fabrication research. The first half considered five assignments dedicated to specific research topics that fed the development of individual proposals in the second half: 1) context and resources, 2) knowledge and machines, 3) site agenda, 4) automation, encapsulation, and workflows, and 5) proposal.

Understanding that every endeavor that comprehends the deployment of a physical project demands attention to multiple factors or "ingredients" that happen before, during, and after a project is completed, students were asked to reframe the notion of 'context' beyond abstract notions related to 'place.'[467] Often avoided or not taken into account inside academic training, environments, tools, materials, energy, time, labor, and the myriad of constraints that emerge from specific contexts are categories that are crucial in the development of successfully built projects. Focusing on 1) machine analysis and availability, 2) material sourcing, afterlife, and processes, 3) resources, time, labor, energy, and budget, and 4) design constraints and qualities, students generated an overview as a foundation and general resource for multiple arguments about interpreting context within this studio.

Students were then asked to explore the relationship between design, making, materials, machines, and knowledge production, thinking critically about what types of knowledge are contained in

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[467] As instructors, we asked students to consider context beyond the typical architectural definition of context as place. In a typical architectural studio, the definitions for the site, place, or context can fall into typical descriptions that focus on the more abstract dimensions of design, such as aesthetics, elemental situations, sensory aspects, etc. Students were asked to go beyond these considerations and come up with an enhanced definition of site, place, and/or context based on other dimensions such as:

- Physical rules and constraints (accessibility, topographical, etc.)
- Rules and permissions (whom to ask for permission to intervene)
- Material qualities/properties (light and shadows, reflections, textures, views (perspectives, vantage points), acoustics, colors.
- What can be intervened and can be manipulated (block a hallway, paint a wall, hang objects) What's 'proper' and 'improper' (is there a way to work around some rules?)
- Topological characteristics (surfaces, volumes, voids)
- Other considerations that can help define a place, site, or context.

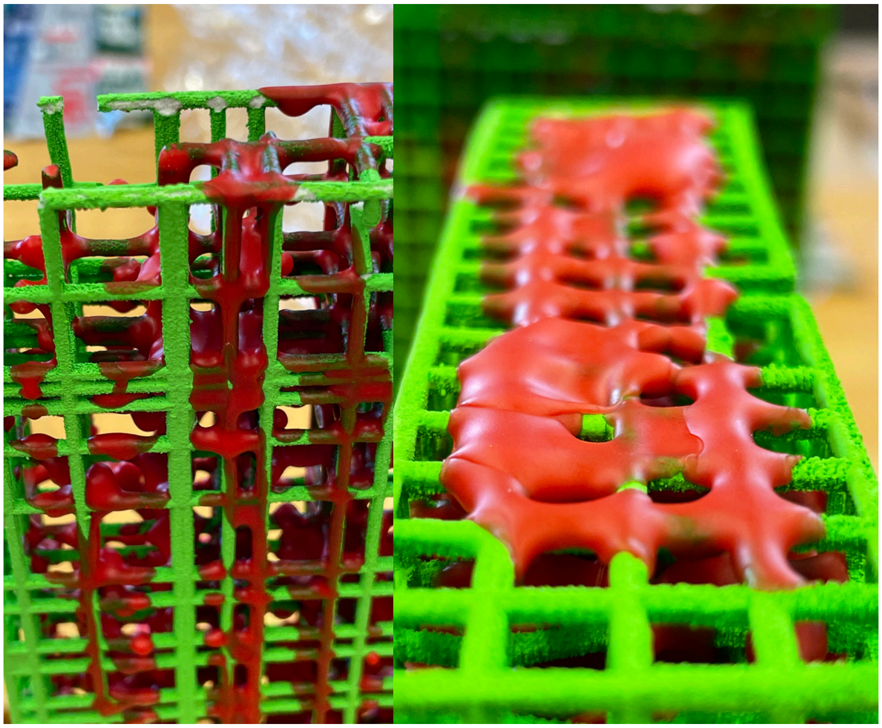

Figure 110
Materials explorations by Ardalan Sadeghikivu
Making Ingredients Studio at SA+P MIT. 2021
Source: author

the machine and which are claimed by the operator. Similarly to how Witt exposes two visions about knowledge -instrumental and design- in relation to architectural knowledge[468], students were asked to establish connections with opposite views of what design is or at least how it is understood regarding knowledge production. Selecting two different materials (with different behaviors and characteristics), students were asked to develop unique processes by selecting machines, operational parameters, and techniques. In an analogous fashion to the 'Discrete Heuristics' studio previously discussed in this chapter, students were asked to develop four different 'recipes' shared with classmates to identify and discern parameters, rules, explicit and tacit procedures, and knowledge. The assignment was oriented toward producing new ways of making by contrasting prescriptive procedures as recipes and particular enactions of those recipes to identify the potential emergence of knowledge about making in light of specific contextual constraints (figure 110). Followed by an exercise focused on scaling the production of prototypes, students were asked -based on the findings from the previous assignment- to refine and diagram their 'making recipes' and 'making ingredients', determining the primary constraints

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[468] Witt, Andrew. "A Machine Epistemology in Architecture." in Candide: The Journal of Architectural Knowledge. no.03, 2010.

to scale up the production of their prototypes[469]. The scaling was oriented toward defining the essential components of the making process proposed and explicating the specific interactions between materials, site, tools, and action sequences[470].

Up to this point, the studio focused on developing and producing a body of knowledge based on the study of the inherent externalities of any physical project. These were determined as the "ingredients" which, in the first half of the course, have been identified, characterized, cataloged, and considered as a repository for application in a project. In this second part of the studio, we required each student to expand the bodies of knowledge that emerged in each research, to develop a project that considers all the contextual variables studied, such as site, material resources, tools, labor, and so on. To do so, we asked them to focus on encapsulation. Based on each research, we asked them to use software of their preference to develop a parametric model that encapsulates the knowledge produced in their research work. We asked them; how knowledge about materials, tools, and constraints is formalized inside a digital environment? How is that knowledge encapsulated and transferred through a digital platform? What are the main challenges and opportunities that a parametric model adds to your research? While there was undoubtedly a significant emphasis on creating a representational component for the purpose of defining a parametric model capable of encapsulating knowledge within a software package, the process of developing this particular assignment proved to be immensely valuable in determining the appropriate discretization of fixed plans versus the expression of indexical steps for action, given the inherent ambiguities of materials, gestures, and other factors at play.

From a contextual standpoint of design and craftsmanship, the students proposed distinct and innovative methods for utilizing fabrication technologies, materials, labor, and design. In this context, the absence of representational aspects in their research served as an implicit limitation, stimulating discussions and instructors' guidance to foster a distinctive and original portfolio of

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[469] Cost, machining time, labor, material quantities, size limitations, etc.

[470] The studio only demanded one specific general constraint to all the projects. We required students to consider the afterlife of their implementations-prohibiting discarding them as landfill- either by recycling, upscaling, or as permanent installations.

Figure 111
Folded paper prototypes by Olivier Fabber
Making Ingredients Studio at SA+P MIT. 2021
Source: author. Used with permission of the student

work. For instance, Olivier Faber's work is focused on establishing a comprehensive life cycle of paper-folded structures with a strong emphasis on the sustainability aspects of recycling (figure 111). Faber's work exemplifies how material concerns surrounding sustainable development, when challenged by the specificity of the context, can lead to the emergence of groundbreaking processes for design and manufacturing. Faber's approach prioritized material aspects as the primary drivers of his proposal, commencing from sourcing and supply to management and the afterlife of paper used in architectural pinups. The proposal framed the development of architectural space through a material process that was primarily influenced by the constraints imposed by labor. In this regard, the geometrical characteristics of his proposal were shaped by both material and human actions, with a focus on temporality in relation to labor and material management.

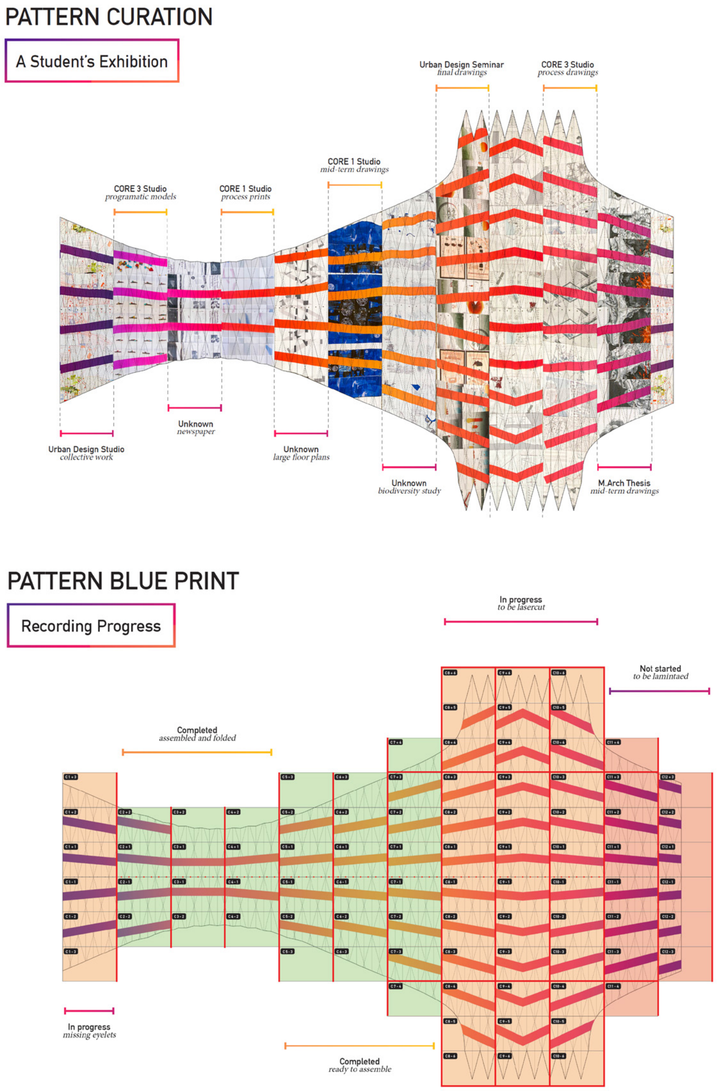


Figure 112
Fabrication pattern and assembly diagram for making paper-folded structures.
Olivier Fabber, 2021.
Source: Olivier Fabber, Used with permission of the student

The Design and manufacturing system proposed by Faber inherently included the embodied aspects of making, where parameters such as module size (figure 112), folding time, and assembly were determined in relation to the productive capacity of a single person over a given period (figure 113 and 114). While this approach was highly deterministic in prescribing rules for producing modules, the system allowed for the inclusion of new information and knowledge that could refine and improve the proposed making recipe, especially when confronted with the reality of materiality. For example, in the case of the construction of the final installation, upscaling of the prototype raised a series of structural concerns arising from

FABRICATION PROCESS

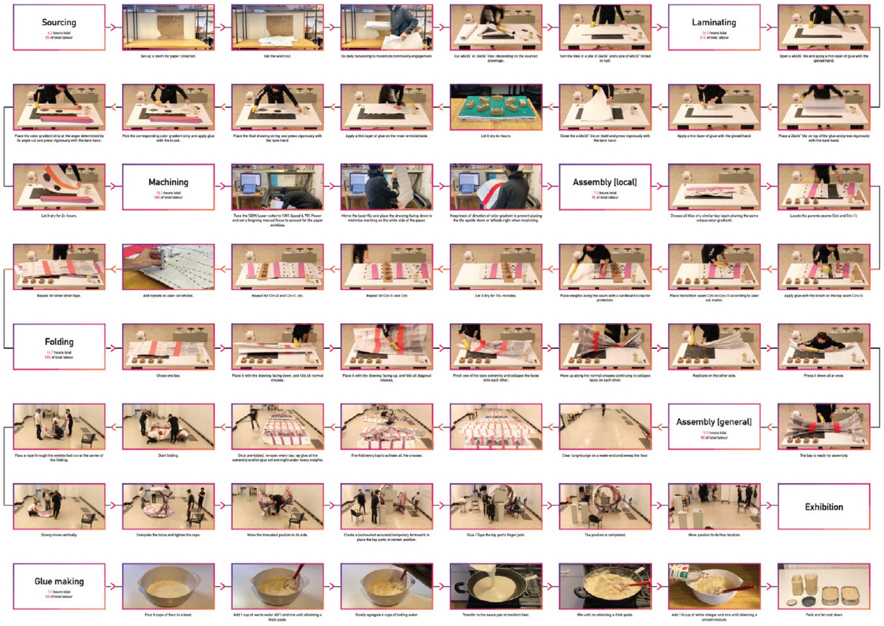


Figure 113
Making recipe.
Olivier Fabber, 2021.
Source: Olivier Fabber, Used with permission of the student

ASSEMBLY PROCESS

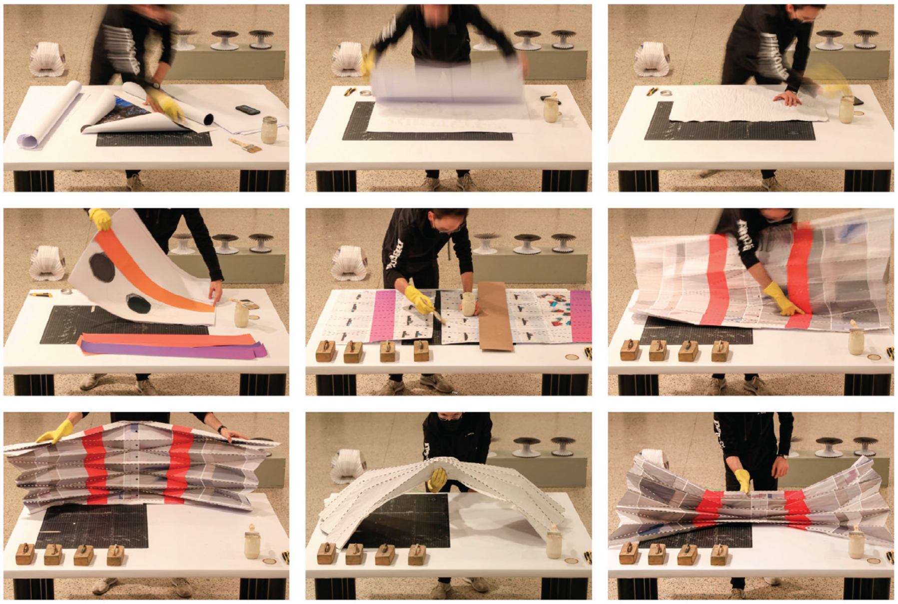


Figure 114
Module fabrication and assembly.
Olivier Fabber, 2021.
Source: Olivier Fabber, Used with permission of the student

Figure 115
Final prototype assembly.
Oliver Fabber.
Making Ingredients Studio at
SA+P MIT. 2021
Source: Author. Used with
permission of the student

the material thickness, which in turn necessitated an impromptu reconfiguration of the assembly process, along with the deployment of provisional scaffolding to facilitate the completion of the project (figure 115).

Tim Cousin's 'Shingle Nest' proposal offers an exemplary illustration of creative design processes from material upcycling (Figure 116). His ingenious method for building self-supporting shingle envelopes using up-cycled elements represents a compelling example of how computational strategies, digital fabrication tools, and traditional woodworking can be mobilized towards a material ethic that

Figure 116
Shingle Nest.
Tim Cousin, 2021.
Source: Tim Cousin
Used with permission of the student

values the essence of matter beyond its commodification (figure 117). Cousin's proposal challenges conventional notions of waste by re-valuing discarded materials and transforming them into a new aesthetic proposition. Cousin's approach involved developing a computational fabrication workflow that accommodated the irregularities of upcycled materials. By managing large tolerances and irregular material stock, Cousin tackled the challenges of working with geometrically irregular elements salvaged from wood through precise, numerically controlled machines. His proposal includes highly precise instructions for sourcing, sorting, processing, and fabricating individual elements and dealing with the complexity of bringing irregular and geometrically unique pieces together into a coherent whole(figure 118).

Cousin's making recipe centered on developing a parametric design system that calculated the joints between each element by embedding fixed registration marks according to a driving surface.

Figure 117
Final prototype.
Tim Cousin.
Making Ingredients Studio at SA+P MIT. 2021
Source: Tim Cousin
Used with permission of the student

The highly deterministic digital procedure for calculating the joints depended on stock availability and the constant recalculation of the assembly process derived from this fact. According to Cousin, “Once this inventory of reclaimed and restored wooden boards of varying dimensions is constituted, the project devises an assembly system to bring them together in an architectural installation.” Cousin’s proposal represents an exceptional accomplishment that highlights in particular ways the concepts postulated in this dissertation concerning the indexicality of design and making. As expressed previously, embedding geometrical knowledge inside a recipe and a set of digital parametric files depended inevitably on material considerations derived from contextual facts.

Finally, the proposal ‘the peel’ developed by Latifa Alkhayat is another example of the development of discrete heuristics in a design process. Her proposal considered the development of a building system based on the elaboration of shape-programming procedures.

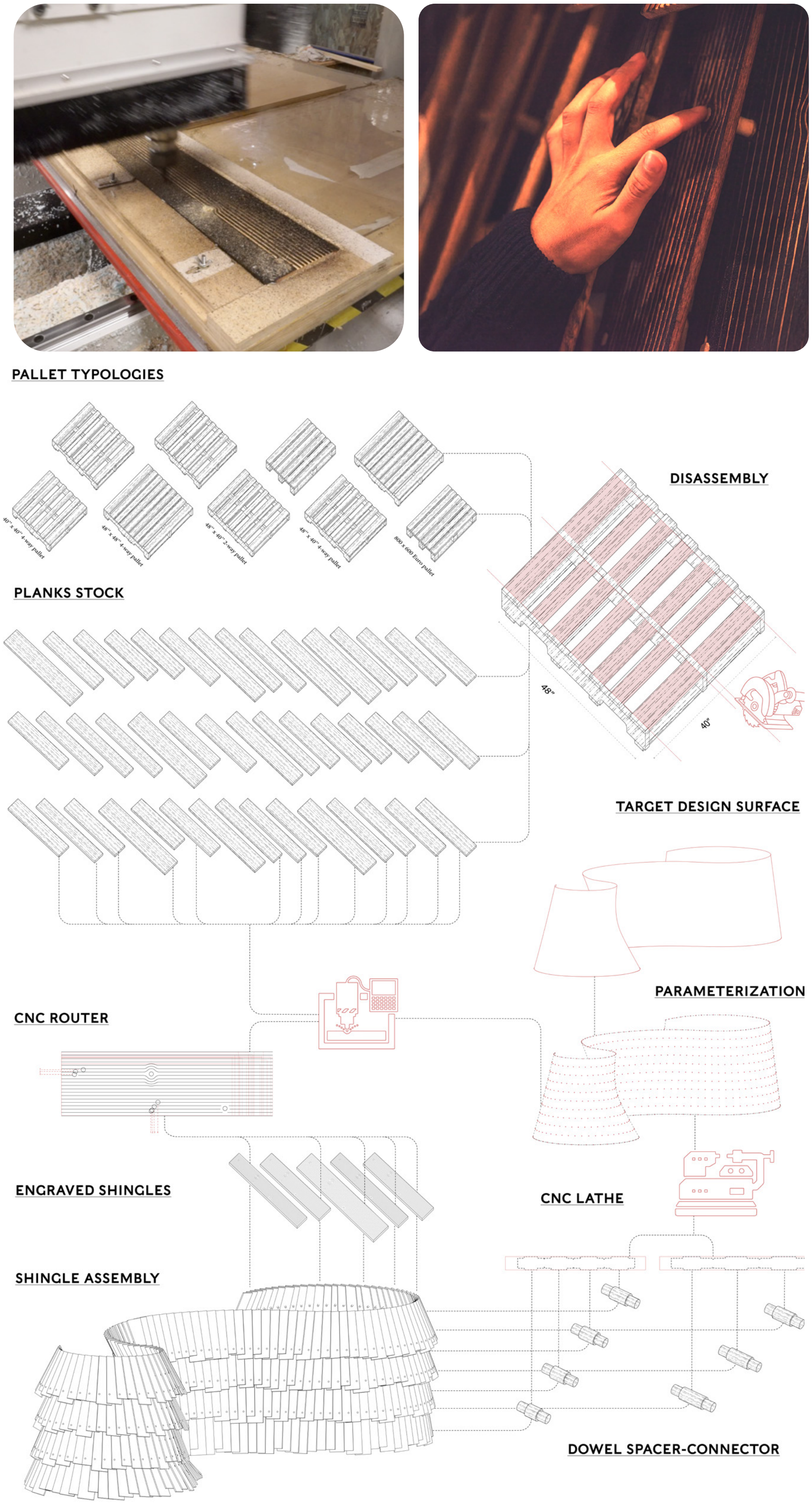
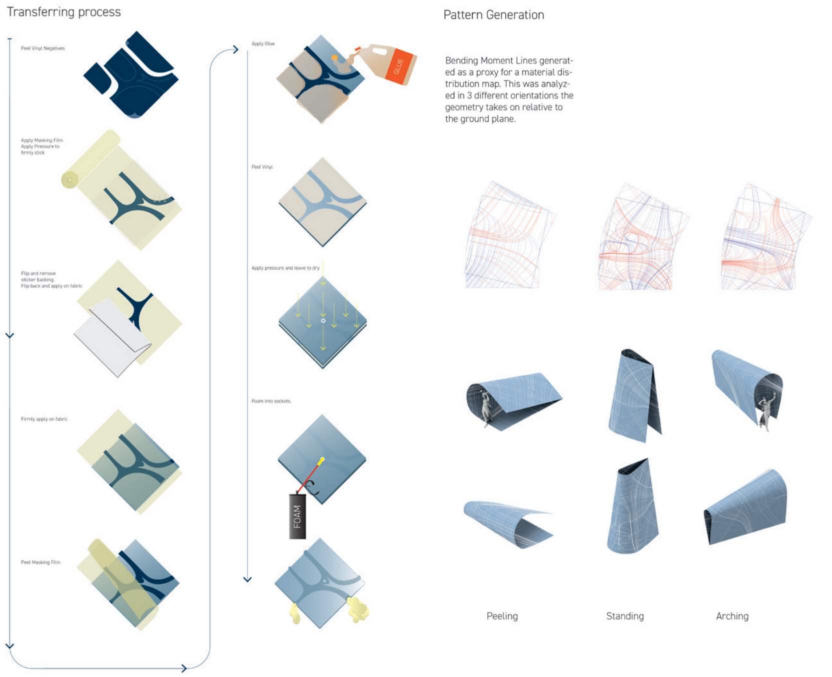


Figure 118
Shingle Nest making recipe
Tim Cousin, 2021.
Source: Tim Cousin
Used with permission of the student

Figure 119
Material experimentations.
Making Ingredients Studio at SA+P MIT. 2021
Source: Latifa Alkhayat
Used with permission of the student

Alkhayat’s proposal is an example of material computation that considered using recycled denim as felt blankets as the primary membrane that was rigidized using expandable Polyurethane foam according to stress lines of the overall shape (figure 119). In a similar fashion as the previous two proposals, Alkhayat’s work wandered between the discreteness of rules (for gathering and preparing the design ingredients, and the use of embedded knowledge derived from a semester of prototyping) inside digital tools) and the heuristic enaction of those rules in light of material behavior that yielded unexpected outcomes in terms of shape and new knowledge that allowed the consolidation of new knowledge about a novel fabrication process. Alkhayat’s work was especially interesting as intermediate representations were only needed for discussion with instructors and were not necessary from a design and making perspective. The focus on actions, the temporal aspects of making in relation to material behavior and the adjustments necessary to achieve a ‘stable configuration’ of a Design idea, proved to be a fertile process of learning and design knowledge production(figures 120 and 121).



Bending Moment Lines generated as a proxy for a material distribution map. This was analyzed in 3 different orientations the geometry takes on relative to the ground plane.

Figure 120
'The Peel' Making recipe
Latifa Alkhayat, 2021.
Source: Latifa Alkhayat.
Used with permission of the student

Figure 121
'The Peel',
Latifa Alkhayat, 2021.
Source: Latifa Alkhayat.
Used with permission of the student

The two aforementioned academic experiences can be considered to some extent, as a natural progression and realization of the concepts introduced in my Master's thesis at MIT. Specifically, that research focused on the idea of Designing as Making, and the pivotal role that technology plays in the creative development of ideas. Additionally, I examined the implications of designing beyond traditional representations, including the vital role of materiality as a determining factor.

The knowledge and insights gathered from these experiences provided me with a broader perspective to advance my research further. I honed in on the areas where technology could be integrated not as parameterized black boxes but as an active participant in the process, capable of facilitating constant reframing and learning within Design and Making processes towards the creation of new things and new knowledge about how those new things are made.

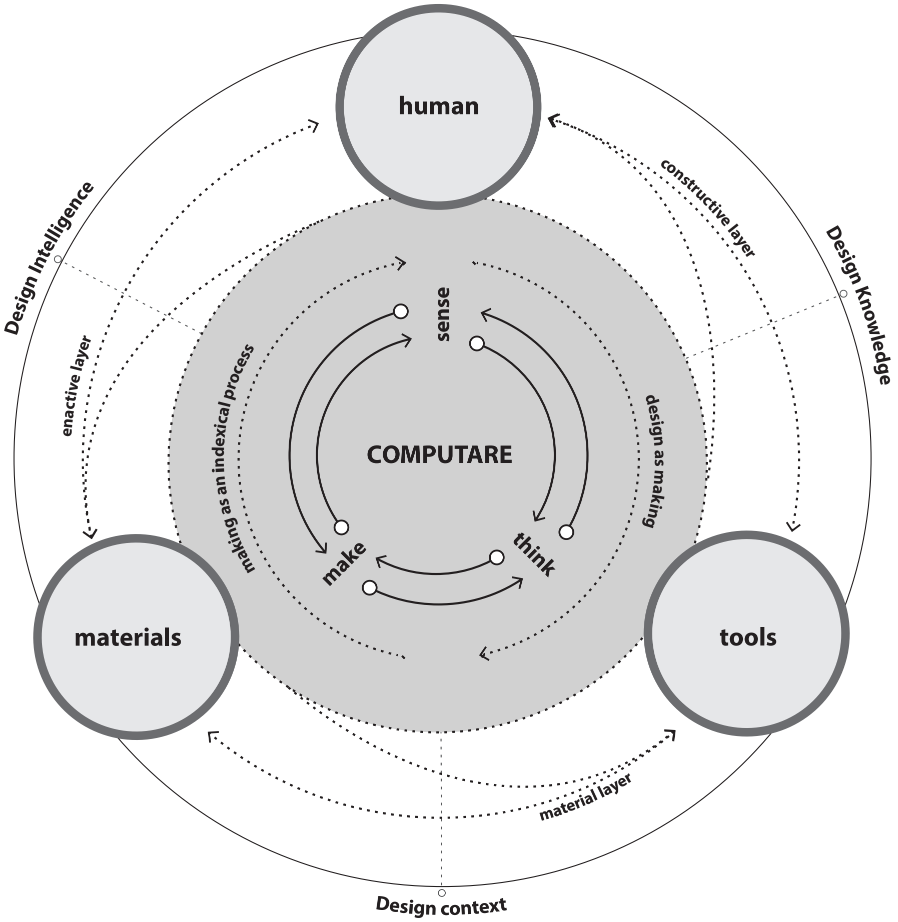


Figure 122
The computation paradigm proposed by this research
Source: author

5.8 Making as a way of designing.

The human experience of insight, wonder, questioning, and action in the world is fueled by hunches, guesses, imaginings, and errors, among other “human things.” These factors contribute to an ever-evolving process of “making things” that is essence interactive. Within this context, I propose that “Design as Making” is an active and dynamic computational process that is closely linked to the concept of an aesthetic experience. In this process, specific sensory elements are combined with broader intellectual considerations to produce new meanings and, over time, new ways of making. By reframing computational design as an enabler of novel and emergent interactions between humans, machines, and materials, we can unlock the potential to capture the unique and produce the novel (figure 122). This approach establishes design as a contingent collective endeavor within a design context, and demands a reevaluation of the interactions between agents involved in computational design processes.

In this last part of my dissertation research, I implement and test the framework for computational gestural making as the integration of the three experiments developed throughout this research in terms of gestures, interactive machines, and materials. I build on top of each component of the framework presented in chapter 4, including the algorithms for gesture recognition, object detection, reinforcement learning and path planning, algorithms for material computation, optimization in real-time, and the logic behind the entire implementation including software and hardware components.

5.9 Implementing the Computational Gestural Making framework

In the face of competing views on the use of technology as an enhancer via automation, or as augmentation to facilitate better thinking and making, new possibilities arise for blurring the boundaries of the traditional trichotomy of computational design. This opens up new modes of computational making as a contingent and intelligent interaction between humans and machines. However, these opportunities also come with challenges in defining the nature of interactions within the making process, and how those interactions become meaningful engagements in intellectual exchanges. The development of systems that capture human gestures as intentions, as well as methods for enabling machines to respond meaningfully to human gestures, are therefore essential in fully realizing the potential of computational design as a transformative force in the making process (figure 123).

As previously discussed, the primary objective of deploying the final experiment in Chapter Three was to test the integration of different models as modules to enable successful interaction between a human and a machine through the use of gestures. The integration of various algorithms to sense and respond to specific outputs in a digital environment, as well as the tests conducted in Chapter Three, serve as exemplary cases that demonstrate how these systems can be applied as a framework with potential applications in the Design and Making domains.

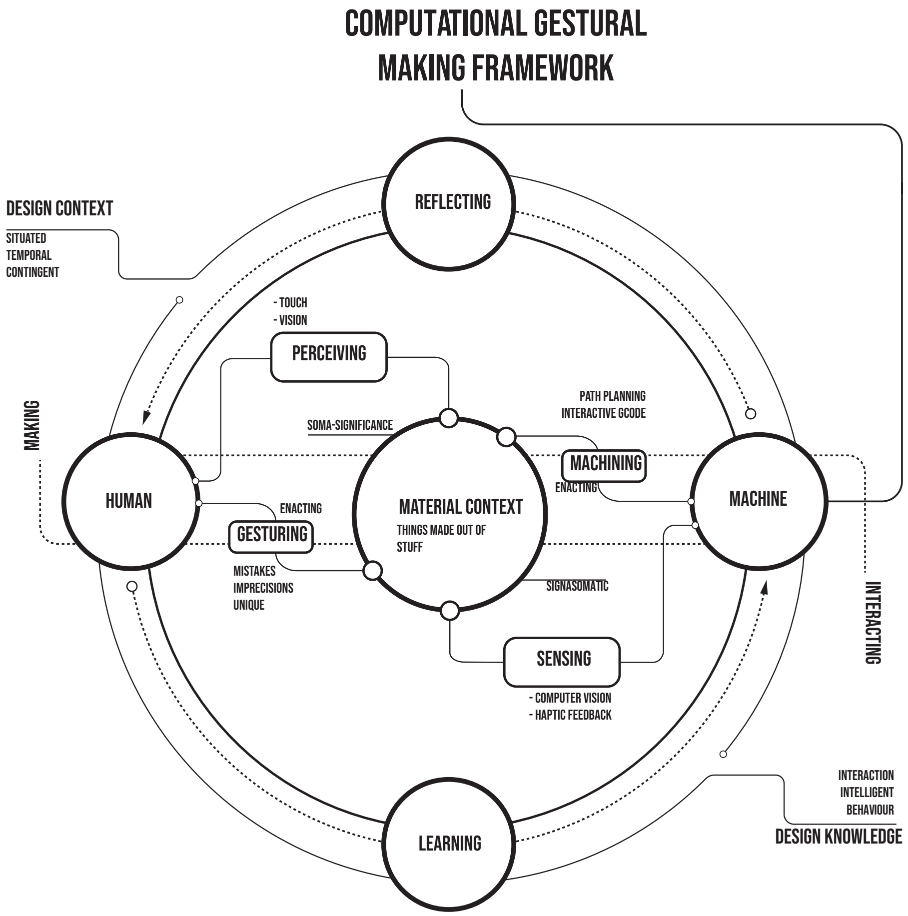


Figure 123
Computational Gestural
Making diagram
Source: author

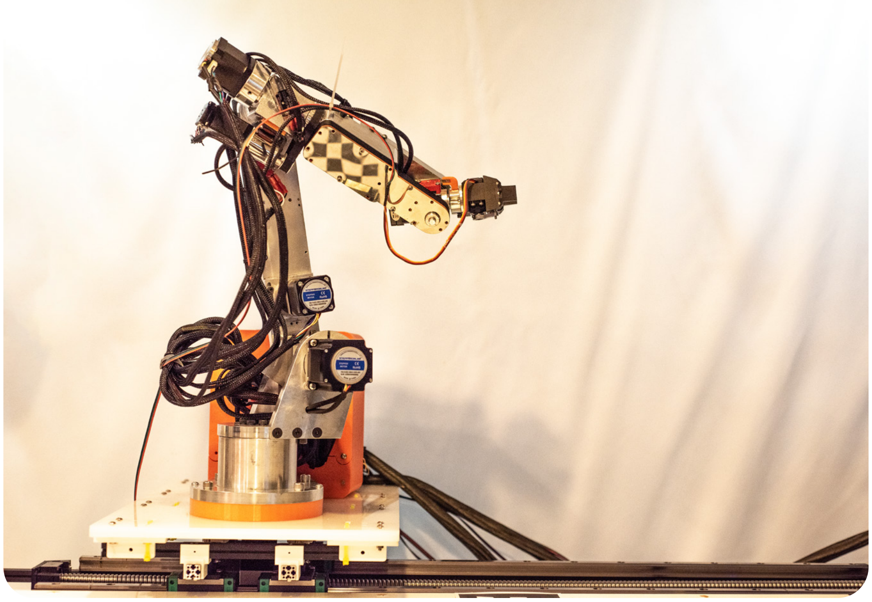


Figure 124
Custom 7 axis robot based on AR platform by Annin Robotics
Source: author

5.9.1 Customizing tools: further hardware implementations

Implementing the system in real life, required determining the appropriate hardware to implement efficiently the Computational Gestural Making Framework. Although the scalability of the robotic control system presented in 4.7.3 can be implemented to any numerically controlled machine from 2 to 7 axes, for the purpose of this dissertation, a custom-made robotic arm was built and programmed specifically for this dissertation research. Starting from the specifications of a desktop-size open-source robotic kit developed by Annin robotics[471], I built and programmed a custom hardware setup that could provide the flexibility needed to implement a real time fabrication system based on gestures (figure 124). The robot is built from aluminum and 3D printed parts with a weight of 12.25 kg (27 lbs), a maximum reach of 62.9 cm. (24.75 inches) a payload of 1.9 kg (4.15 lbs) and a repeatability of 0.2mm (figure 125). The robot was built as a closed loop robotic system using stepper motors with embedded encoders (as depicted in figure 126), controlled by a Teensy[472] development board with a custom firmware to receive in real-time the information needed for IK calculation and to compensate motion using the information provided by the encoders. The robot control was programmed in CSharp (C#) and integrated into grasshopper for fast prototyping purposes and debugging.

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[471] https://www.anninrobotics.com/.

[472] https://www.pjrc.com/teensy/

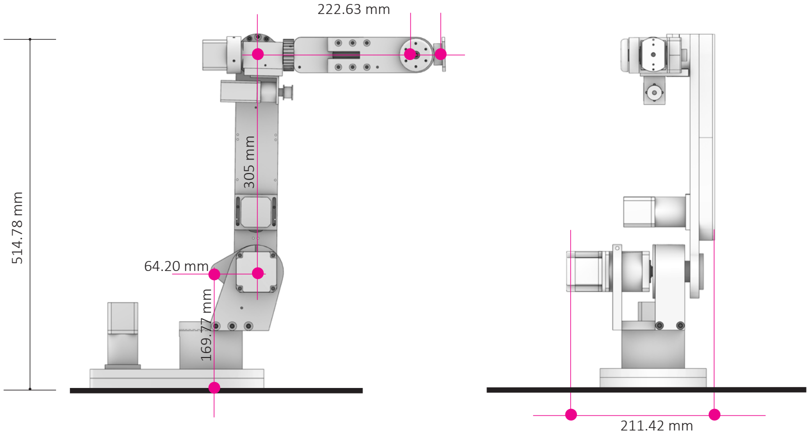


Figure 125
Custom Robot general dimensions
Source: author

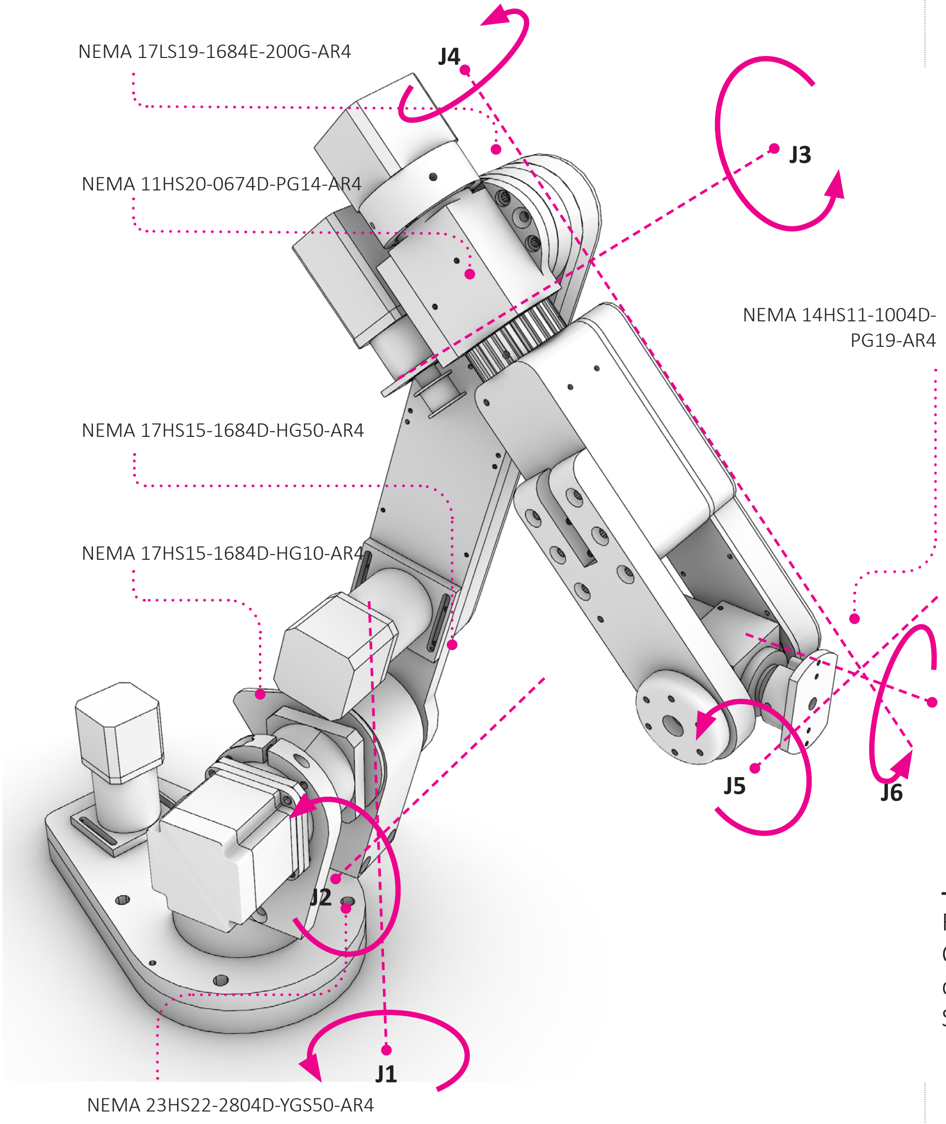


Figure 126
Custom 7 axis robot description diagram
Source: author

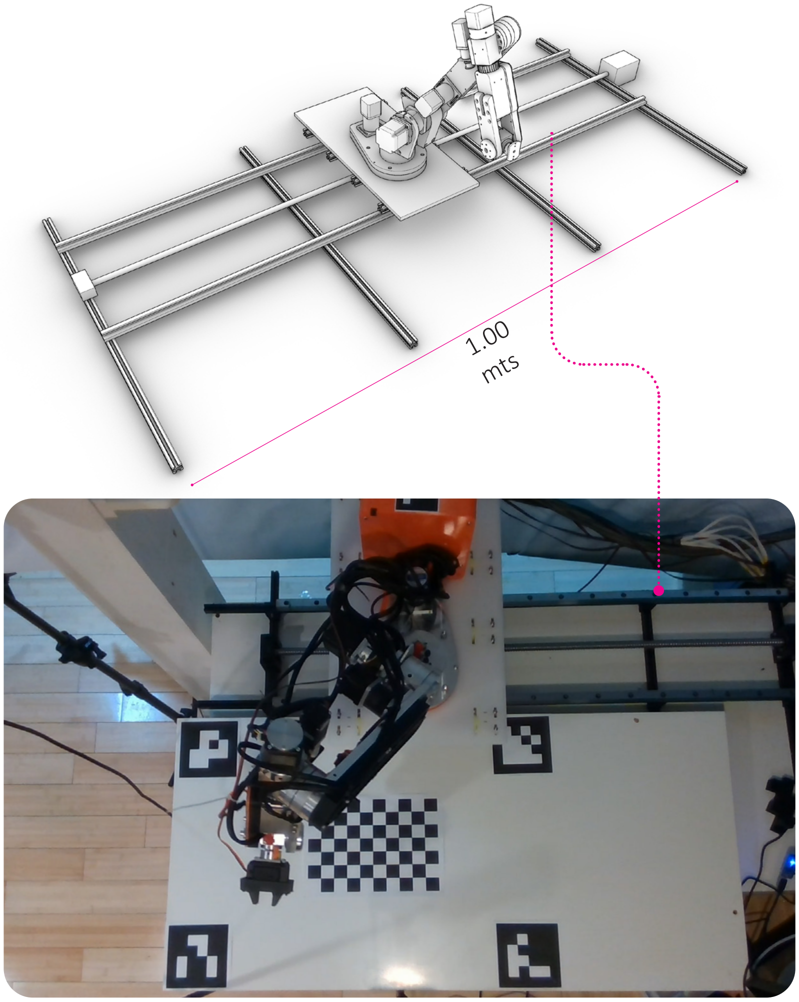


Figure 127
7th axis setup for larger workspace
Source: author

Using the Inverse Kinematic implementation presented in 4.7.3.1, the software provides communication through serial port to send and receive real-time data to and from the robot. Furthermore, the robotic arm was installed on top of a 7th axis to increase the work area as depicted in figure 127.

5.9.2 Robotic movement test.

In this part, I delve into the interaction of a designer with fabrication machines and physical objects, to test the potential for real-time designing and making. I introduce the development of a general-purpose hardware system for the experiments and implementing the gestural making framework in a real scenario.

As discussed in the project described in the previous chapter, the

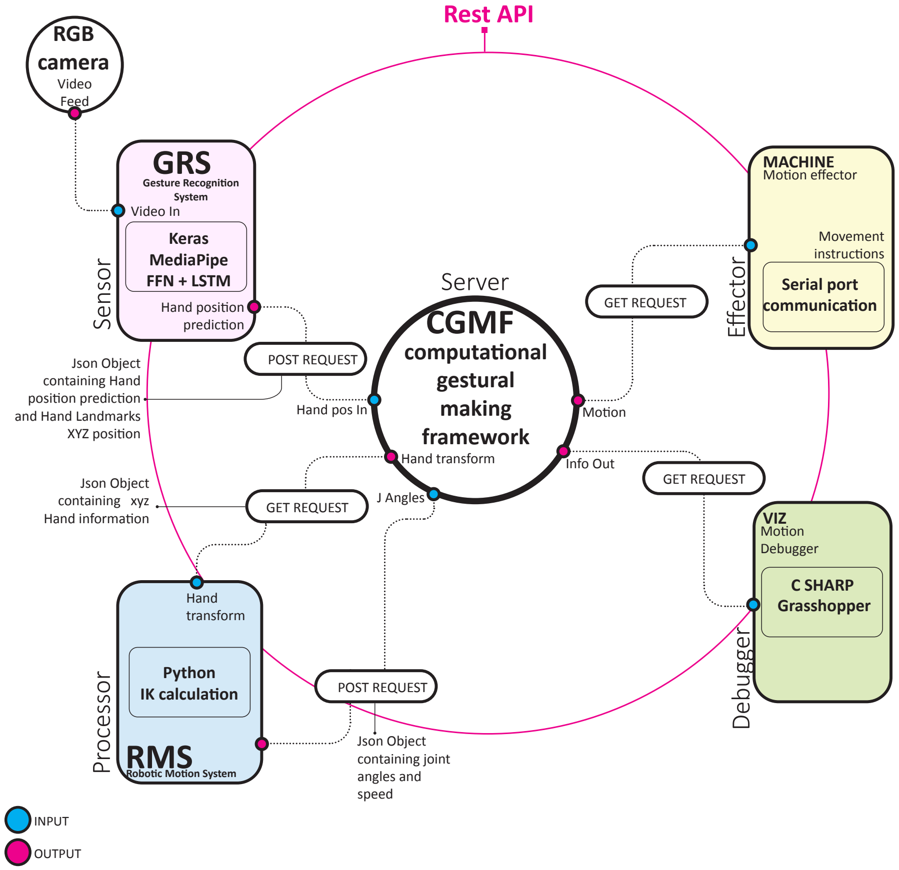


Figure 128
CGMF implementation for trajectory prediction.
Source: author

primary interaction between humans and machines was enabled by using gestures and establishing a language that could be interpreted as actions by a deep learning model to trigger different behaviors. In implementing the system in a real machine, it was crucial to replicate the tests conducted in a digital environment to corroborate that the system works and performs fluidly.

5.9.2.1 Testing trajectory prediction

The first tests were focused on testing the free movements (trajectory prediction) of a designer's hands and the replication in the robotic arm. Integrating the gesture recognition model and the robotic motion model (with simple IK calculation), the system was tested and calibrated in relation to speed and latency between human action, recognition, and machine response (figure 128). Testing with trajectory prediction was crucial to test motion compensation from the encoder's data and also the hardware limit mechanisms to avoid self-collision or movements that could damage the robot's hardware. As depicted in the sequence in figure 129, the robot is

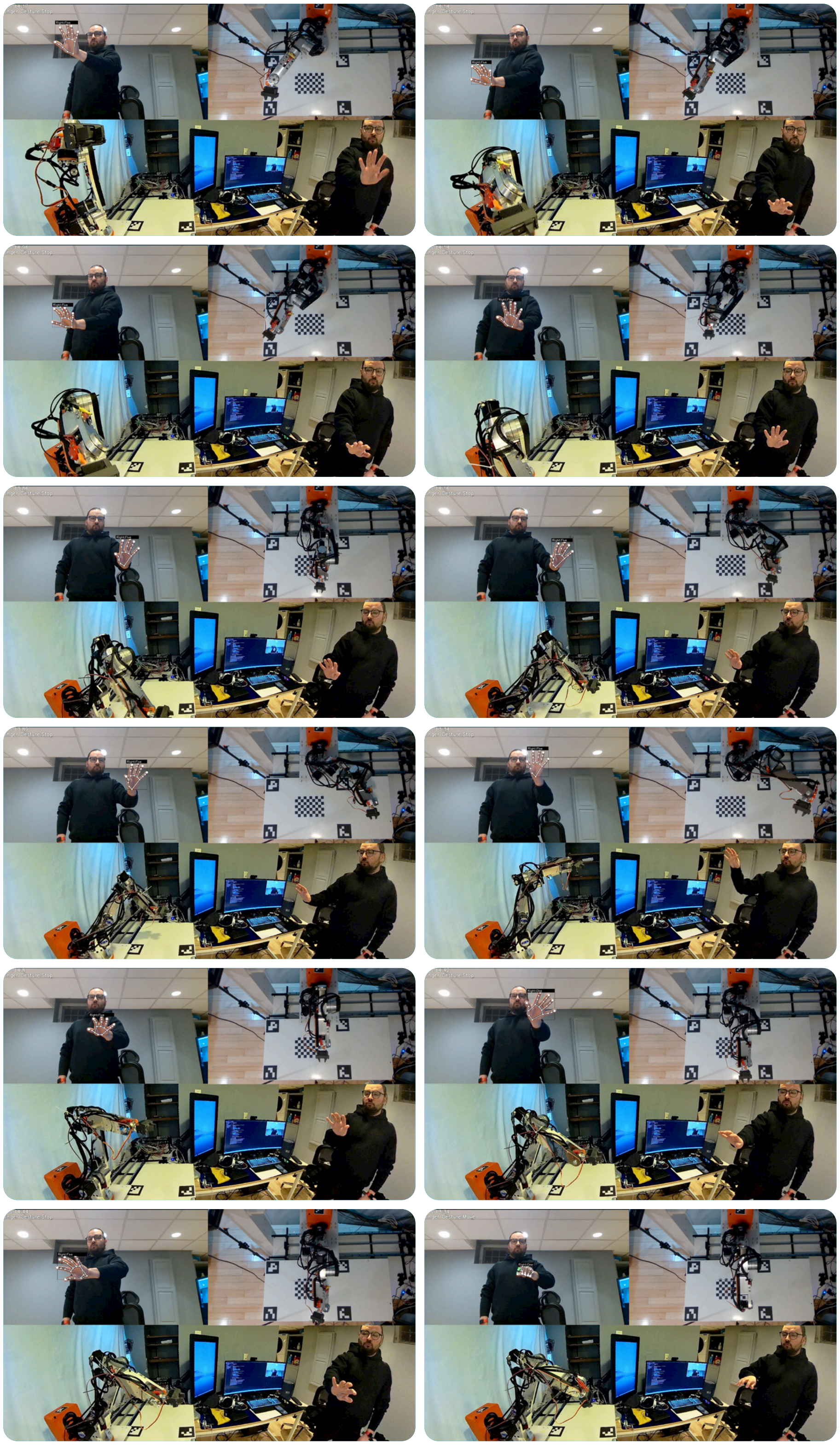


Figure 129
Trajectory prediction tests
Source: author

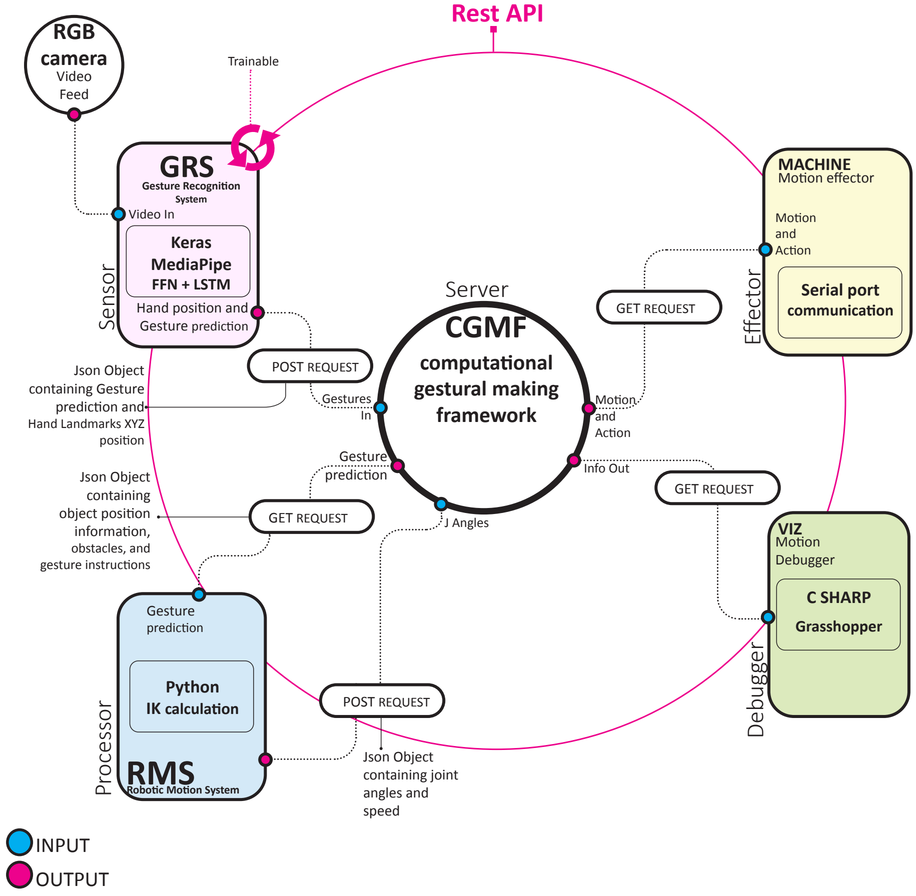


Figure 130
CGMF implementation for symbolic gesture prediction.
Source: author

capable of following the designer's hand movement with minimum lag. It is worth noticing that for trajectory prediction, the system doesn't need to be trained on new data.

5.9.2.2 Testing symbolic gestures to machine action

After evaluating the real-time Inverse kinematic calculation for enabling free movements based on trajectory prediction, I explored the potential of symbolic gesture prediction and autonomous robotic action using the simple IK calculations discussed in chapter 3 without the use of Reinforcement Learning or path planning aided by the depth vision system (figure 130). By employing commands such as "go to home position," "move," "standby," "grab," or "release," (figure 131), I assessed the system's response to symbolic gestures, while also evaluating its effectiveness in performing simple pick-and-place tasks. In addition to enabling autonomous machine action through symbolic gestures, this testing sought to determine the mechanical device's ability to complete a task successfully, accounting for real-world constraints such as object weight, friction, and stiffness.

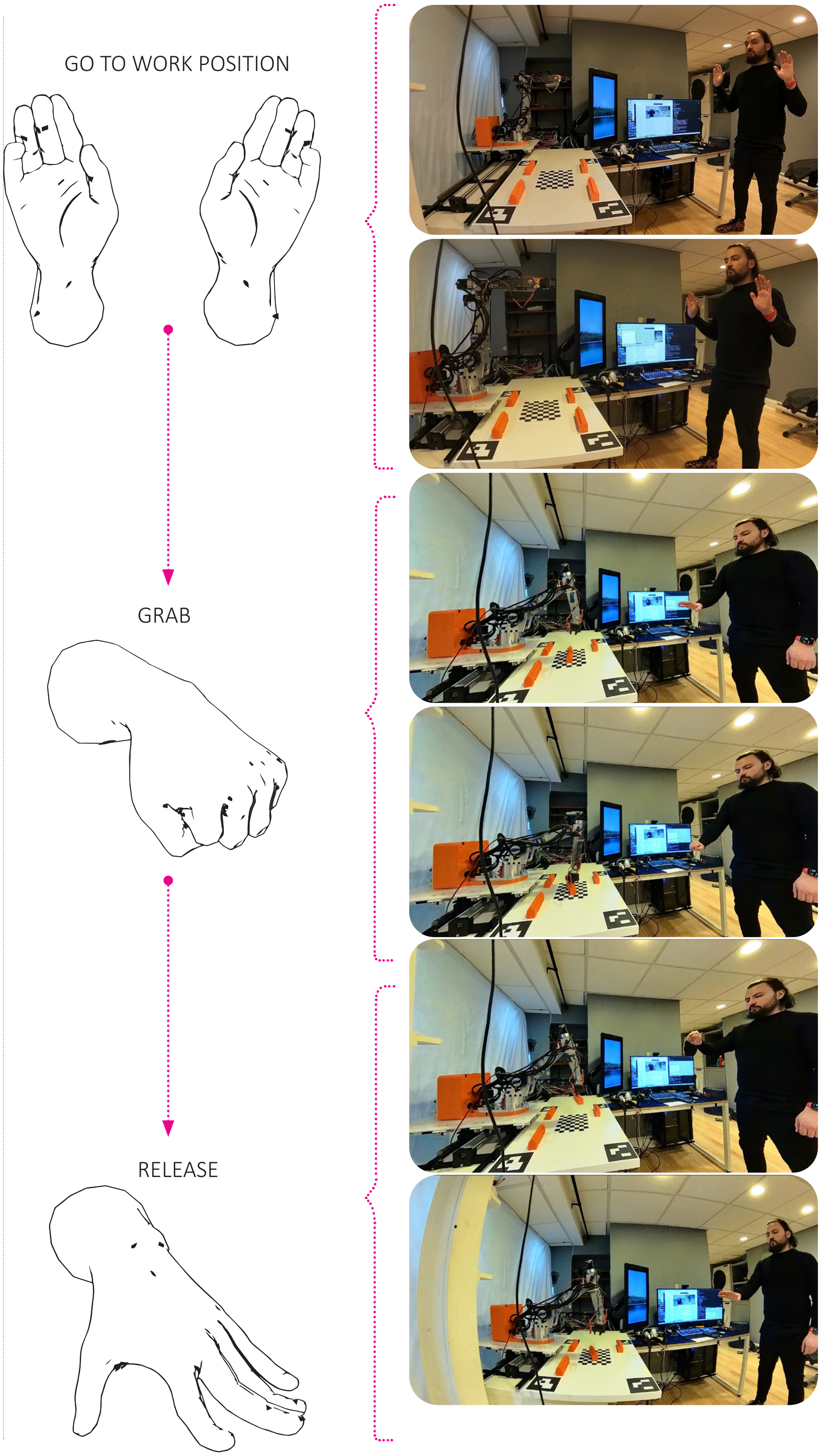


Figure 131
symbolic gesture tests
Source: author

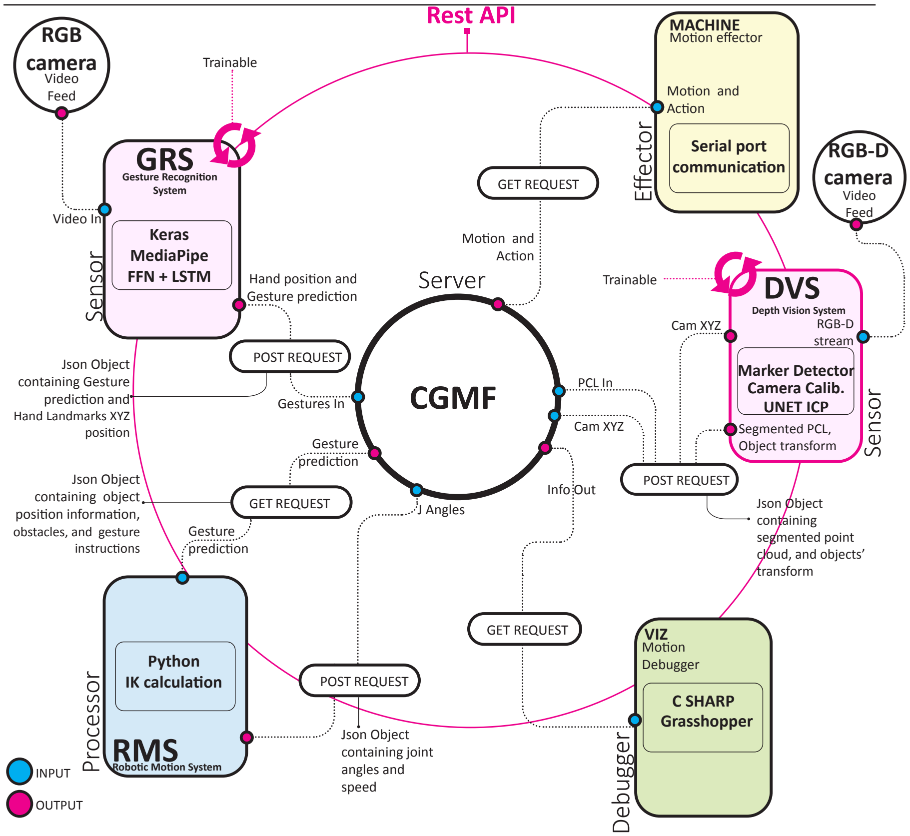


Figure 132
CGMF with the depth vision model enabled
Source: author

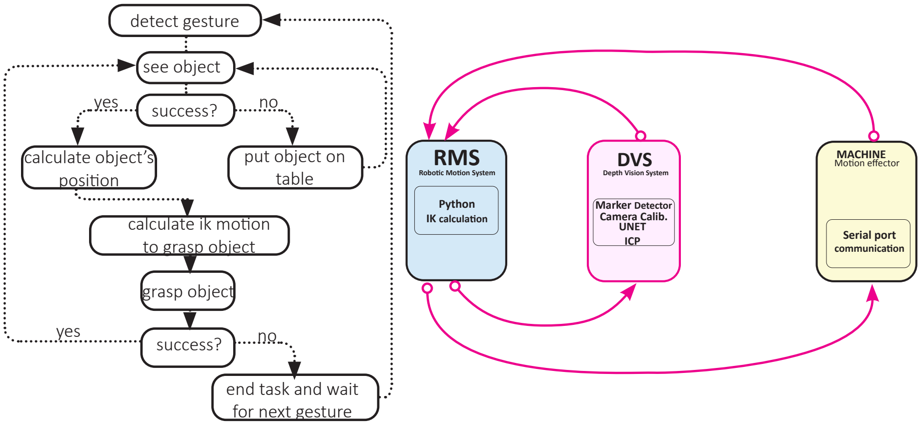


Figure 133
The DVS module calculates the object's position and the RMS module performs the IK calculation to go to an objectbased on the adjusted position. After a new position is recalculated, the RMS modiule sends the information back to the machine effector module that will perform a new grasp of the object that will be corroborated by the DVS module again.
Source: author

5.9.2.3 Adding the Depth vision module

The depth vision system was critical in this evaluation, as it facilitated the calculation of an object's position in real-time, thereby ensuring task success. Figures 132 and 133 underscore the importance of the depth vision system in this regard. If the robot failed to grasp an object, the depth vision system recalculated a new set of Inverse kinematic calculations to approach and grab an object correctly as depicted in figure the 134 sequence.

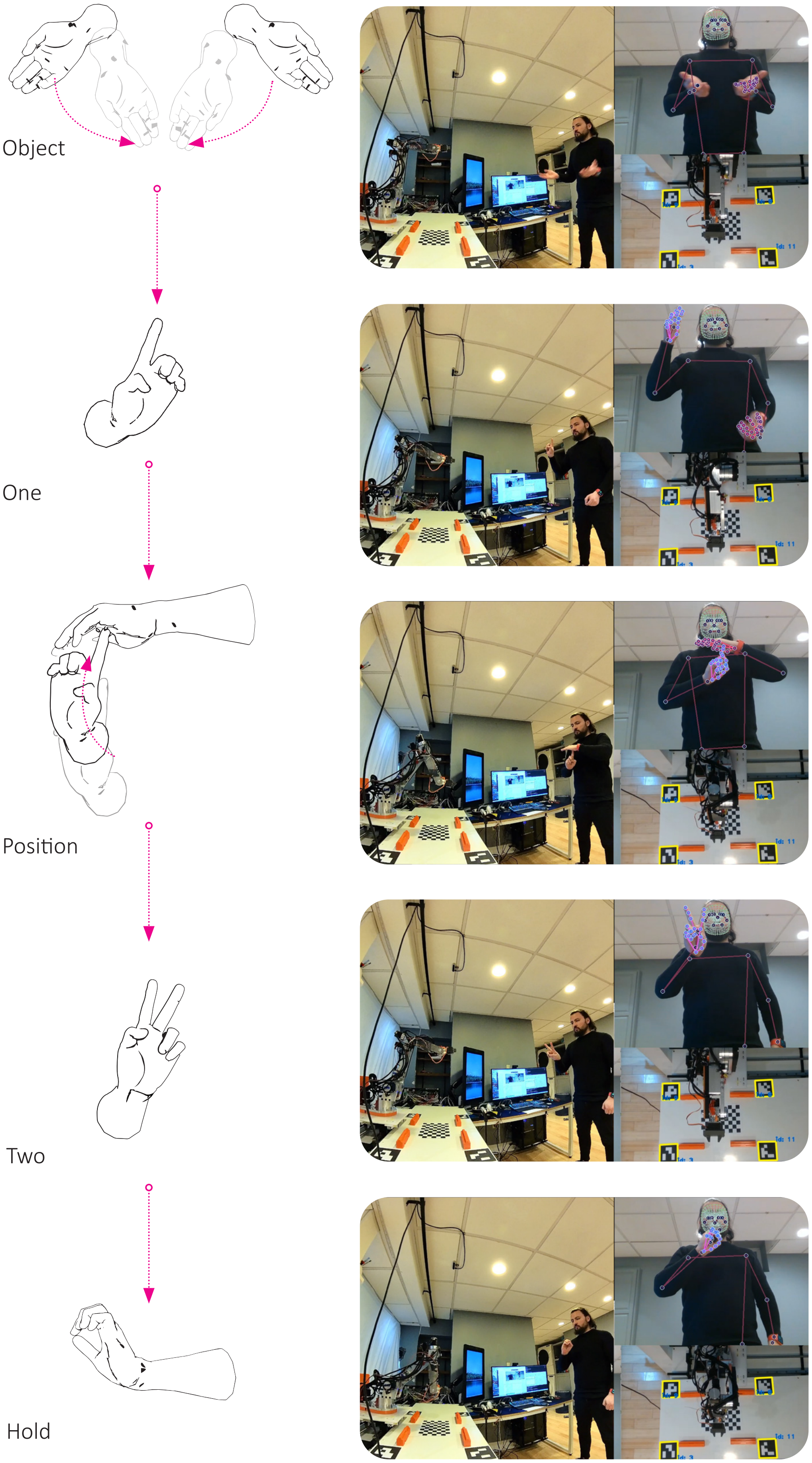


Figure 134
Gesture sequence detection
Source: author

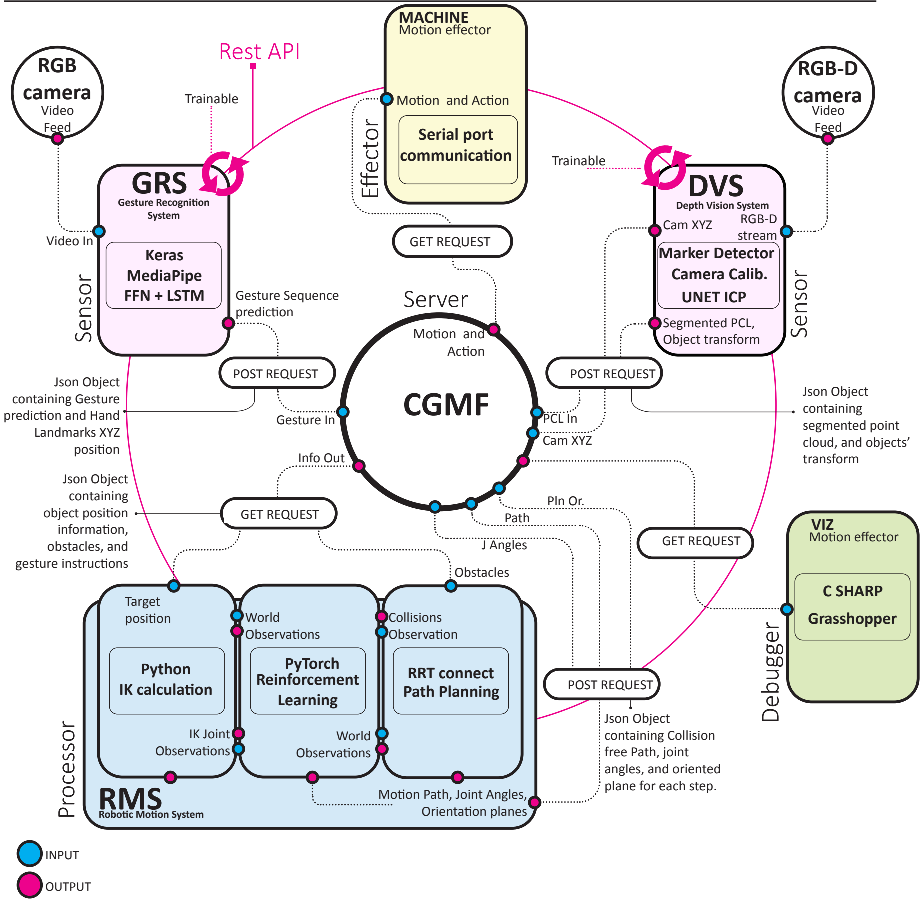
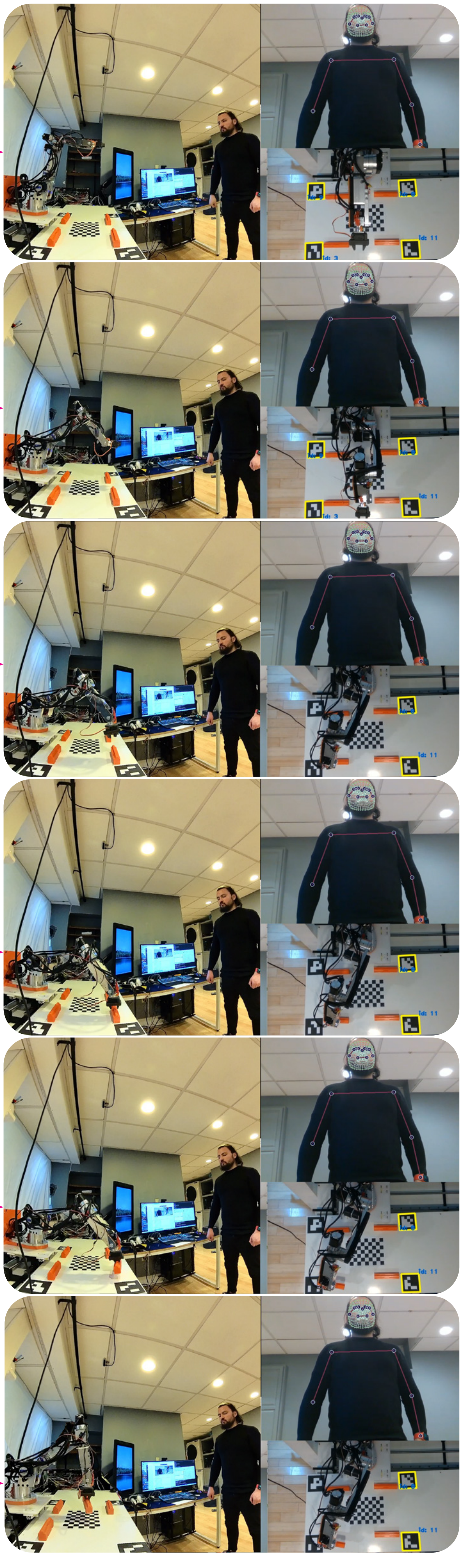


Figure 135
Computational gestural making framework implemented
Source: author

5.9.2.4 Testing gesture sequences to machine action.

Finally, to test the system's full integration, I replicated the same tests shown in 4.7.4. Using the same gestures and setup used in the digital examples, I tested the robot's success completing a given task derived from a compound sequence of gestures using all the modules in the RMS (figure 135) including path planning and the reinforcement learning to move (instead of simple IK calculation). As depicted in figure 136, the robot performs correctly according to gesture sequence prediction. When not using direct free-hand movements to control the end effector directly (direct interaction), the robot shows reliable behavior in determining a satisfactory trajectory given the presented obstacles (figure 137). Although calculating a collision-free movement requires a calculation time that takes between 0.8 to 1.65 seconds for a simple configuration, in terms of real time interaction, those times are negligible. Using RRT



The robot gets the sequence and calculates the path to object

The robot calculates grasp object’s 1 at position 1

The robot moves to position 1

The robot picks the object at position 1

The robot moves to position 2

The robot holds position at 2

Figure 136
Machine action responding to gesture sequence prediction
Source: author

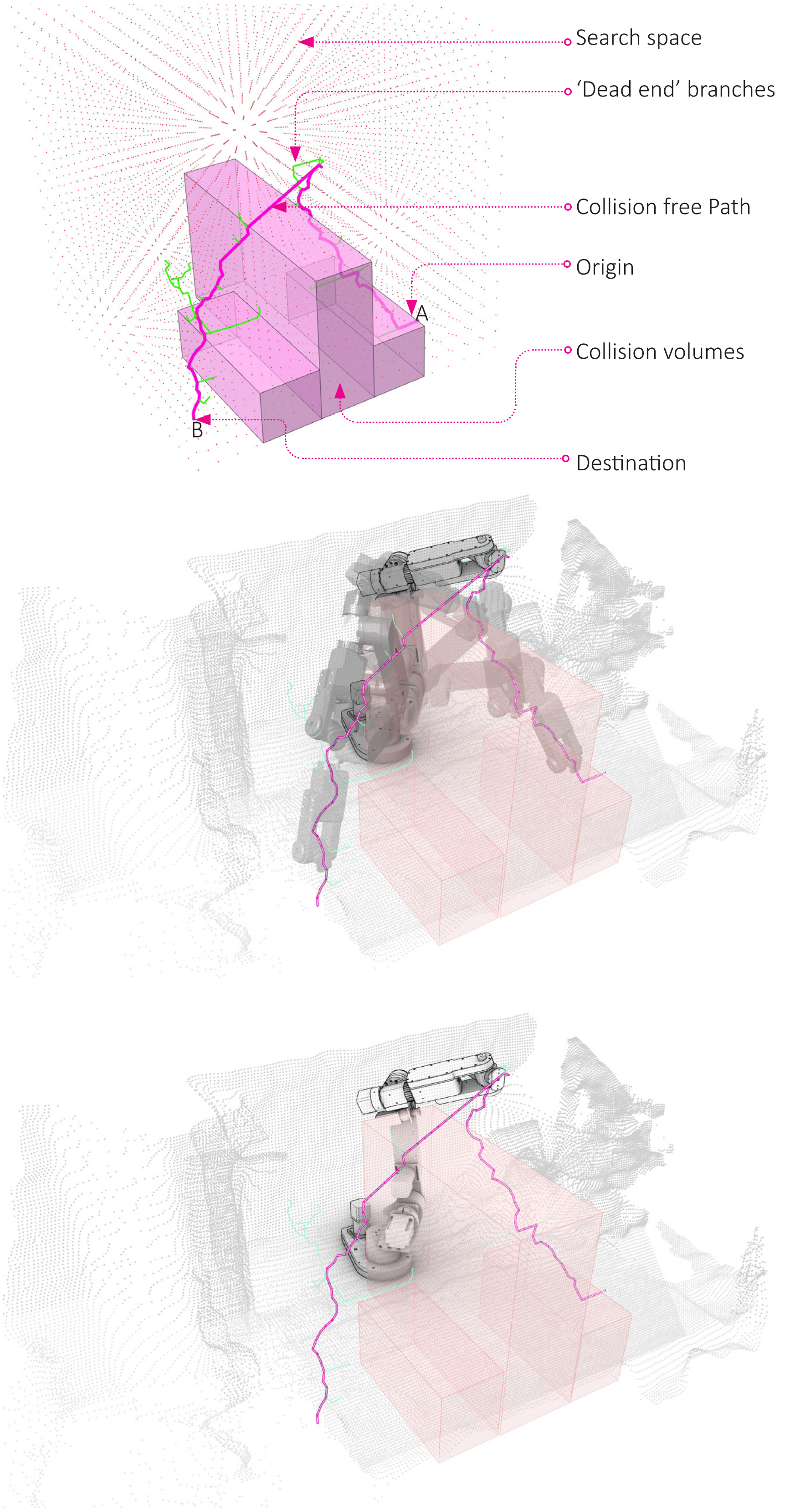


Figure 137
Visualization from the Debug module of Path planning calculation using RRT connect algorithm from gesture sequence prediction
Source: author

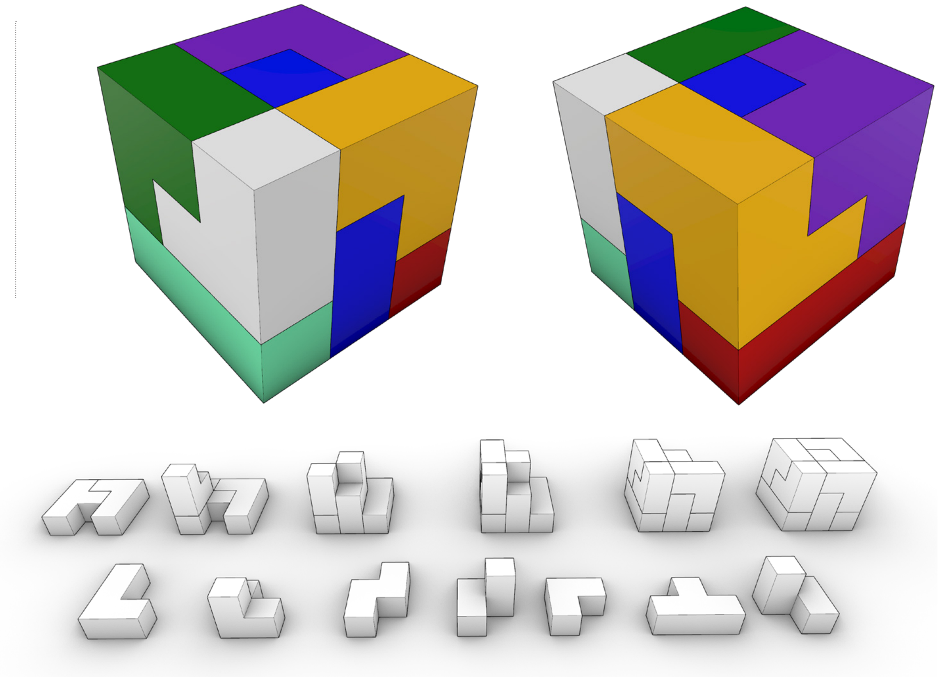


Figure 138
A tetris cube configuration (above) and the shapes and assembly sequence (below)
Source: author

Connect[473] algorithm delivers fast and realiable free collision paths for autonomous robotic movement when required.

5.9.3 Making through collaborative assembly

The correct functioning of the system allows for the implementation of a design exercise for assembly. Whereas the system shows a robust functioning in terms of detecting gestures, predicting hand trajectories and performing a succesful motion according to predictions, the system's capacity to perform a successful assembly process through the collaboration of a human and a machine was challenging. An initial test to accomplish collaborative assembly was testing an autonomous assembly process with the robot given a predefined shape.

As depicted in figure 138 and figure 139, the system recognizes the shapes and given an assembly sequence, it performs the necessary calculations to move and build the requested shape. In this case, the robot is not programmed, only ordered via code, to pick and assemble the pieces in a given order and positions. The robot capacity to detect a shape, calculate

---

[473] Kuffner, J.J., and S.M. LaValle. 2000. "RRT-Connect: An Efficient Approach to Single-Query Path Planning." In Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065), 2:995–1001 vol.2. https://doi.org/10.1109/ROBOT.2000.844730.

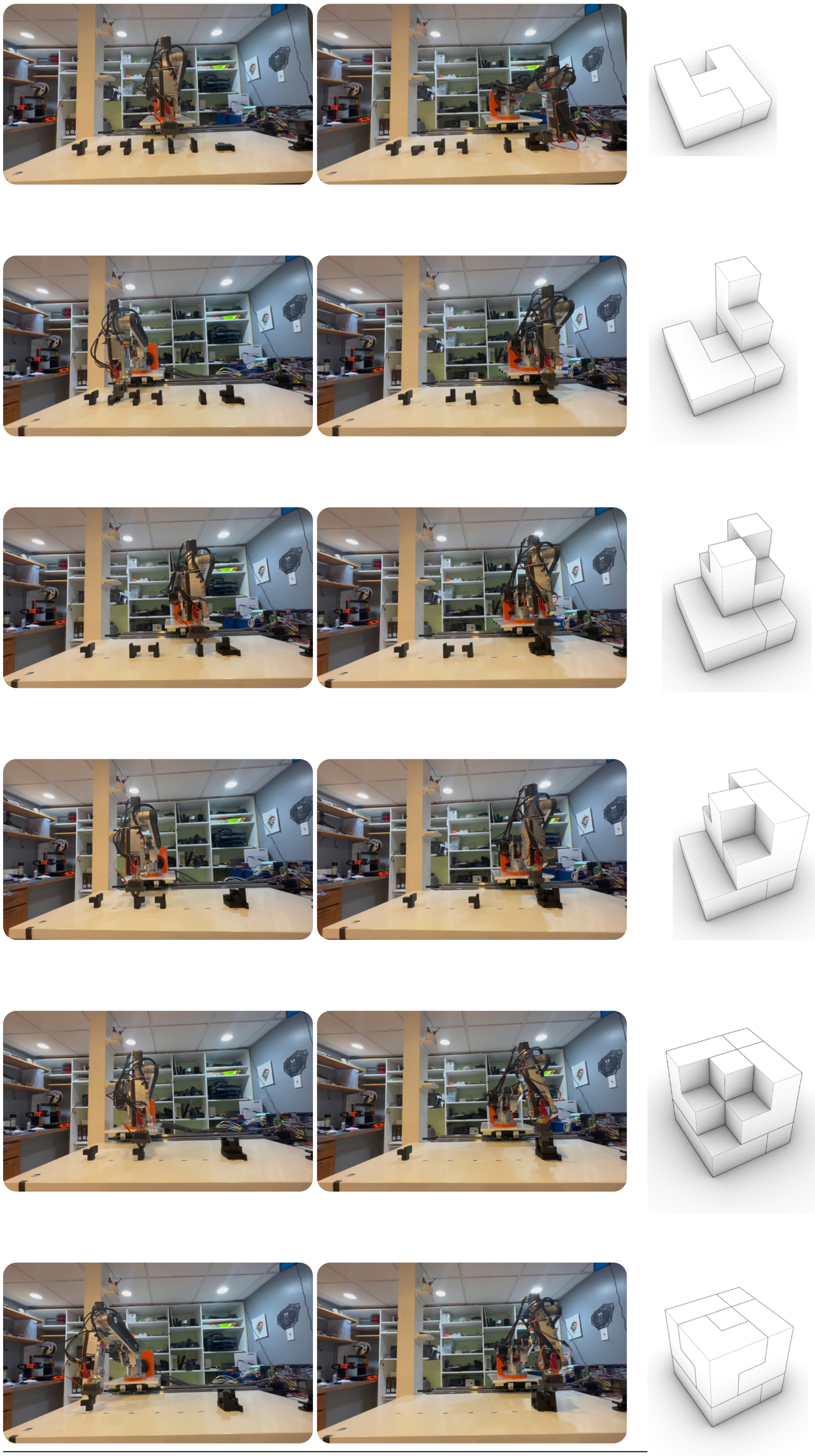


Figure 139
Autonomous assembly using the Depth vision, reinforcement learning and Path planning modules.
Source: author

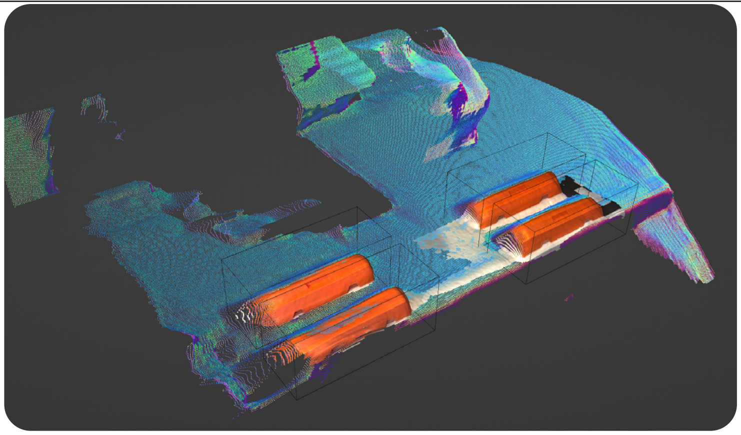


Figure 140
Shapes arranged in the work area.
Depth Vision System live feed from camera 1
Source: author

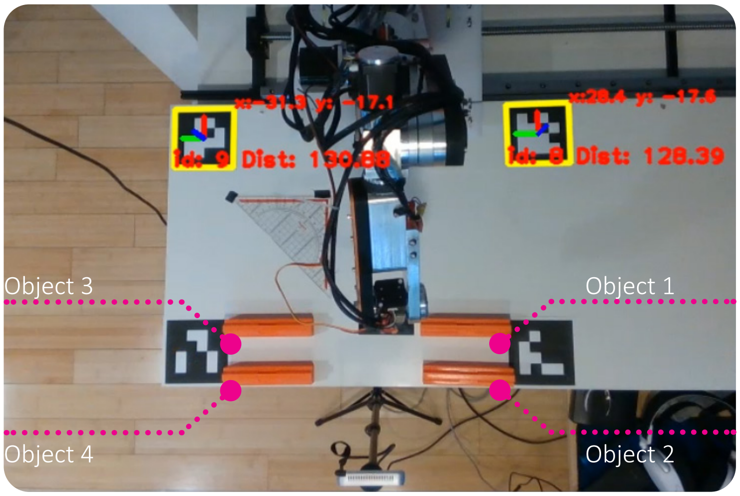


Figure 141
Pose estimation system from Depth Camera 2)
Source: author

a grasp position and move autonomously calculating angles and avoiding collisions to assemble a shape was the goal of this initial test. The next step was to move to a collaborative making project by assembling simple components and test the interactivity of the system.

Following the autonomous assembly test, I tested the system in a simple collaborative assembly scenario in which the designer performs sequences of gestures that are interpreted by the machine to perform a specific configuration according to the design intentions. Using four identical shapes, arranged in a specific and predetermined places in the work area (figure 140 and 141), I performed a series of compound gestures indicating an object, a position and orientation in the form of <object> + <X> + <position and orientation> + in relation to <object> <X> as depicted in figure 142. The system then performs the necessary calculations according to the gestures detected and assembles the shapes as requested as depicted in the sequence shown in figure 143. Further steps in the assembly are shown in the sequence depicted in figures 144, 145, 147,148, and 149. Final assembly details are shown in figure 150

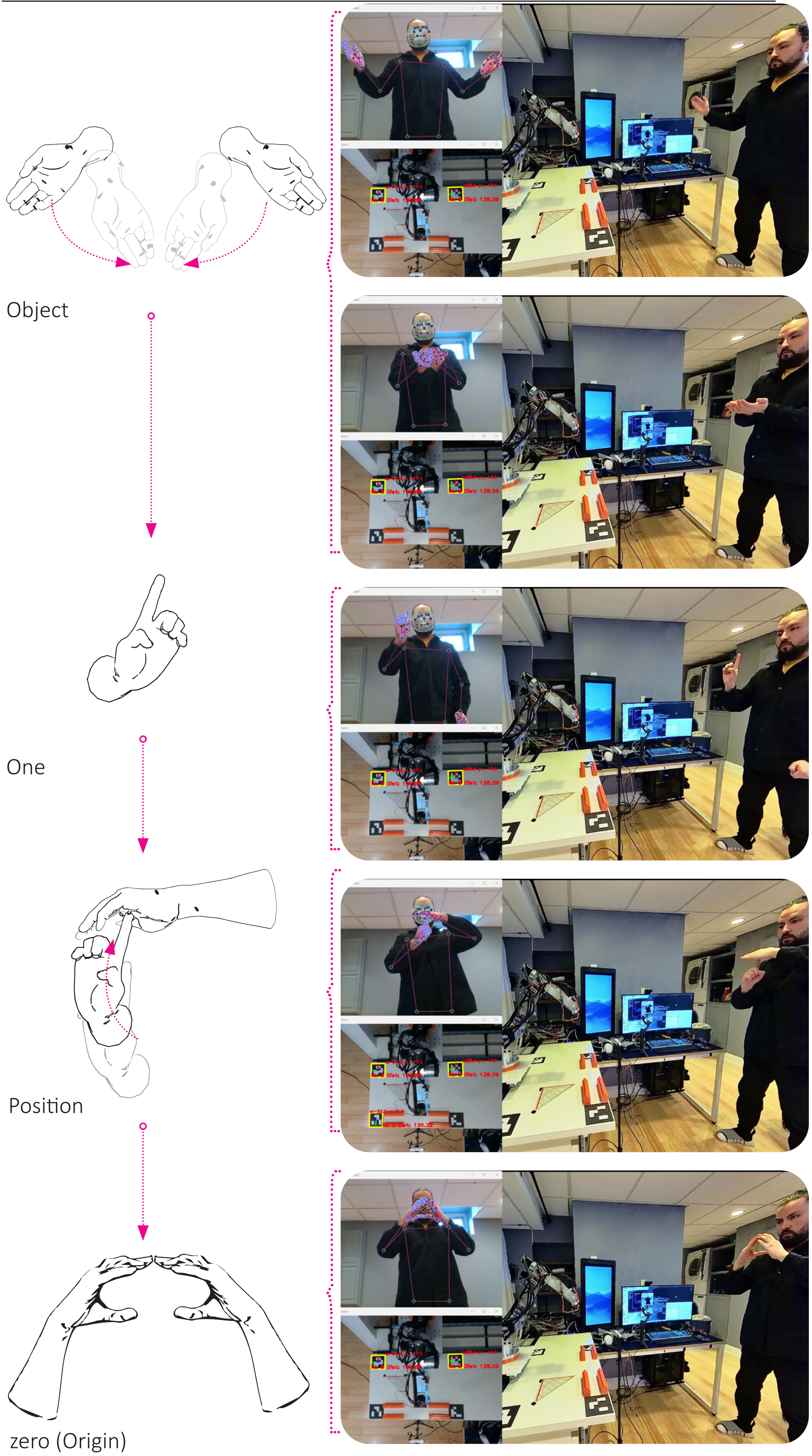


Figure 142
Initial gesture sequence
Source: author

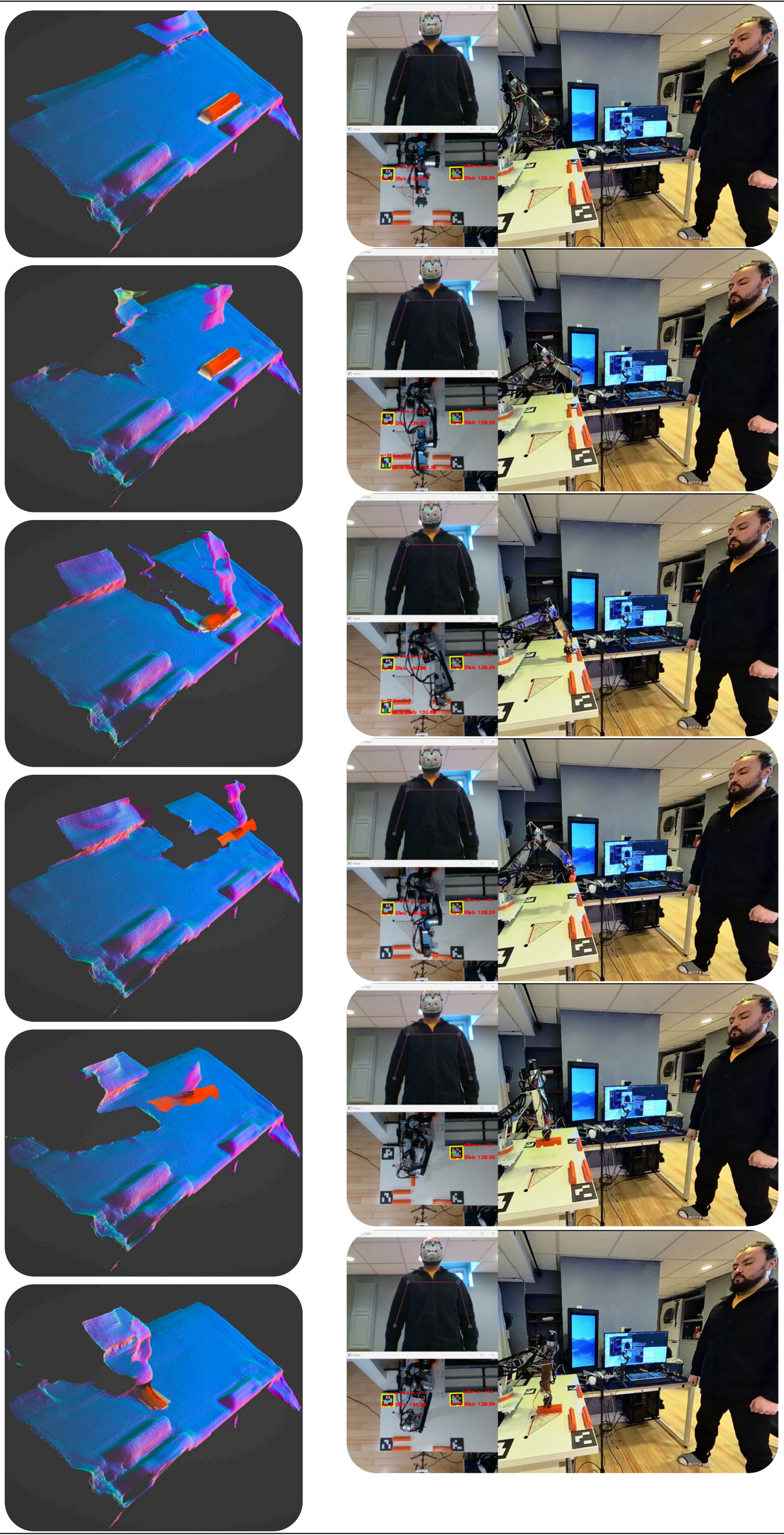


Figure 143
Robotic action sequence
Source: author

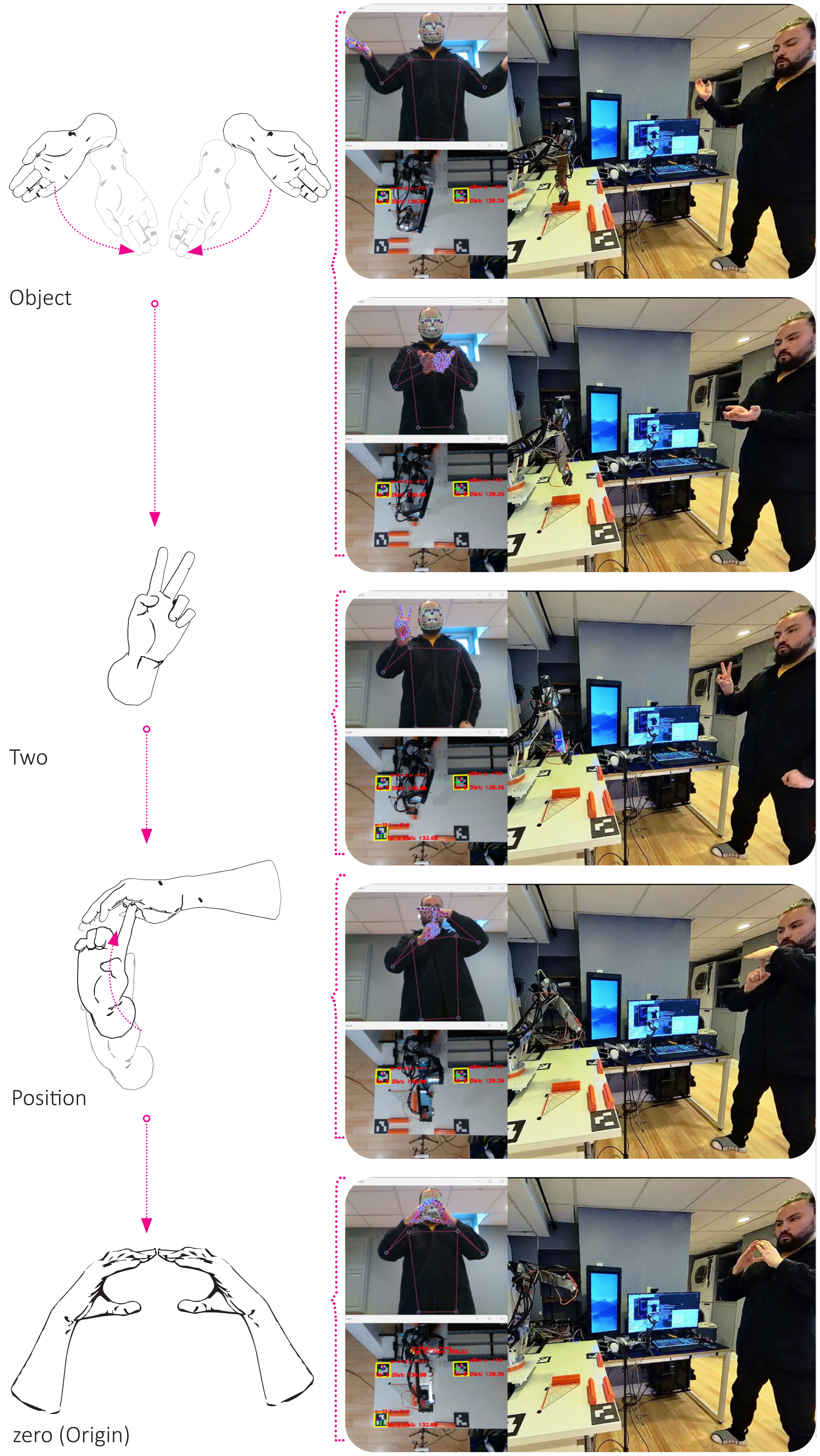


Figure 144
gesture sequence
Source: author

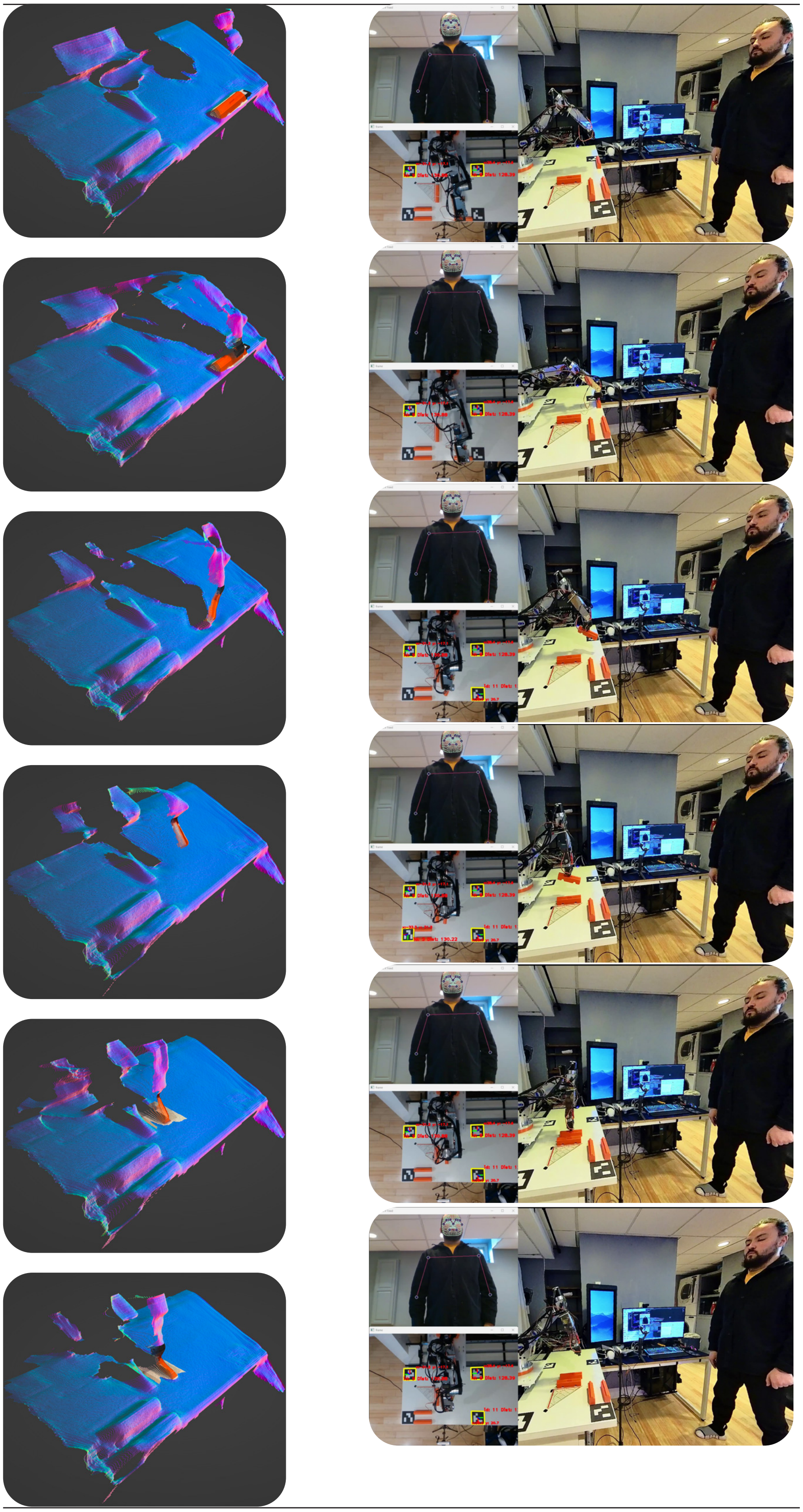


Figure 145
Robotic action sequence
Source: author

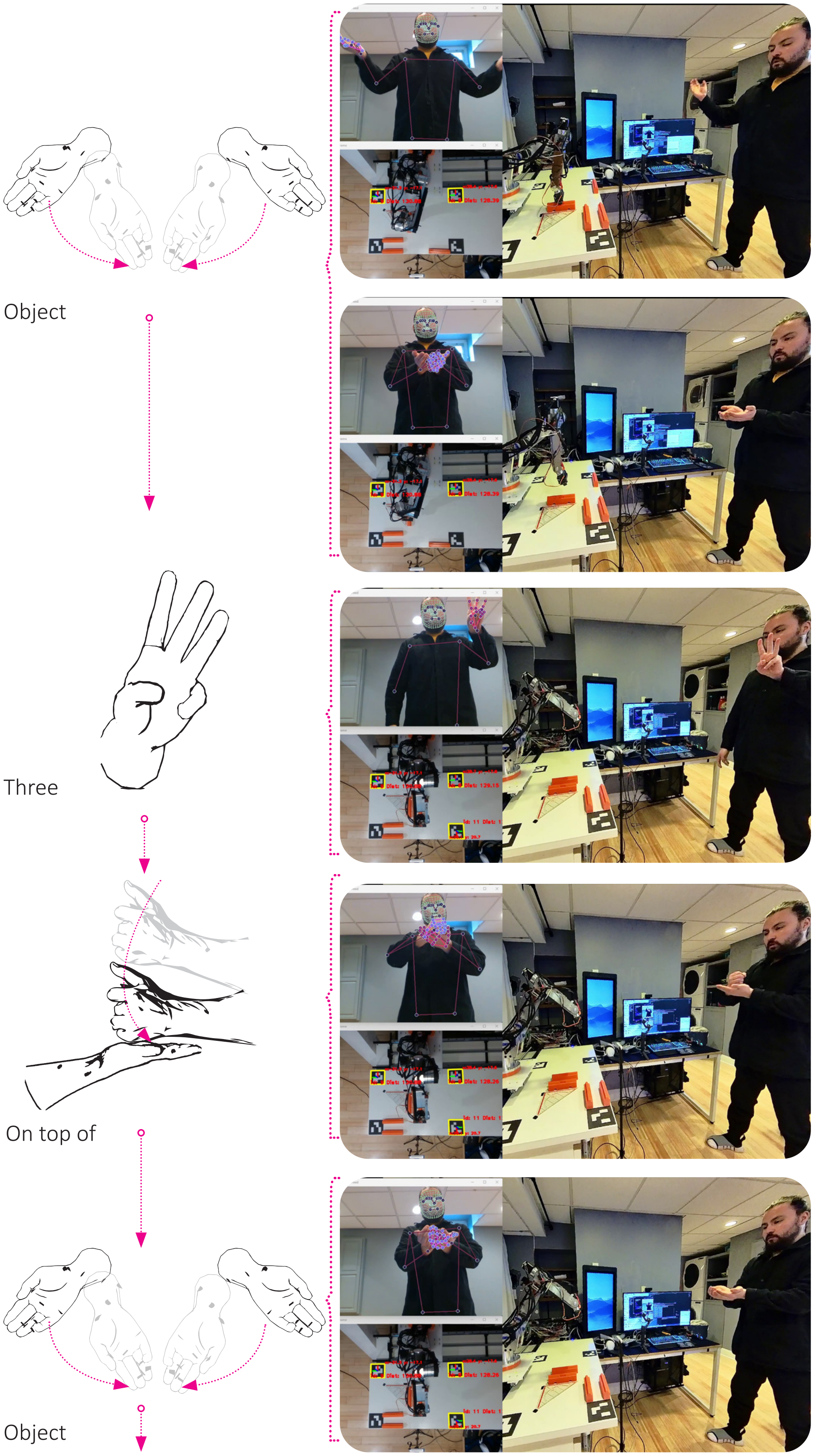
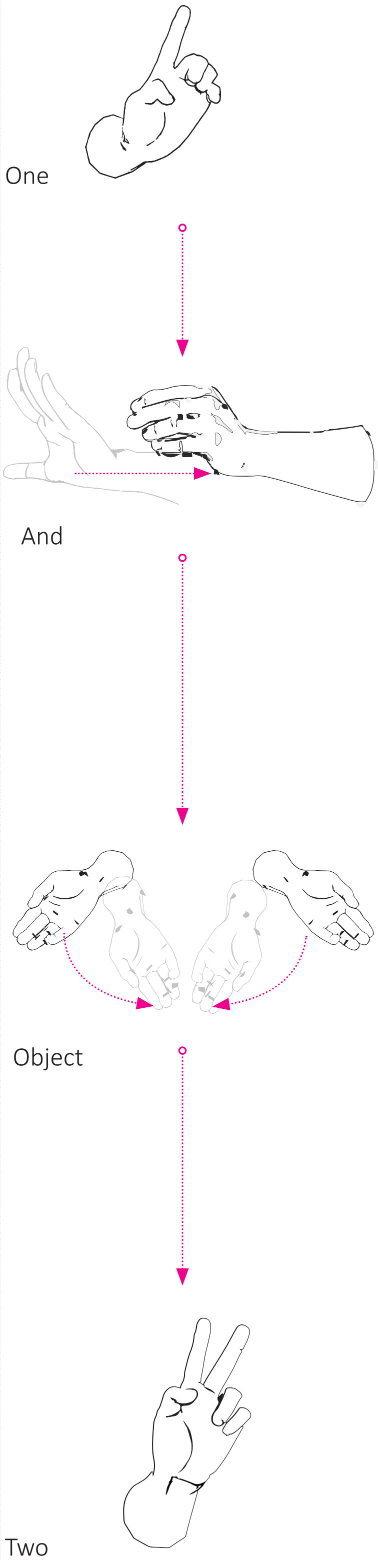
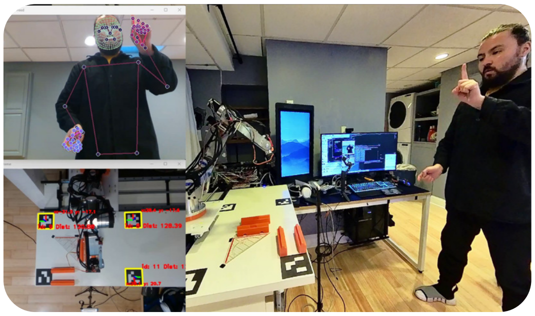
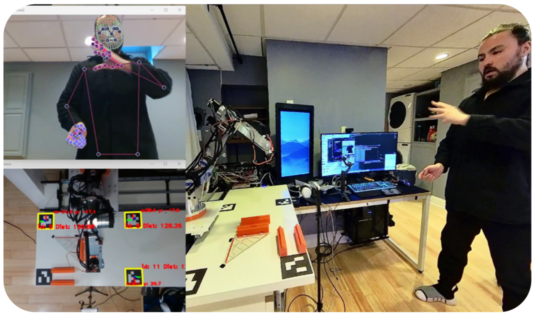
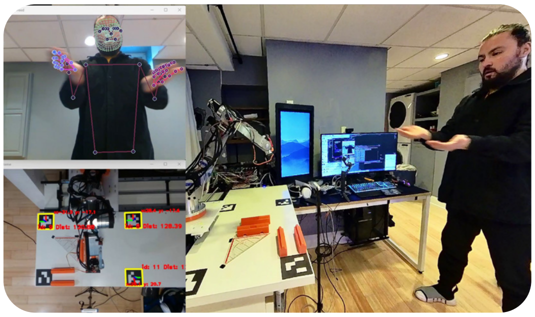


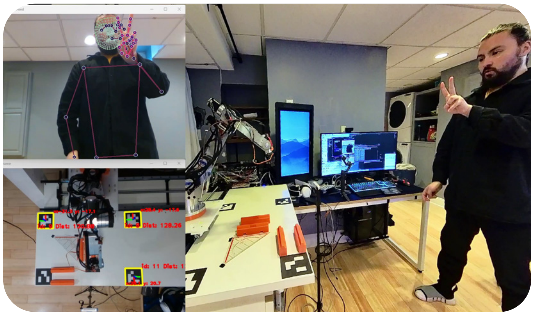
Figure 146
Gesture sequence
(continues in next page)
Source: author


One
And
Object
Two









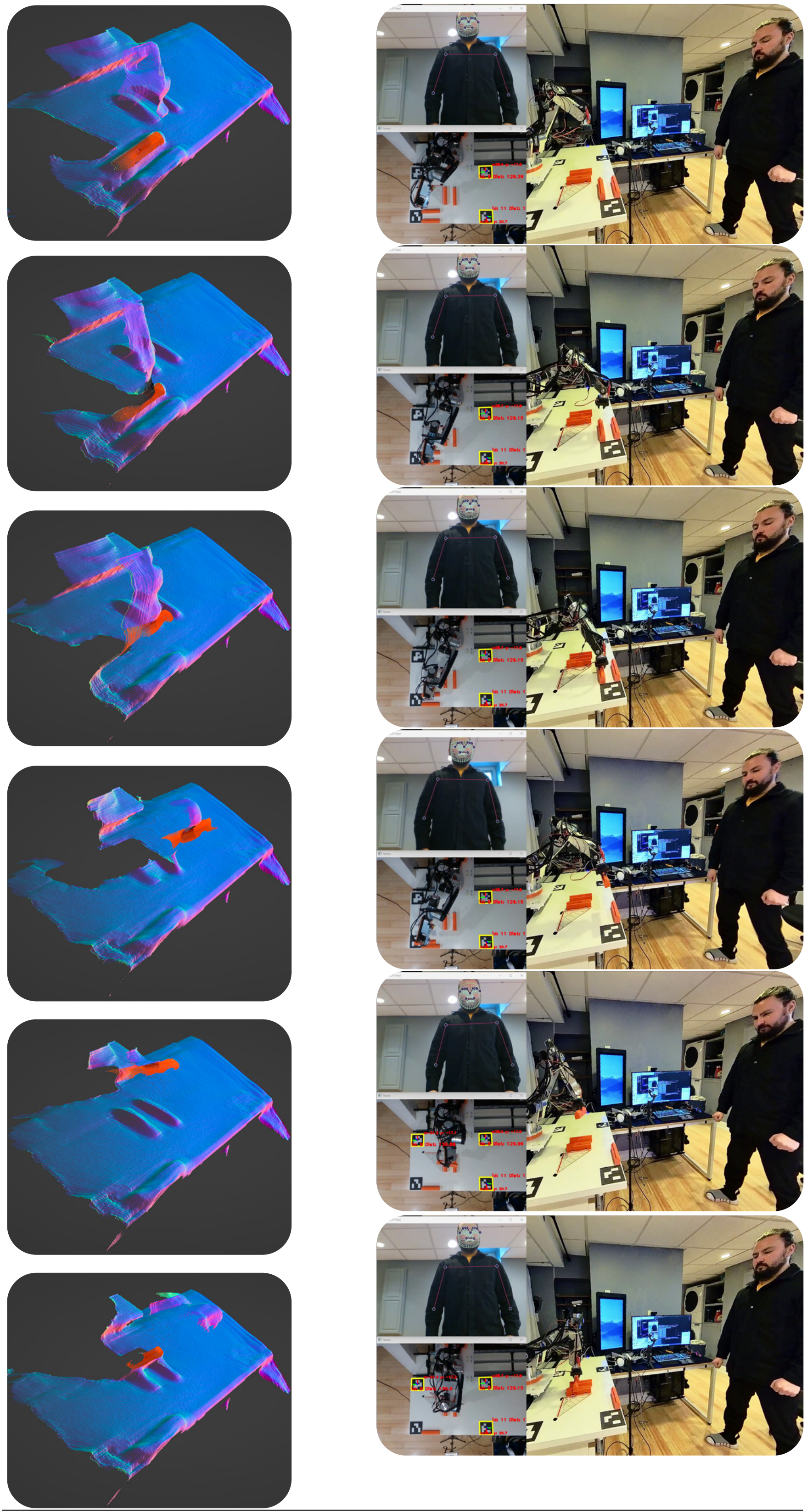


Figure 147
Robotic action sequence
Source:author

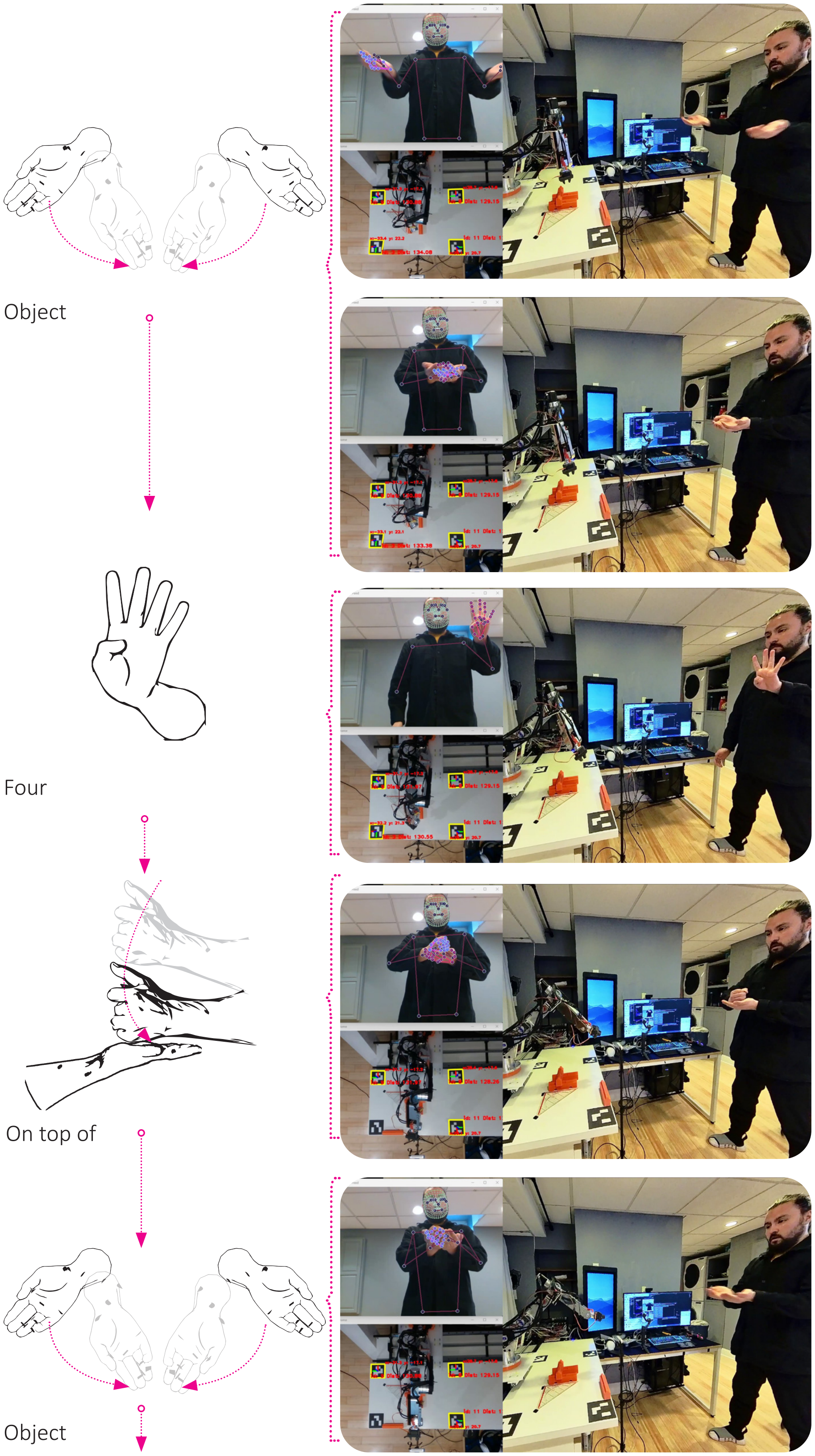
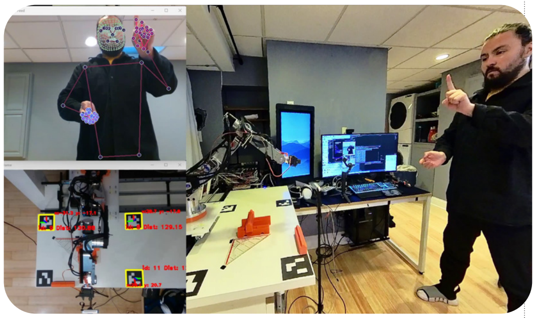
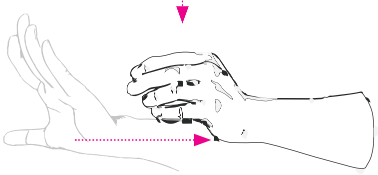


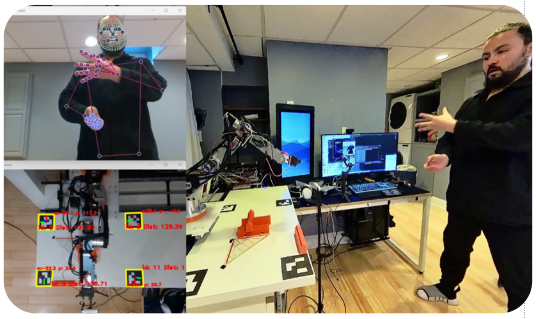
Figure 148
gesture sequence
source: author

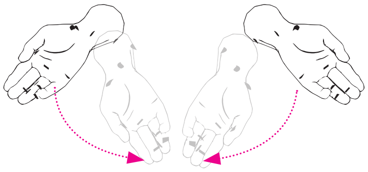
One



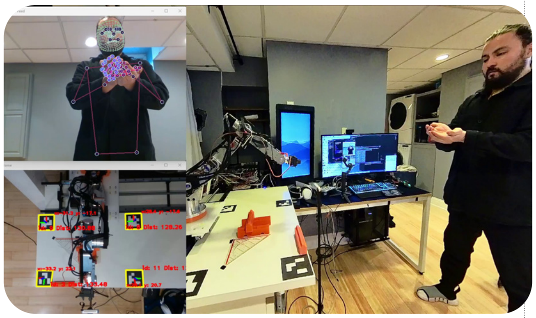


And

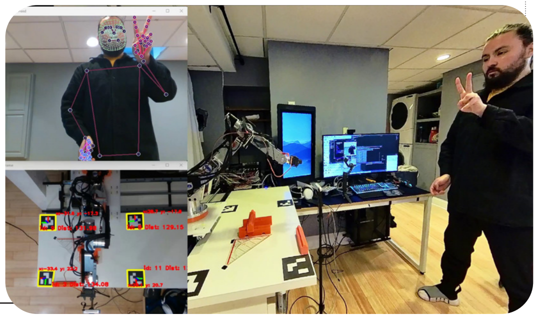




Object



Two



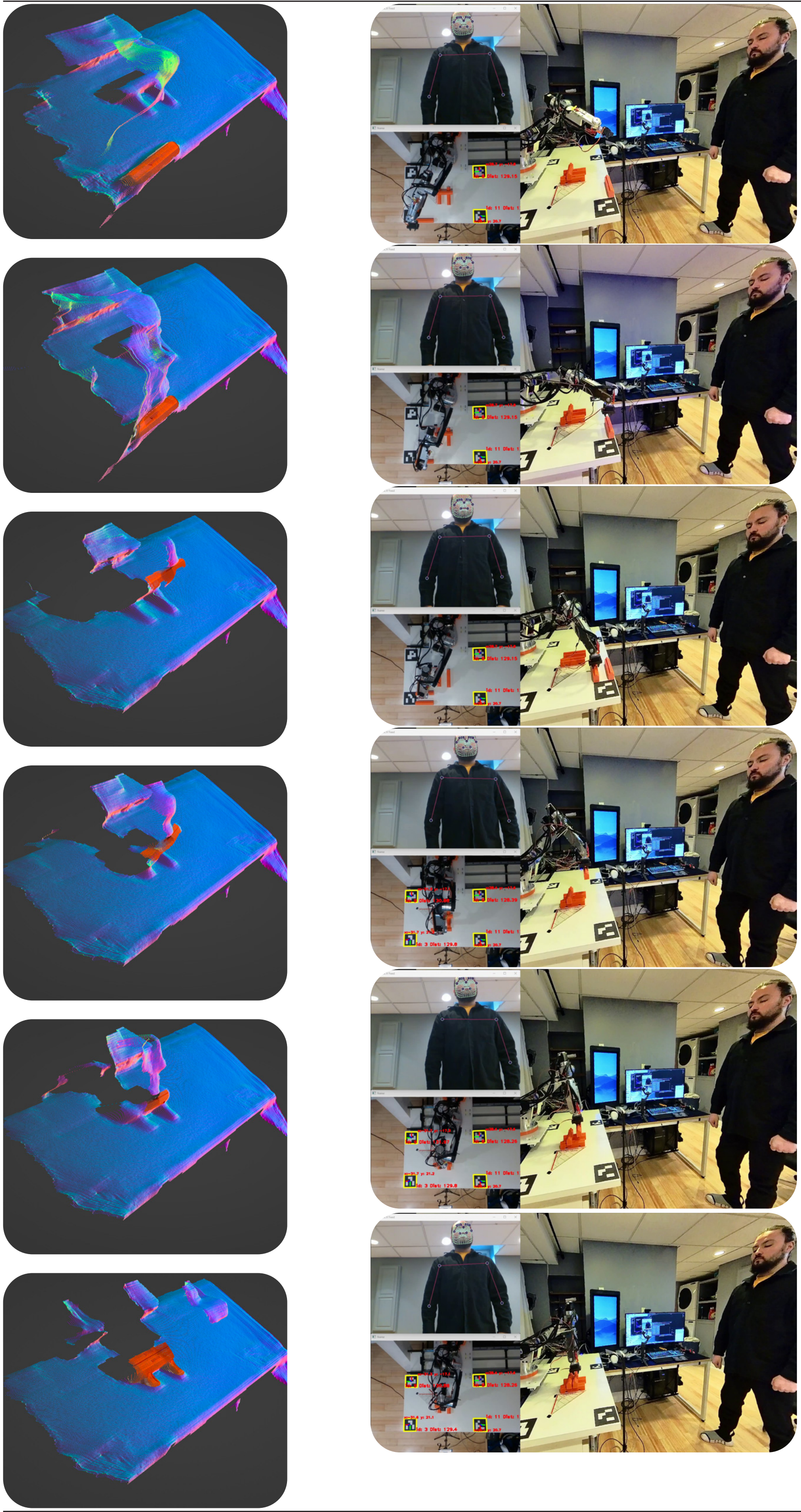


Figure 149
Robotic action sequence
Source: author

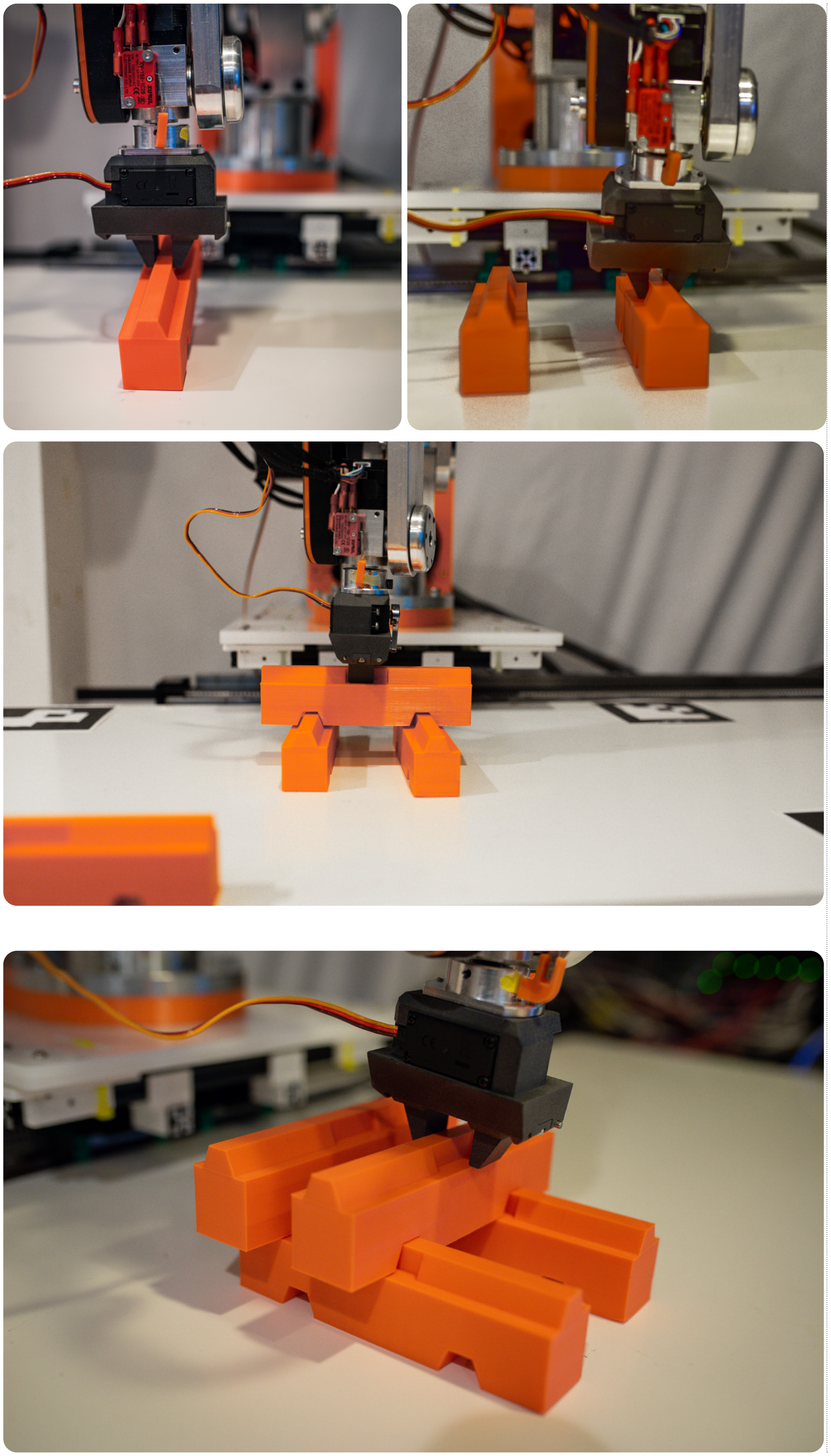


Figure 150
Robotic assembly details
Source: author

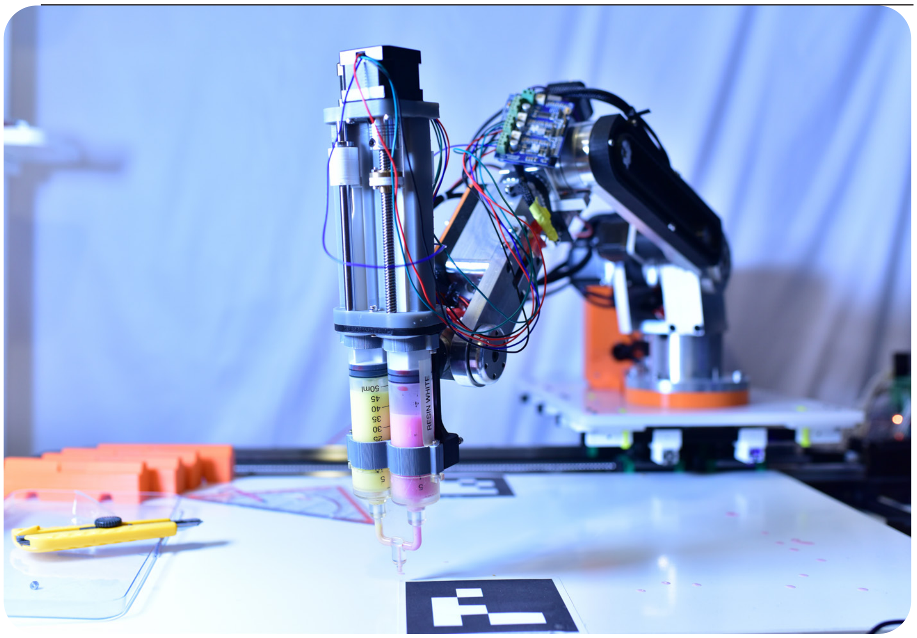


Figure 151
The alchemic printing setup
Source: author

5.10 Expanding the Computational Gestural making framework: The alchemic printer project

Beyond assembling tests, testing other ways of collaborating and interacting with a machine in terms of making was of special interest for this research. Starting from the question, In which areas a computer can complement the maker's labor, expanding the creativity and thinking in digital fabrication processes? I developed a project called the alchemic printing that aimed to explore the Computational Gestural Making Framework in material processes focusing on the complementary qualities of humans and machines. To do so I designed and developed the hardware and software to test mult material printing processes based on gestural interaction and real time material computation (figure 151 and figure 152).

5.10.1 3D printing as an alchemic process

The development of multi material 3D printing technique was based on the work presented SKeXl at the end of chapter 3. Based on the consideration that shape generation based on scalar fields opened up the space for new fabrication techniques bridging the digital and the physical through material computation, my interest was focused on both the generation of 3D models in real time by user input (sketches) focused

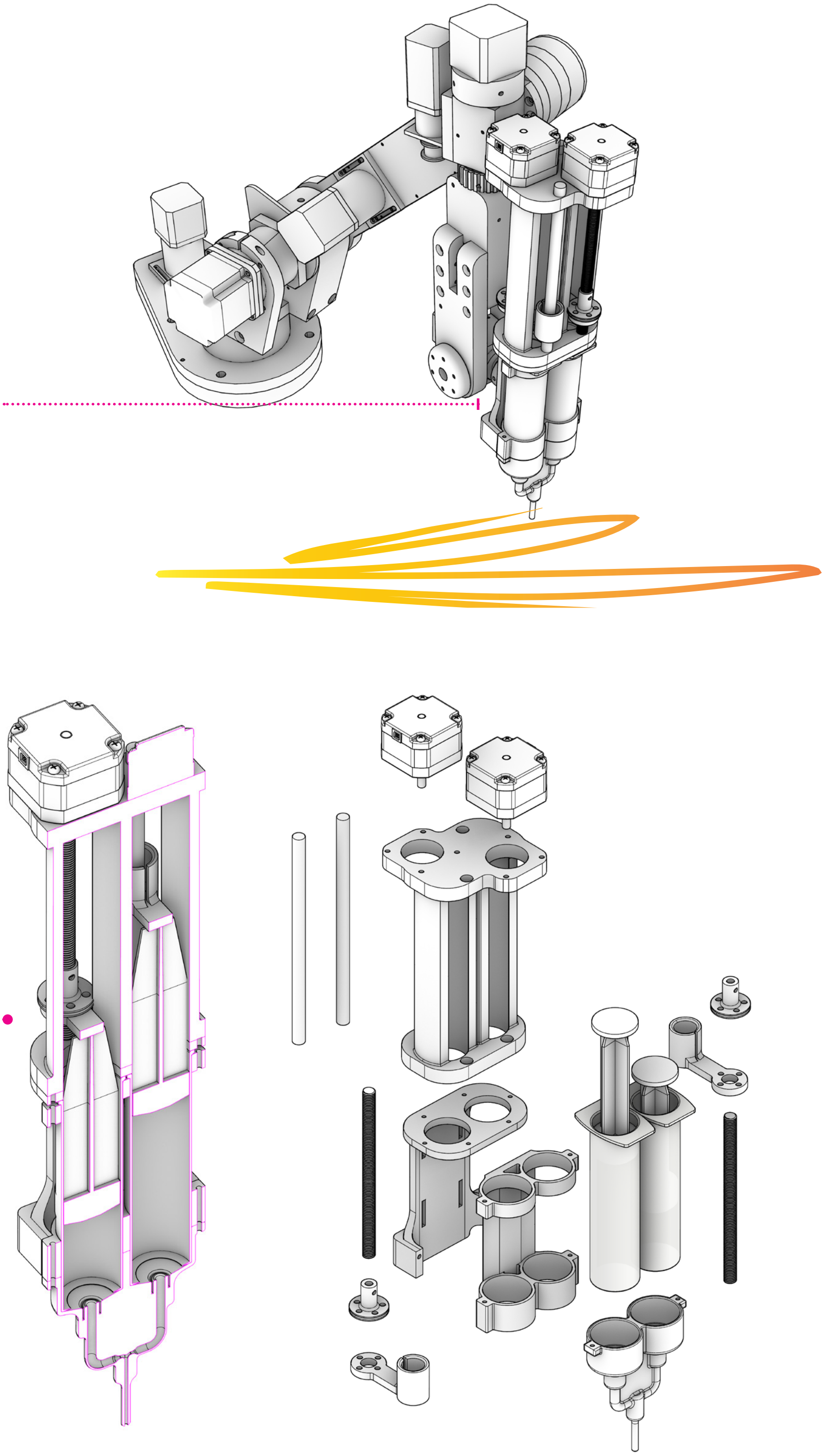


Figure 152
Robot and alchemic extruder details
Source: author

on the qualitative aspects of design and also the computation of material processes for their fabrication based on quantitative criteria. Starting from the fact that the development of voxelized methods for shape generation broadened the exploration of multi-material 3d printing and the use of Functionally Gradient Materials (FGM) through the creation of shapes based on their material properties known as Property representations (P-reps) as opposed to Boundary representations (B-reps)[474]. Tsamis' seminal work on Property Representations through the use of scalar spaces to represent shape boundaries (B-reps) and material distribution in space opened the door for the exploration for the design of architectural shapes using FGMs. Tsamis' material approach proposed a design methodology based on material gradients responding to different environmental conditions setting a novel way to implement multi-material 3d printing. By bridging software[475] and hardware[476] implementations, Tsamis's work established a new design ethos that reconfigured the whole to parts relationships in architecture, seeking a new topology based on continuity instead of discretization. Along the same lines and based on Tsamis research, the work of Michalatos and Payne[477] shows the use of a voxelized-based approach to volume 3d modeling considering material distributions in Monolith, a discontinued software bought by Autodesk[478]. Monolith emerged as the paradigm for voxel modeling implementations as a general-purpose modeling software based on material distributions, closely related to the work of other authors such as Richard and Amos[479], Grigoriadis[480], Oxman[481] oriented to physically manufacturing FGMs.

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[474] Tsamis, A.: Software Tectonics, Ph. D. thesis, MIT Department of Architecture, Cambridge, MA (2012)

[475] ibid, pp. 42

[476] ibid, pp 302

[477] Michalatos and Payne. Working with Multi-scale Material Distributions http://papers.cumincad.org/cgi-bin/works/Show?acadia13_043

[478] https://static1.squarespace.com/static/54450658e4b015161cd030c-d/t/56ae214afd5d08a9013c99c0/1454252370968/Monolith_UserGuide.pdf

[479] ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 9781926724478]Los Angeles 23-25 October, 2014), pp. 101-110

[480] Grigoriadis, Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016) / Melbourne 30 March–2 April 2016, pp. 589-598

[481] Oxman, N., Keating, S., and Tsai, E., Taylor & Francis, Proceedings of VRAP: Advanced Research in Virtual and Rapid Prototyping in: "Innovative Developments in Virtual and Physical Prototyping ", P.J. Bártolo et al.

After the development of SKeXl, I focused on the development of the necessary hardware and software to implement the fabrication of multimaterial shapes with the aim of performing real-time material computation based on gestures. I implemented a process in which the designer focuses on the qualitative aspects of a design while the Machine focuses on the quantitative aspects of it such as solving paths, material distribution, and potentially any performative aspect such as structural performance.

As a first step, I developed a novel approach for the fabrication of P-reps by generating optimized 3d printing paths by mapping shape internal stress into material distribution through a single optimized curve oriented to the fabrication of procedural shapes. Whereas Additive Manufacturing tool path optimization research focuses on time reduction, this paper considers tool path optimization to relate shape performance metrics and material properties using the most efficient single path applied to infill areas. While there is a significant body of work using algorithms such as the travel salesman problem (TSP) for path optimization in the world of CNC milling toward reduction of air time[482] (the time the machine moves in z direction to perform rapid movements) or by covering a planar area efficiently by the shortest path possible in the minimum amount of time[483], the optimization of tool paths opens the door for further novel applications in alternative FDM processes. This paper proposes using self-organizing maps (SOM) to produce an optimized path based on Kohonen[484] and Brocki[485] to solve a geometric-fabrication problem of multi-material 3d printing. By the use of a modified version of the traveling salesman problem (TSP), an optimized Spline is generated to map trajectories and material distribution into voxelized shape's slices. As a result, we can obtain an optimized P-Rep G-code generation for multi-material 3d printing and explore the fabrication of P-Rep as FGMs based on material behavior.

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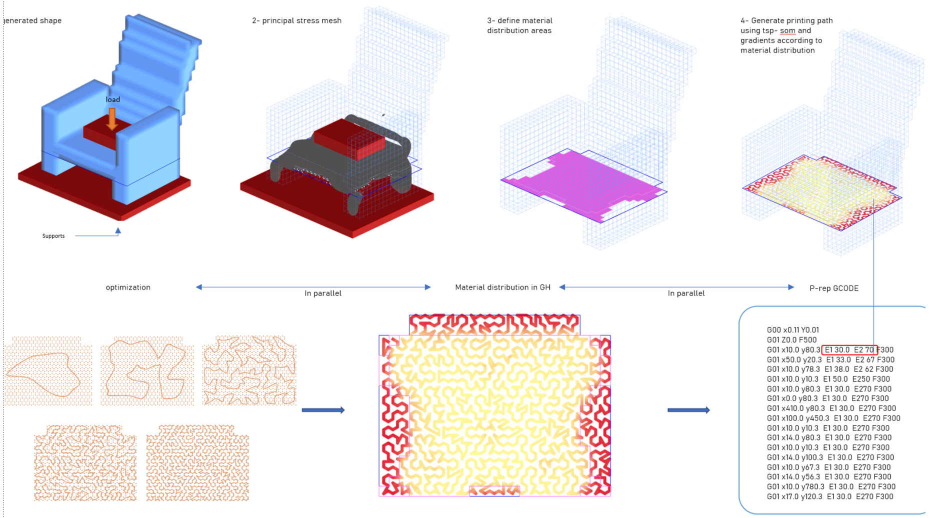
[482] Gregory Dreifus, Kyle Goodrick, Scott Giles, Milan Patel, Reed Matthew Foster, Cody Williams, John Lindahl, Brian Post, Alex Roschli, Lonnie Love, and Vlastimil Kunc.3D Printing and Additive Manufacturing. Jun 2017.98-104.http://doi.org/10.1089/3dp.2017.0007

[483] Castelino, Kenneth, Roshan D'Souza, and Paul K. Wright. "Toolpath Optimization for Minimizing Airtime during Machining." Journal of Manufacturing Systems 22, no. 3 (2003): 173-180

[484] Kohonen, T. (1998). The self-organizing map. Neurocomputing, 21(1), 1–6.

[485] Brocki, L. (2010). Kohonen self-organizing map for the traveling salesperson. <u>In Traveling Salesperson Problem, Recent Advances in Mechatronics (pp. 116–119</u>)



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G00 x0.11 Y0.01
G01 Z0.0 F500
G01 x10.0 y80.3  E1 30.0  E2 70 F300
G01 x50.0 y20.3  E1 33.0  E2 67 F300
G01 x10.0 y78.3  E1 38.0  E2 62 F300
G01 x10.0 y10.3  E1 50.0  E250 F300
G01 x10.0 y80.3  E1 30.0  E270 F300
G01 x0.0 y80.3  E1 30.0  E270 F300
G01 x410.0 y80.3  E1 30.0  E270 F300
G01 x100.0 y450.3  E1 30.0  E270 F300
G01 x10.0 y10.3  E1 30.0  E270 F300
G01 x14.0 y80.3  E1 30.0  E270 F300
G01 x10.0 y10.3  E1 30.0  E270 F300
G01 x14.0 y100.3  E1 30.0  E270 F300
G01 x10.0 y67.3  E1 30.0  E270 F300
G01 x14.0 y56.3  E1 30.0  E270 F300
G01 x10.0 y780.3  E1 30.0  E270 F300
G01 x17.0 y120.3  E1 30.0  E270 F300
```

Figure 153
Using Self organizing maps to optimize 3D prionting paths for multimaterial 3d Printing. Pinochet and Tsamis , 2021.
Source: author

The findings of that exploration were presented in the paper 'Path optimization for multi-material 3D printing using self-organizing maps'[486]. In that research I developed a way to compute, using Artifitial Neural Networks, a 3D printing path that solves efficently in time and lenght, the calculation of areas and the mapping of two or more materials (figure 153). The software implementation was developed initially to generate toolpaths from a voxelized shape generated in SkeXl to be fabricated in a system such as the original version of the Alchemic printer as depicted in figure 154. In that regard I focused on the generation of toolpaths as a complex problem that could be calculated by a machine in short time that could be applied to interactive fabrication problems where toolpath calculation is in general time consuming.

Considerable work in tool path optimization has been produced in the past ten years. Several techniques and algorithms have been used to optimize parameters, for example, air time, the vertical movement for rapid end effector travel in 2D, covered (visited) area, and path length.

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[486] Pinochet, D., Tsamis, A. (2022). Path Optimization for Multi-material 3D Printing Using Self-organizing Maps. In: Gerber, D., Pantazis, E., Bogosian, B., Nahmad, A., Miltiadis, C. (eds) Computer-Aided Architectural Design. Design Imperatives: The Future is Now. CAAD Futures 2021. Communications in Computer and Information Science, vol 1465. Springer, Singapore. https://doi.org/10.1007/978-981-19-1280-1_21

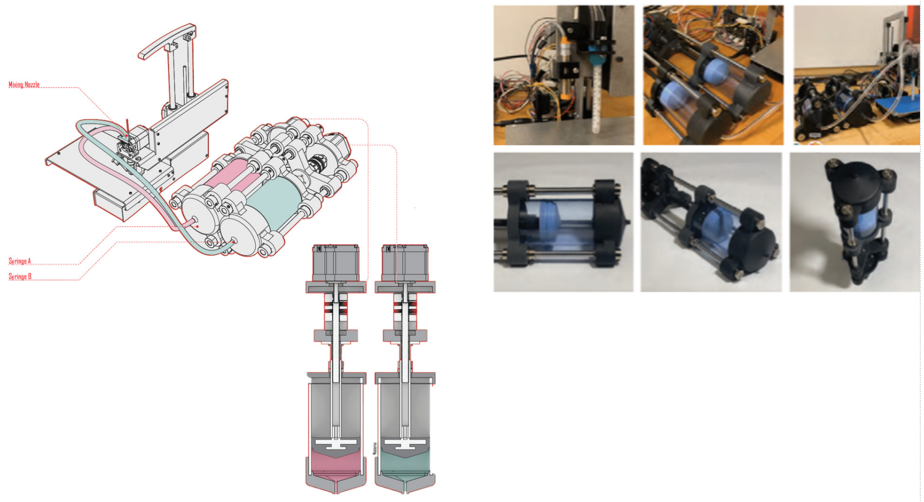

Figure 154
Second iteration of the Alchemic printer. Pinochet, 2019
Source: author

Lechowicz et al.[487] proposed the use of Greedy algorithms (2opt and Annealing) to optimize 3d printing time. Alternatively, the works of Dreifus et al.[488] or Ganganath et al.[489] use the Chinese Postman Problem[490] and the Traveling Salesman problem using the Cristofides algorithm, respectively, to optimize similar problems like the ones from Lechowicz et al. Whereas the use of the TSP algorithm and variations has shown promising results in optimizing printing time while reducing travel of the end effector, as detailed information has not been provided concerning calculation times.

The traveling salesman problem is a well-known problem in computer

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[487] P. Lechowicz, L. Koszalka, I. Pozniak-Koszalka and A. Kasprzak, “Path optimization in 3D printer: Algorithms and experimentation system,” 2016 4th International Symposium on Computational and Business Intelligence (ISCBI), Olten, 2016, pp. 137-142, doi: 10.1109/ISCBI.2016.7743272.

[488] Dreifus Gregory, GoodrickKyle, GilesScott, PatelMilan, FosterReed Matthew, WilliamsCody, LindahlJohn, PostBrian, RoschliAlex, LoveLonnie and KuncVlastimil. “Path Optimization Along Lattices in Additive Manufacturing Using the Chinese Postman Problem.” (2017).

[489] K. Fok, N. Ganganath, C. Cheng and C. K. Tse, “A 3D printing path optimizer based on Christofides algorithm,” 2016 IEEE International Conference on Consumer Electronics-Taiwan (ICCE-TW), Nantou, 2016, pp. 1-2, doi: 10.1109/ICCE-TW.2016.7520990

[490] Gregory Dreifus, Kyle Goodrick, Scott Giles, Milan Patel, Reed Matthew Foster, Cody Williams, John Lindahl, Brian Post, Alex Roschli, Lonnie Love, and Vlastimil Kunc.3D Printing and Additive Manufacturing.Jun 2017.98-104. http://doi.org/10.1089/3dp.2017.0007

science. It consists of finding the shortest route possible that traverses all cities in a given map only once. Considered as an NP-complete hard problem-implying that the difficulty to solve it increases rapidly with the number of nodes to calculate, a general solution that solves the problem is unknown, resulting in an algorithm that tries to find good enough solutions when applied. The TSP and variations of it have been used to solve tool path optimization for 3d printing and milling because of its advantages in finding reasonable solutions that can be applied directly to fabrication problems.

The implementation of an alternative approach to solving the TSP is used in this project through Kohonen's Self-Organizing maps SOM. In 1975, Teuvo Kohonen introduced a new type of Neural network using competitive, unsupervised learning[491]. Kohonen proposed the description of a self-organizing map as a 2D nodes grid, inspired by a Neural Network (NN). By relating the idea of a map to a model, the purpose of Kohonen's technique was to represent a model in a lower number of dimensions while at the same time maintaining the similarity relations of the nodes contained. Kohonen's approach was through the use of Winner Takes All (WTA) and Winner Takes Most (WTM) algorithms. As explained by Brocki[492], by a combination of both algorithms, it is possible to, on the one hand, use WTA to calculate the neuron whose weights are most correlated to a current input as the winner, and on the other, use WTM – that has better convergence- to adapt neuron's synaptic weights in one learning iteration making the neuron's 'neighborhood' also adaptable[493].

Kohonen's technique was modified by Brocki introducing a change in Kohonen's algorithm, considering a circular array of nodes instead of a grid. By applying such modification, a dimension reduction is performed, so the neighborhood condition of neurons considers a neuron in front and back of it. This change in Kohonen's technique allows the SOM to behave like an elastic ring while getting closer to the nodes while minimizing length by the neighborhood condition. According to Brocki, this is represented by showing fast-global self-organization at the beginning and local adjustment behavior in the end. Convergence is ensured by applying a learning rate α controlling the exploration -at the beginning- and exploitation -at the end- of the algorithm. A decay in

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[491] Kohonen, The self-organizing map. Neurocomputing, 21(1), 1–6.

[492] Brocki, Łukasz and Danijel Korzinek. "Kohonen Self-Organizing Map for the Traveling Salesperson Problem." (2007). And Brocki, L. (2010).

[493] Kohonen self-organizing map for the traveling salesperson. In Traveling Salesperson Problem, Recent Advances in Mechatronics (pp. 116–119)

the neighborhood and the learning rate are applied to ensure the proper function of the algorithm. While decaying, the learning rate ensures low displacement of the neurons in the model. Decaying the neighborhood produces moderate exploitation of local minima. The regression expressed by Brocki is based on Kohonen's result in the following equation.

$$\gamma_\alpha \cdot \alpha_t, \ \ h_{t+1} = \gamma_h \cdot h_t$$

Similar to the function of Q learning, α is the learning rate in time, γ is the discount, and h the neighbor dispersion. By traversing the ring starting from an arbitrary point and sorting the nodes by order of appearance of their winner neuron -associated with the corresponding node.

5.10.1.1 implementing path optimization for toolpaths and multi material 3d printing.

The proposed workflow takes a solid voxelized shape, which is analyzed using topological optimization[494]. From the topological optimization, the resulting geometry is conformed from 2 meshes; the overall boundary and the principal stress mesh. The system takes both shapes and generates slices according to an initial layer height parameter determining areas for material distribution. Both areas are populated with different point distributions according to a desired infill percentage and printing nozzle. An optimization process that solves the traveling salesman problem using self-organizing maps is implemented from the array of points using different distributions - random, square, radial, hexagonal, and triangular. A single spline is generated, traveling most efficiently through all the point-set, minimizing the length of travel and eliminating airtime (reducing print time) and self-intersections (to avoid undesired collisions with the printing nozzle) while maintaining the lowest calculation time possible.

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[494] Millipede. An analysis and optimization tool http://www.sawapan.eu/ based on the work shown in Kaijima, S. and Michalatos, P.: 2011, Intuitive material distributions, Architectural Design,

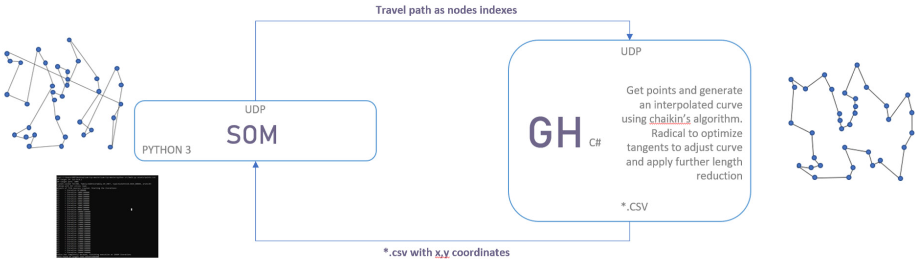

Figure 155
Software implementation pipeline
Source: author

Applying the TSP algorithm for toolpath optimization presents some challenges. It is considered an NP-complete hard problem, implying that the difficulty to solve it increases rapidly with the number of nodes, and we do not know a general solution that solves the problem. This is why through the algorithm, we can find good – enough solutions for fabrication problems that could reduce, in the case of this implementation, printing time and path calculation. Because of this reason, an alternative technique to solve the TSP problem is implemented.

The implementation of an alternative approach to solving the TSP based on Kohonen's Self-Organizing maps SOM previously described is used in this project. Based on Vicente's[495] implementation to implement's Brocki's modification, a Python 3 script is written and connected to Grasshopper (GH) to obtain the optimized path (figure 155). A CSV file is generated by taking a distributed point set inside a shape slice containing the node's data as IDs and x y coordinates. The python script takes the information and tries to generate an optimized path in the lower amount of iterations possible (10000 per epoch) while avoiding any self-intersection. If any of the parameters in the equation decays over a certain useful threshold, the optimization stops and sends over a socket communication, the ids of the nodes back to GH. After receiving the id of the nodes, the GH definition

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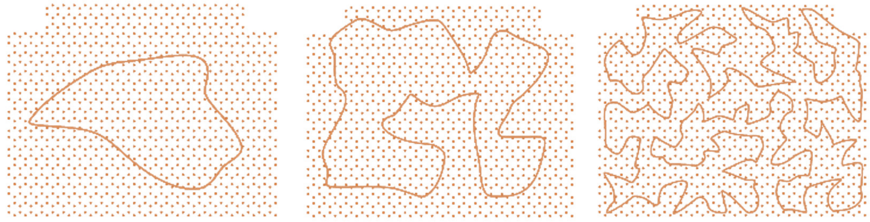
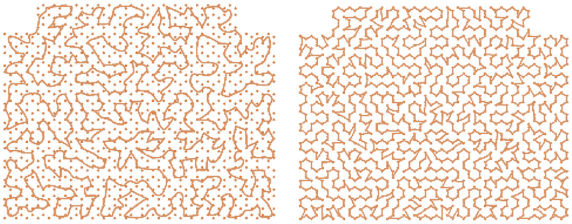
[495] https://github.com/diego-vicente



Initial state

50 iterations

1000 iterations



5000 iterations

10000 iterations

Figure 156
Path optimization using SOMs implemented in Python 3 and GH. The sequence shows the progression of the calculation using the SOM. In this example, the path calculates the most efficient way to travel all the points in a uniform grid to generate a single path (to reduce air time and calculate material continuity in the extrusion process.)
Source: author

takes the index pattern and generates an interpolated curve using Chaikin's algorithm[496] implemented in C#. Once a path has been obtained, A final optimization using Constrained Optimization by Linear Approximations (COBYLA)[497] is applied to the tangents of the generated curve to get an extra length optimization of the path (figure 156). Finally, a function that calculates Nurbs' points distances to the areas resulted from the topological optimization. This set of distances calculates a material concentration between material A or B to be applied during the printing process. The function to principal stress data to a path results in a gradient path that will be printed as the infill of the printed object (figure 157).

The methodology to test the application of SOMs for optimized path generation consider the application of two additional versions of the TSP algorithm. A vanilla version using the Cristofides[498] algorithm and a 2Opt[499] (implemented in Python3) versions of the TSP are used

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[496] George Merrill Chaikin, An algorithm for high-speed curve generation, Computer Graphics and Image Processing, Volume 3, Issue 4, 1974, Pages 346-349.

[497] Implemented using RADICAL , a component part of the DSE tool-kit. http://digitalstructures.mit.edu/page/tools#design-space-exploration-tool-suite-for-grasshopper

[498] https://en.wikipedia.org/wiki/Christofides_algorithm

[499] https://towardsdatascience.com/how-to-solve-the-traveling-salesman-problem-a-comparative-analysis-39056a916c9f

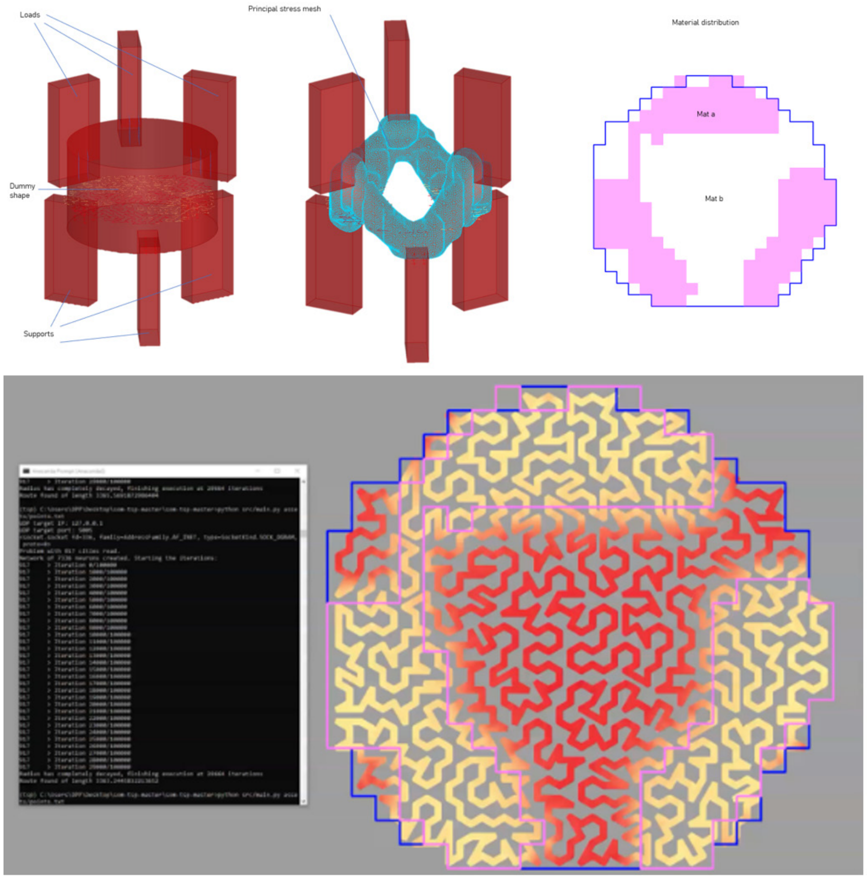

Figure 157
Applying the SOM optimization to a dummy shape's slice after topological optimization is applied to the initial mesh. The geometry is processed and calculated using topological optimization, then sliced and populated with a point distribution (in this case an ordered grid) and sent to the program for gradient material distribution calculation.
Source: author

to have comparative optimization metrics through SOMs. Whereas the Cristofides version is considered the most optimal approach to solve the TSP, it doesn't ensure the avoidance of self-intersections for the generated path, making it useless for fabrication purposes. A 2-opt TSP solver was used to compare the results of the SOM TSP approach.

After the implementation of the path optimization algorithms, I tested it using a new version of the alchemic printer that could be combined with the Computational Gestural Making framework (figure 158). As stated previously, the intention was to test how a collaborative computation between a designer and a machine could be driven by the development of qualitative and quantitative respectively. I tested the implementation in two ways. The first considered the determination of printing areas indicated by gestures that the machine uses to fill with the SOM-TSP described previously in this chapter. In that way the machine takes care of calculating an infill path of the determined area, while the Human designer is in charge of 'regulating in real-time' the distribution of two materials as depicted in figure 159.

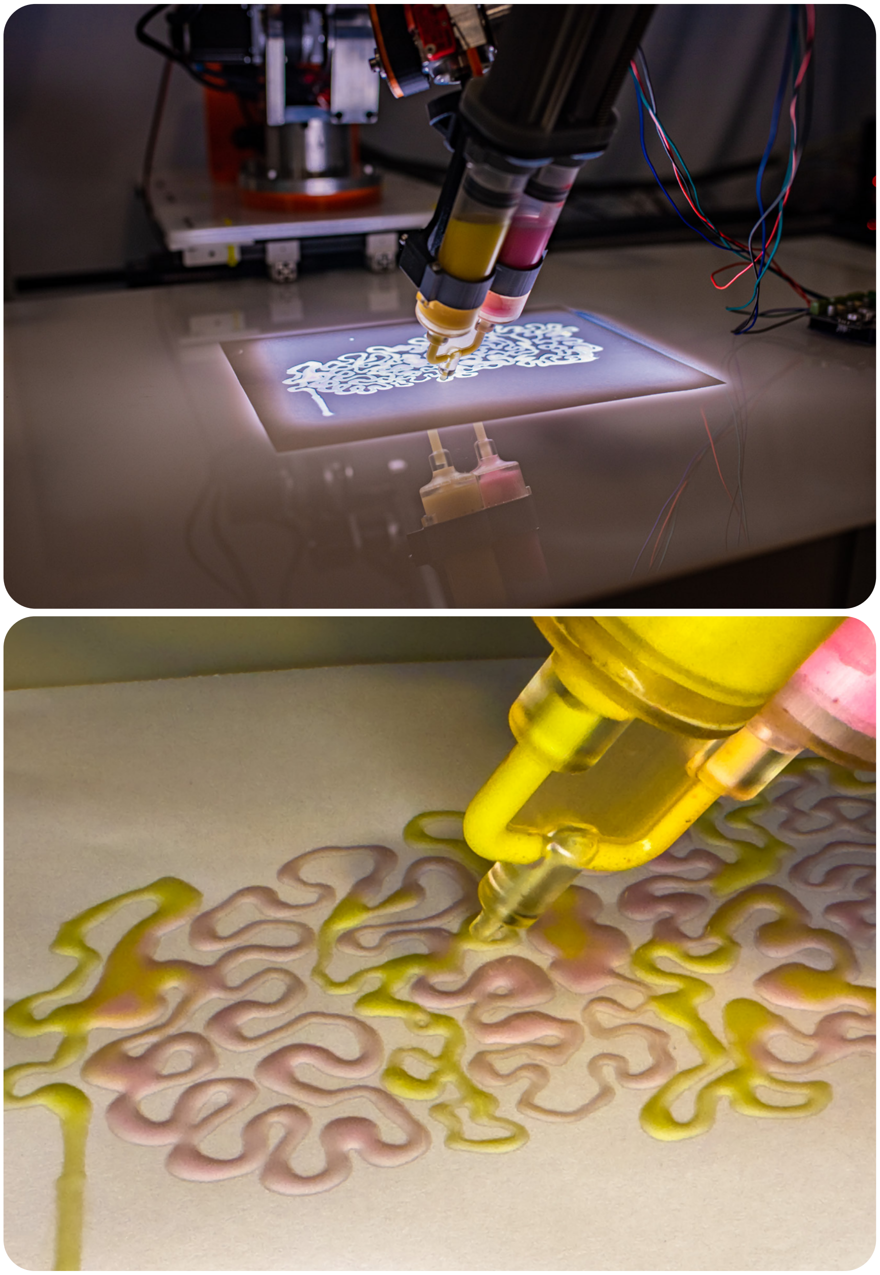

Figure 158
Material tests with the
alchemic printer
Source: author

The regulation of material is achieved by using simple trajectory prediction gestures to indicate more concentration of material A or B as a hand moves more to the left or to the right respectively as depicted in figure 160. Finally, the system adds UV light to ‘cure‘ resins on the go (figure c5-50). This is particularly important because the system could be implemented in future iterations to print and add layers in the Z vertical direction (not developed during this dissertation).

Figure 159
Alchemic printing tests
Source: author

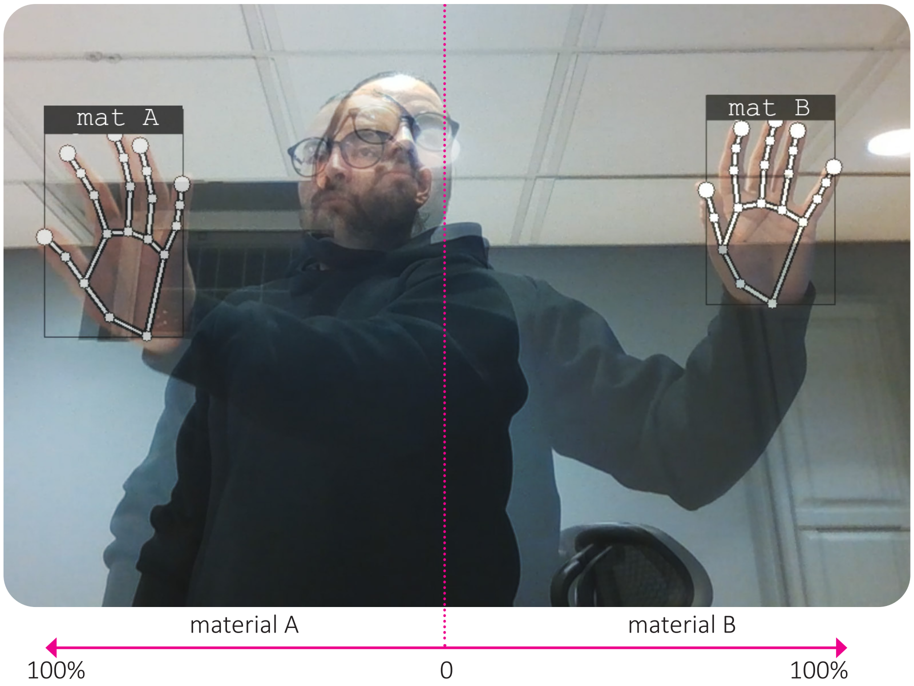

Figure 160
trajectory prediction
to calculate material
concentration in real time.
Moving the predicted hand
to the right or left dictates
the material distribution to
be printed
Source: author

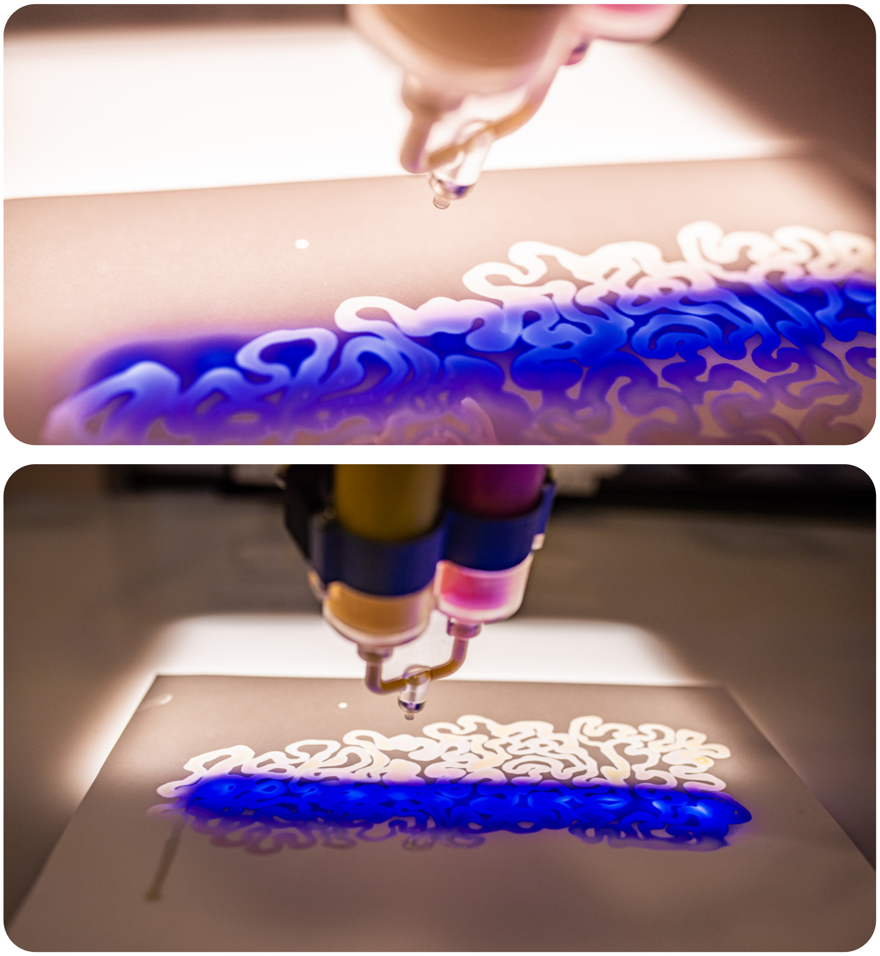

Figure 161
Resin curing process using
UV light
Source: author

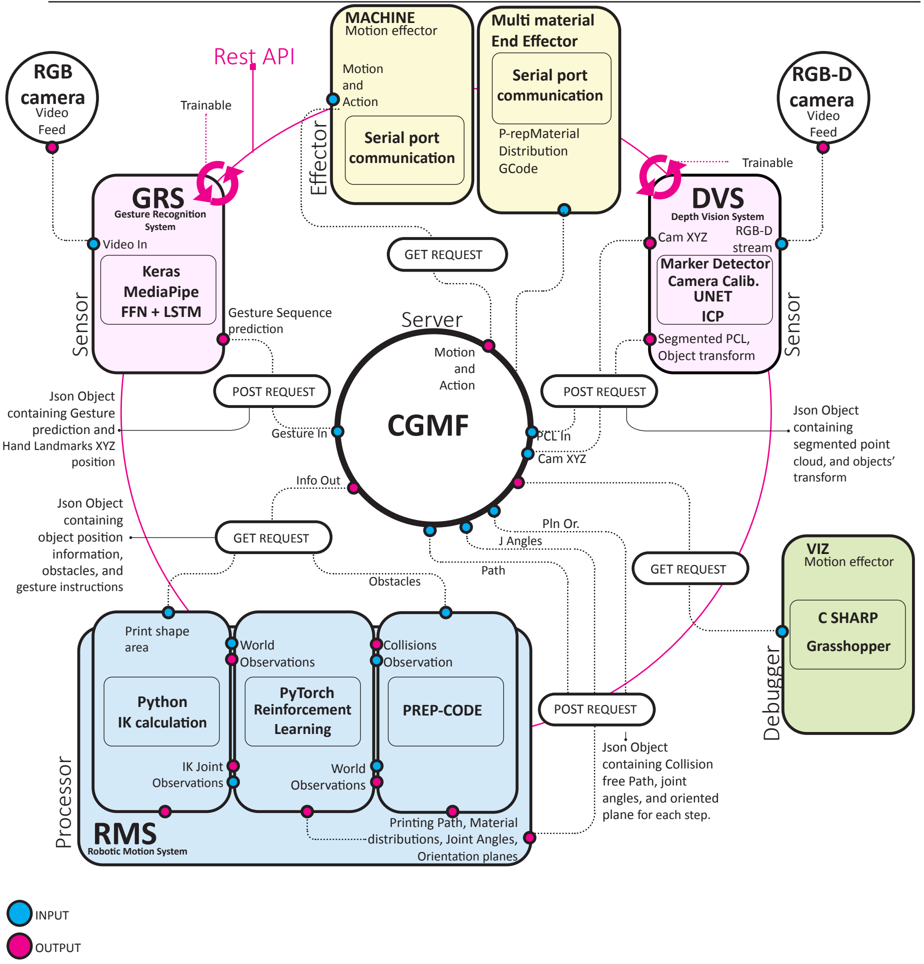

Figure 162
trajectory prediction
to calculate material
concentration in real time.
Source: author

5.10.2 Alchemic Free printing

The last experiment of the system was testing freeform printing. In this scenario, the Designer explores free movement to print and continously deposit material in a thick gelatinous material. Inspired by the work of Johns[500] and Harms[501] developed in 2012, I implemented my own version of a what they called 'buoyant' or 'suspended' 3D printing processes respectively[502]. Building upon their systems as a reference, I implemented the alchemic printing taking advantage of the zero-support and zero-gravity properties of a gelatinous environment to test both free gesturing and variable multi-material computation. Following the same modular implementation

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[500] https://greyshed.com/work/buoyant-extrusion/

[501] https://www.nstrmnt.com/#/suspended-depositions/

[502] Years later, a similar apporach was adopted by the self-assembly lab at MIT to comercialize a 4D silicon printing technique.

Figure 163
Alchemic free printing
Source: author

of the CGMF, a module for calculating the SOM TSP and the material disibutions were added (figure 162). Although these are early proof of concept tests and are part of future iterations of the project, the developed system is able to detect free hand gesturing from a user to control with one hand the printing nozzle trajectory and with the other hand calculate in real time the material concentrations of the path (figure 163) to generate and make shapes out of two resin materials (figure 164). This iteration shows promising results for the implementation of gestural 3D printing as a concept with potential

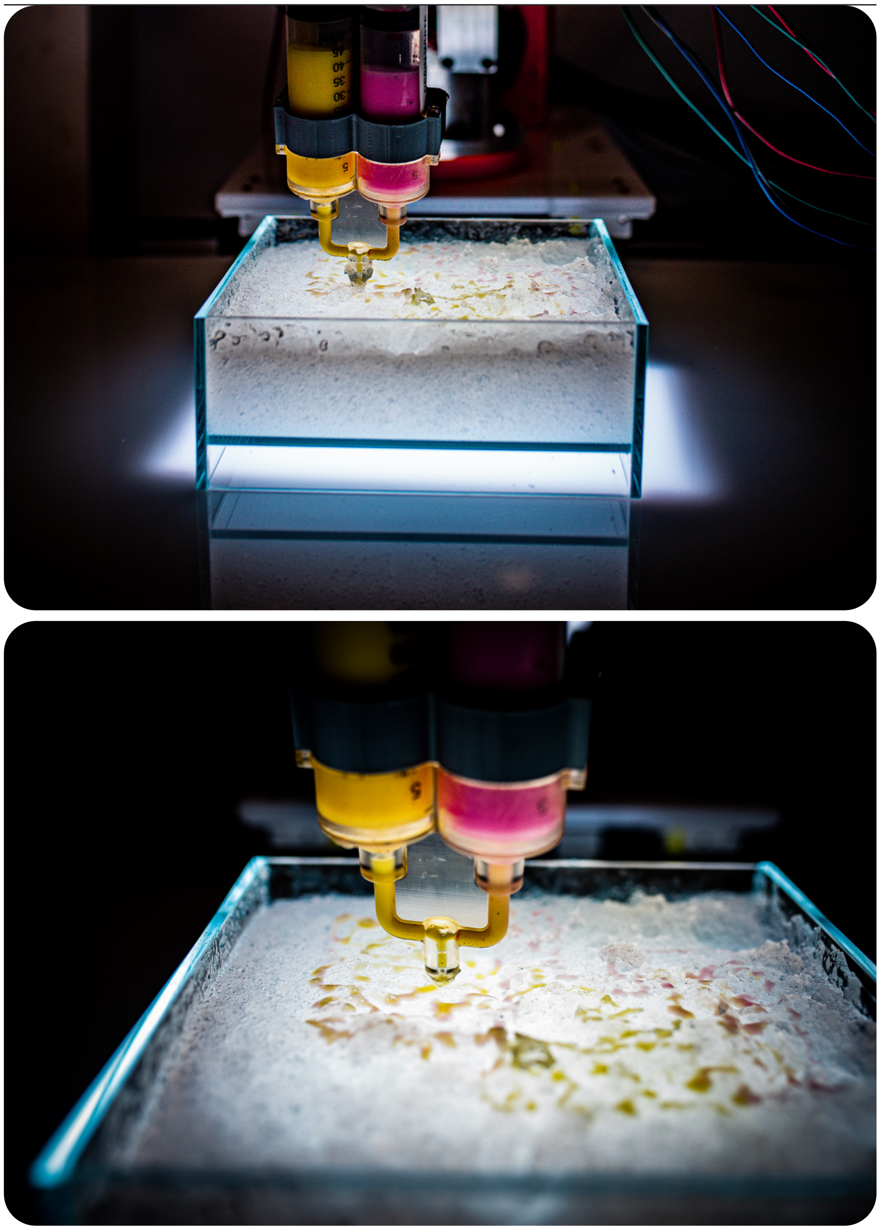

Figure 163 (continuation)
Alchemic free printing
Source: author

applications for manufacturing that resembles the use of similar applications in VR setups such as the work I developed in 2015 called 'from VR to 3D print'[503] (figure 165 and figure 166) or the more contemporary comercial apps such as 'Gravity sketch.'[504]

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[503] From VR to 3d Print. International workshop taught at FAB 12 conference in Shenzhen, China 2016.

[504] https://www.gravitysketch.com/

Figure 164
Alchemic free printing
Source: author

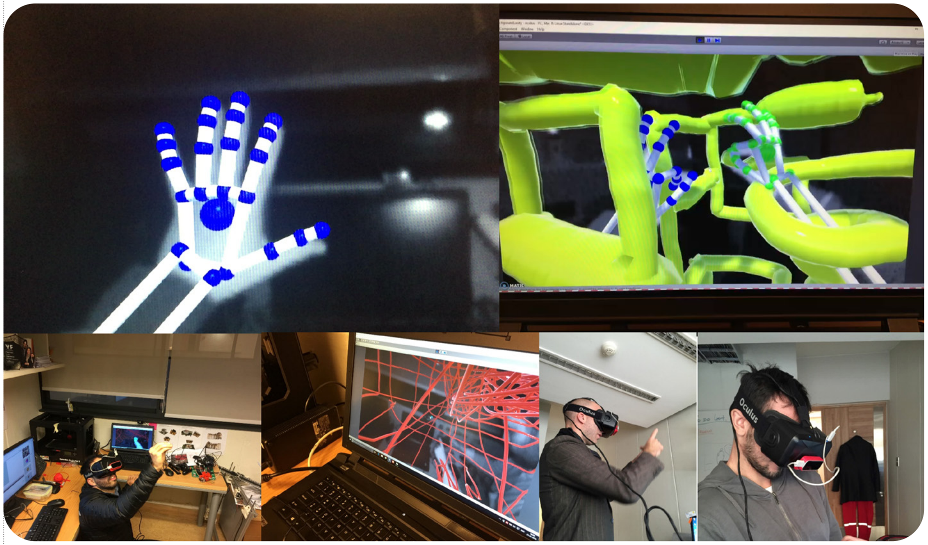

Figure 165
From VR to 3D print (2015-2016)
Shenzhen, China.
Source: author

Figure 166From VR to 3D print (2015-2016)
Shenzhen, China.
Source: author

5.11 Conclusions and future work

In this chapter, I delved into the notion of designing as making in the light of physical and material processes, expanding the findings of chapter 5. I discussed how the elaboration of action plans involves creating open-ended procedures that allow designers to engage in free performances to explore, think and generate new things and knowledge. Furthermore, based on Suchman's foundational theories of situated action, I present my approach to Making as the ultimate way of designing.

I elaborate on the discussion around the relevance of materiality and the transition from a traditional design process based on representations to one focused on the performative aspects of making. I probed into the indexical nature of making that considers the qualities bundled in any object vary in terms of their salience, value, utility, and relevance across different contexts, giving each object the potential to resemble something different each time we attend to it. In that regard, I elaborate on how the semiotic character of material things implies that their outcome is not determined, but their semiotic orientation points towards their unrealized future potential.

Building on top of the 'deep enactions' project presented in chapter 4, I presented the Computational Gestural Framework as a way to establish a path to embrace interactivity through language development. I argued that instead of elaborating representations of a design idea, elaborating action plans can embrace effective communication as a system for real-time interactions between a designer and a machine. Moreover, elaborating templates or guidelines for action emerges as a path for enabling human-machine interaction and the use of technology beyond mere efficient production, engaging participants into a computational process as a collective endeavor. In the case of this dissertation, the collective is considered not as a collective of one or more humans using tools, but as humans, tools and material things interacting collectively. In that sense, I argued that moving from traditional interactivity toward conversation, promotes computational design processes in which tools become devices for thinking while setting a fertile field for exploration and divergent thinking for solving problems and expanding them toward new questions and perspectives.

Before applying the Computational gestural framework, I introduced two experiences as an educator as concrete approaches to materiality and making from a computational perspective inspired by shape and making grammars. These experiences represent the work developed during the last eight years as an academic instructor that helped the author build the foundational characteristics behind the Computational Gesture-Making framework. Developing a pedagogical framework for computational design called "Discrete Heuristics" helped me shed light on how to tackle the development of interactive fabrication systems beyond the computational design trichotomy. I presented the experiences using this framework in pedagogical scenarios as an approximation to material and physical computation that can be applied to human-machine interaction applications. That's how the experiences derived from the Discrete heuristics studio and the Making ingredients studio presented are used to reflect on the elaboration and design of processes for Making in which the outcomes are envisaged as potential outcomes that can mutate and transform as we go.

Finally, I showed the application of the Computational Gestural Making framework by replicating most of the tests presented in chapter 4. I showed the results derived from the incremental application of the different modules of the framework toward effective communication and computation between A designer/maker and a robot. As applied in this dissertation, the system enables real-time collaboration with many potential applications in making scenarios. I showed working examples that, if applied to design and making, could expand design problems and generate new knowledge and 'ways of making' derived from the unexpected nature of computing as a holistic endeavor considering the environment's concurrent, temporal, and contingency.

As future work, I aim to continue the development of the alchemic printing project. One of the challenges and paths to continue this work is on the calibration of material distributions from gestures to develop a new multimaterial extruder and refine the P-REP code generator capable of adapting to the temporal characteristics of the alchemic printing.

6

CONTRIBUTIONS AND CONCLUSION

6.1 Contributions

6.1.1 Building a vision

I asked, *can computation based on gestures provide the means to establish a framework for interaction between humans, machines, and materials and, at the same time, reframe the way we design, make, and think through technology?*
I answered, yes!

I also asked, *what computation is needed to establish methodologies that facilitate the interaction between a designer, tools, and materials so that thinking and making are merged and inseparable?*

I answered this question by developing the Computational Gestural Making framework from a scientific and theoretical standpoint. I found myself calibrating the development of this dissertation to find a middle ground in which the theoretical discussion arises as a strong statement toward the definition of making as an embodied thinking process and the scientific approach as the technical application of a multimodal methodology to facilitate the integration of thinking and making through technology.

The task of summarizing the contributions of this thesis is multifaceted. The content of this dissertation and its contributions span a range of topics that are closely and sometimes indirectly related to the field of Design and Computation. These contributions resulted from a transformative journey of personal and professional growth that spanned over a decade. Throughout my time in the Design and Computation group, I had the opportunity to explore and expand upon the questions that have fueled my curiosity since I first became an architect. This pursuit necessitated extensive exploration and self-improvement, drawing upon various disciplines, including cognitive science, philosophy, robotics, computer science, and anthropology, to develop and support my unique vision for Design and Computation.

This dissertation seeks to make dual contributions. Firstly, it endeavors to contribute to the field of Computational Design by constructing a theoretical framework that it's situated at the confluence of technology and design. The central focus of this framework is on the role and significance of creativity in the making process. Secondly, this dissertation aims to establish a technical framework that facilitates the emergence of interactive computational processes. Such processes foster continuous and seamless collaboration between humans, machines, and materials to generate personal and original work that can potentially yield new design knowledge.

More specifically, this dissertation seeks to push the boundaries of research in the fields of Computational Design and Digital Fabrication. It proposes the development of body-centric interactive fabrication processes that utilize artificial intelligence, fabrication machines, and digital tools to facilitate the design and creation of novel artifacts.

With each chapter's development, I incrementally built upon the knowledge and work that arose from applied research and its associated papers. Through this approach, I sought to demonstrate the potential relevance of 'Computational Gestural Making' as an innovative paradigm that explores the creative potential of the human hand and its ability to imbue designs with uniqueness within a material context. This paradigm shift challenges the traditional design workflows that rely on a computational design trichotomy, offering a new technical paradigm that critically leverages computation as a collective, concurrent, and contingent endeavor.

6.1.2 Theoretical contributions.

6.1.2.1 Beyond the trichotomic approach to Design.

I started this dissertation by discussing the concept of what I called a trichotomy between ideas, representation, and execution. Furthermore, this dissertation was structured around those three components of the trichotomy that allowed me to expand and introduce a discussion around the relationship between design and technology. From this discussion, I unveiled important concepts to frame the role of technology in the intellectual development of a design. In that regard, the general discourse and enthusiasm around technological implementations, although targeting the implications of it in terms of creative augmentation, seems to remain entrenched within the limits of the trichotomy as prescriptive or analytical devices. The discussion allowed me to unveil a different perspective on technological implementations in design, to set a stream of thought focusing on computation as an integrated, contingent, and concurrent process to leverage knowledge toward novelty production.

By looking at design and making through the lens of other domains and disciplines, I built a theoretical framework that locates computers, humans, and materials within a design context that includes a big part of the equation to make new things using computation. Furthermore, I reframed the role of representation as the bridge between ideas and matter as discretized components of a ‘design workflow,’ identifying the challenges and opportunities to propose a computational framework that frames making as a definitive way of designing in which representations are considered as stable configurations that are the by-product derived from the enaction of generic plans for action, instead of frozen imagery toward potential future realities. Finally, the contributions from the theoretical discussion allowed me to identify crucial insights about the relationship between computation and creativity, not directed to define what creativity is but where it should be located.

6.1.2.2 Situating creativity.

Although creativity is a word or concept whose definition remains elusive, it is constantly used in computational design discourses as one of its leading associations concerns the generation of novelty, originality, and innovation in the light of whatever ‘new technology’ is adopted by designers. Incorporating the insights of physicist David Bohm, I introduced the notion that creativity is a catalyst for originality, marked by the emergence of novel patterns that extend beyond mere observation into the realm of experience. Rather than attempting to define creativity, I sought to explore its placement within computational processes. This inquiry challenged the conventional view of creativity as originating solely in the mind and the early stages of design. Instead, I proposed that creativity arises from experience, serving as a generative force that expands and spreads throughout the whole act of making as we engage with and compute our surroundings.

6.1.2.3. Interactiveness

This said, I render the nature of computation as the act of ‘putting things in order’ and the ‘togetherness’ of calculating as a collective endeavor. I argued that reframing computational design as the enabler of novel and emergent interactions between humans, machines, and materials can foster creativity throughout the entire design and making process to deliver the answers to capture ‘the unique’ to generate ‘the novel.’ I posit that the way the agents involved in computational design processes interact is needed to establish design as a contingent collective endeavor within a design context.

I focused the discussion on addressing the development of a new computational design framework based on interactivity. From this discussion, I identified and built the conceptual arguments behind interactivity, such as addressing the effective communication between two or more entities and establishing a language of mutual understanding and meaningful (intelligent) exchange of information. I established the Computational Gestural Making Framework as a cybernetic system. From a constructivist and cybernetic perspective, I focused on the importance of considering design tools as non-trivial machines as inherently conversational devices due to their recursive and circular nature. I argued that recursiveness allows us to reach stability. In that regard, I posit that stability can be related to meaning-making in the sense that in the myriad ways we can interact with our surrounding environment, we make sense of things by reaching stable perceptions of objects every time we attend to them. Directing the conversation toward the interactive nature of design and how the development of digital tools as conversational systems can embrace computation as a contingent process constitutes a contribution to the field of computational design.

6.1.2.4. Beyond the visual, the importance of gestures as a design language.

Although it is possible to summarize several projects that embraced interactivity from different areas, such as architecture[505], computer science,[506] or design/art[507], the development of a deeper discussion about the implications of the implementations of such interactive systems that transcend making robots more accessible and easier to use, making robots more efficient to empower non-designers, or to making robots more inclusive, is needed. By this, I refer to the development of a discussion that definitely puts and repurposes the relationship designers have with technology to generate new knowledge. In that regard, this thesis contributes from an intellectual point of view to the identification of a global perspective about interactive systems for design and fabrication, as well as providing a more in-depth understanding of how to tackle such interaction by focusing on the critical elements involved in those interactions. By this, I refer to the problems such as the interface, the language, and the actual performance carried out in a computation.

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[505] Garcia del Castillo Lopez, Jose Luis. “Enactive Robotics: An Action-State Model for Concurrent Machine Control.” PhD diss., 2019.

[506] Peng, Huaishu, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. “RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer.” In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–12. CHI ’18. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3173574.3174153.

[507] Gannon, Madeline. “Human-centered Interfaces for autonomous fabrication machines.” (2017).

I expanded the discussion initiated in my research on gestural making from 2013, focusing on the technical elements to improve communication with machines and establish a way to perform effective, meaningful communication with digital fabrication tools. Key to this discussion was a focus on the idea of gestures as the vessel for meaningful communication. I discussed and contributed to the discussion about gestural enaction for design by discussing the nature of different types of gestures, and their potential uses to converse with machines. By developing a multimodal approach to interactive systems supported by artificial intelligence, I was able to elevate the discussion focused on the elements that need to be integrated to foster, beyond technicalities, a true computational system for making. This dissertation contributes to the discussion by presenting a global and in-detail perspective on embracing interactive making to foster the cognitive aspects of design using an inherently unique mechanism: our gestures. Beyond discussions about precision, I advocated through the discussion for the adoption of interactive making as a process to make mistakes, be imprecise, be dumb, be naive, and learn from ourselves.

6.1.3 Technical contributions.

My research made several contributions that hold the potential for designers, fabricators, and those interested in exploration through design and Computation. As a computational designer, I navigated an ocean of knowledge outside design, integrating it into my practice and building my vision.

6.1.3.1 Computational Gestural Making Framework: A multimodal approach to computational design.

One of this research's most important technical contributions is the multimodal approach to computational design and making. I built upon recent developments and techniques in Machine Learning to leverage the use of technology as an active component of thinking. I built the Computational Gestural Making framework developing a modular REST API to connect all the pieces of a complex puzzle that involved gesture recognition, object and pose detection, Path planning, reinforcement learning, and path optimization. The CGMf results from years of research that has been compiled into a full-fledged flexible system that is modular, fast, and easy to deploy. Beyond the use of machine learning models and algorithms used by others (such as Google's mediapipe), I contributed to integrating such models into a robust platform, requiring re-training, hacking, and repurposing existing machine learning techniques into a design environment. I developed interfaces (NNN) to use machine learning models interactively and seamlessly. I developed Grasshopper tools to integrate the CGMf into Grasshopper for Rhino3D, I will make available for users as a plugin.

6.1.3.2 Interactive making.

I developed an inverse kinematic implementation to cope with real-time performance. As described in chapter 4, starting from an open-source robotic arm as a general-purpose fabrication tool, I developed the firmware and software necessary to integrate it into the CGMf. I implemented all the software in python and C# to connect the robot controller to the CGMf and perform the instructions computed by the Robot Motion system module, including developing my own path planning algorithms and implementing Reinforcement learning as I described in chapters 4 and 5.

6.1.4 Pedagogical contributions.

I’ve been an educator for 15 years, pushing computational design and fabrication methodologies inside architecture and design curriculums. In the case of this dissertation, I had the opportunity to develop a particular vision about Making and Designing that expands computational making. I had the opportunity to share the knowledge gained during the last 10 years through several workshops, seminars, studios, and also through a YouTube channel, I started to support students with Computational Design literacy during the pandemic times. Sharing the knowledge I gained during my Ph.D. journey represented an opportunity to nurture my research and lay the foundations supporting the implementation of the CGMf.

That said and beyond a biographical description of my journey as an educator, it is important to remark how the development of an curriculum for teaching design studios based on the phenemenological aspects of making focusing on understanding the emergent properties derived from the interaction between humans, machines, and materials engenders alternative ways of producing design knowledge. The work presented from the *discrete heuristics* and *making ingredients* studios are examples of novel ways of learning based on making focused on the production of personal knowledge beyond representations in which the developments of plans for action can drive unique authored work.

6.1.4.1. Discrete heuristics as a model for computational making.

I developed Discrete Heuristics as a pedagogical model for computational making that I used to test the intellectual concerns behind this research. I tested this framework as an instructor at Adolfo Ibañez University in Chile (Discrete Heuristics Studio, 2016, 2017, 2018) and as an instructor here at MIT (Making Ingredients option studio, 2021). The teaching experience gained from applying the Discrete Heuristic framework inside design studios allowed me to develop a novel computational-making approach beyond representations that contributes to the design and computation field in academic environments.

6.5 Conclusion

Beyond the partial conclusions that are presented at the end of each chapter, this research work, like any other design exploration, is by no means complete or definitive in its findings. I have endeavored to construct my vision by broadening the discussion on computation and technology, focusing on aspects that are often impractical and challenging to scale to real-life scenarios. The design field is not exempt from the allure and urge to make everything smart, intelligent, automated, fast, optimized, and precise. In this context, my dissertation is not detached from that specific debate or trend. Moreover, I adopted Machine Learning and robotics in a particular way in this thesis. I wanted to make things wrong and find where things could break and hit all the possible walls I could hit. My approach involved detaching myself from the traditional excitement of using new technologies in design and venturing into territories that are frequently challenging to explore, which tend to be overlooked in conversations and debates concerning technology and design. Nevertheless, the conclusions drawn from this investigation can be subject to scrutiny from various perspectives regarding the degree of usefulness, effectiveness, and feasibility of what I have formulated. In regard of the work (both theoretical and technical) presented in this dissertation, specifically the proposition of the Computational Gestural Making framework.

Does it work? Yes.

Is it useful? It depends on specific case-to-case applications related to scale or final goal. In the current state of development, the Computational Gestural Making framework gives designers the possibility to generate alternative workflows and pipelines to explore freely ideas while making them. However, if the implementetion and use is oriented toward construction of precise manufacturing, considerable work is needed.

Is it relevant? Definitely.

Technology, especially Machine learning, advances at a pace that is impossible to cope with. Therefore, I needed to look from a distance, go outside my comfort zone, and adopt a critical perspective on what we do as computational designers with the avalanche of emerging methods and tools. I would argue that what I developed during five years is yet another step of a more significant journey that will continue in the upcoming years. I can explicitly address any potential criticisms of my work by affirming that achieving usefulness was not the sole objective. Rather, I viewed this research primarily as a statement and as an expression of immense potential for individuals who are enthusiastic about technology and driven to create. I am confident that, similarly to what happened with my work in 'Making gestures' in 2015, this will inspire more work along the same lines. I wrote this dissertation because I think design is active, open-ended, continuous, and about finding new questions. All the work produced over the past five years talks about that and, as an invitation, aims to give directions to future readers toward embracing the aspects that make Design a unique and intellectual discipline, which, beyond gadgetry and sophisticated toys, allows us to produce new knowledge by embracing our 'designerly,' tacit, and unique skillful ways of thinking through making.

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