TOWARDS AN INTEGRATED DESIGN-MAKING APPROACH IN ARCHITECTURAL ROBOTICS

A Thesis in Architecture by Ardavan Bidgoli
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The thesis of Ardavan Bidgoli was reviewed and approved* by the following:

Daniel Cardoso Llach
Assistant Professor of Architecture
Thesis Adviser

Loukas Kalisperis
Professor of Architecture

Darla Lindberg
Professor of Architecture

Ute Poerschke
Director of Graduate Studies in Architecture

*Signatures are on file in the Graduate School
Abstract

Using industrial robots in creative design has generated a wide interest among designers, artists, and architects. While generic, combined with custom or task-specific mounted tools and digital descriptions, these machines have recently become the vehicle of creative explorations in design, architecture, and the arts. Even though numerous researchers and practitioners have proposed applications of robotics in architectural practice, this field is still in its infancy and thus needs more exploration by design and architectural researchers.

In this thesis, I have investigated the architectural robotics opportunities by reviewing its design space and characteristics in academia and practice. It resulted in a hypothesis stating that currently available software toolboxes are not sufficient mediums between architects and robots. Accordingly, we need a medium to embed all the constraints that affect a specific robotic system, its mounted tool, and related material system, from early stages of design to materialization.

To test this hypothesis, I proposed an analytical grammar to codify spatial design, form finding process, and robotic fabrication behavior through visual computation and
algorithmic approaches. The system affordances were later studied through physical prototypes.

**Keywords:**

Thesis Supervisor:

**Daniel Cardoso Llach**
Title: Assistant Professor of Architecture
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Chapter 1 | Introduction

Cedrick Price once said: “Technology is the Solution, but what is the Question?”

John Frazer once said: “Computing is the Solution, but what is the Question?”

I am wondering, if Robotics is the Solution, what is the Question?

1-1. Problem Statement

Using industrial robots in creative design has generated wide interest among designers, artists, and architects. These machines have fascinated designers by their human-like behavior, flexibility, and being capable of actuating designated commands with high levels of precision. These generic machines, combined with custom or task-specific mounted tools and digital descriptions, have recently become the vehicle of creative explorations in design, architecture, and the arts.3 & 4

1 (Reichert et al. 2014), (Willmann et al. 2013), (McGee, de Leon, and Willette 2014)
2 (Johannes Braumann and Brell-Cokcan 2012)
3 (Gramazio, Kohler, and Willmann 2014), (Budig, Lin, and Petrovic 2014), (Gramazio and Kohler 2008)
4 Braumann and Brell-Cokcan called robots “…ideal tools for architectural design” while mentioning robots’ lower cost, larger physical work span and inherent multi-functionality.
1-1-1. Obstacles
Despite the increasing interest in architectural robotics, obstacles against its widespread implementation are abundant. Robots force designers to interact with the real 3D environment that profoundly challenges their conception of the geometric world, rendering their understanding of Computer Graphics’ virtual 3D representation obsolete.5 While designers have already mastered Cartesian coordinates to command most 3d modeling packages, laser cutters, and three axes CNC machines, robotic control combine transformation matrices with six values to codify their end-effector’s position and orientation. Accordingly, they can be considered as non-Cartesian machines. Robotic control requires highly-skilled users to overcome “...the uncertainty between control (action) and movement (reaction) of robots”, which crucially depends on a robust notion of robotic kinematics.6 Meanwhile, mainstream CAD packages suffer from the lack of native robotic programming functionality support, which is critical for planning and managing any robotic fabrication process.7 Producing control data in robots' native programming languages urges adding programming to designers' repository of skills.8

Additionally, adapting architectural robotics with real world construction context is a robust barrier. Industrial robots are designed to work in secluded cells in 100% predictable and neatly tuned work spaces, protected from users who may interfere with their agile and programmed movements. Construction sites are on the opposite side of the work environment spectrum.

Finally, execution-time errors including reachability, singularity, and (self) collisions are inevitable due to the variation of design solutions. Handling all these matters requires the presence of users to work with the robot

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5 (Picon 2014)
6 (Johannes Braumann and Brell-Cokcan 2012)
7 (Jason Lim, Fabio Gramazio 2013)
8 (Budig, Lim, and Petrovic 2014)
simultaneously, observing unpredicted motions, removing waste materials and feed raw ones while constantly checking the tools and dressing packs. Therefore, behind the scene of every robotic installation, there is an army of operators dancing with the robots to handle material, watch the mounted tool(s) and manage real-time parameters. The irony is bold, robotics promotes construction automation, but at the very same time it critically relies on well-experienced and highly educated users to handle its basic needs.

1-1-2. Current Approach
Addressing these issues, several software packages have sought to facilitate the incorporation of robots into design workflows. KUKA | PRC and HAL are among the most successful representatives of this movement by providing interfaces that help designers orchestrate robotic procedures while developing design solution. These two software packages were built on top of Grasshopper, a visual programming environment in Rhinoceros, an NURBS modeling software for Windows, to simulate the robot behavior in off-line mode. The combination of off-line simulation and visual programming proved itself as a robust generic toolbox for architectural robotic studies, reflecting its contributions to the discourse in several research projects and papers since their advent. These packages have helped designers to overcome technical issues that may interfere with compiling algorithmic definitions into robots’ executable codes. However, they are merely all-purpose compilers that can translate algorithmic definitions into a series of sequential motions and reduce technical difficulties.

1-1-3. The Gap
Even though numerous researchers and practitioners have dedicated their efforts to explore architectural robotics,

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9 I borrowed the term “Dance” from Kate Davis’ “Raven: Robotic Field Operations” (Davies 2015). She referred to the robot’s reaction into the external unknown environment as the poetic of robotics, an act of chirography. I used the term to address the two-way interaction of users and robots, which at least in the early steps is unknown for both sides.

10 (J Braumann and Brell-Cokcan 2011)
11 (Johannes Braumann and Brell-Cokcan 2012), (Schwartz 2013)
12 (McGee, de Leon, and Willette 2014)
many of them have indicated a barrier that prevented them from further development; the lack of sufficient mediums to communicate and control robots.

Currently available toolboxes act as a platform that every researcher should build its own medium on top of that. However, in many cases these mediums fail to make a dialogue between the robot and design process, making robots an end-effector rather than an active part of design process.

1-2. Research Structure
This research aims to address this gap, to reach this goal I organized the research activities as below:

1-2-1. Research Questions
My research questions is:

How can an analytical rule-based design method help changing robots' role from an end-effector to an active part of the design process?

1-2-2. Hypothesis
While software toolboxes that were introduced in section 1-1-2 are playing a pivotal role by enhancing the architectural robotics workflow, they are not sufficient to explore this new realm. An ideal medium should embed all the constraints that affect a specific RTM from early stages of design to materialization.

1-2-3. Research Scope and aim
This research is focused on the industrial robotic arms' applications in the field of digital fabrication and will not address other digital fabrication methods, neither other types of robotic systems.

Moreover, it is concentrated on the integration of design process and the robot, accordingly further studies on the optimization, structural analyzes, and fabrication design is not the main subject of focus in this thesis. Meanwhile, any of these issues might be partially elaborated during the research as a vehicle to achieve defined goals.
These limitations are inevitable since architectural robotics is a multi-disciplinary and fast growing field that has roots in diverse disciplines including industrial engineering, computer science, and architecture.

Based on different mounted tools and exploited materials, different grammars with a variety of design spaces can be developed to facilitate the dialogue between human, robot, and material system. Among the pool of possibilities, I have selected hot wire cutting technique using architectural-grade EPS foam. Benefits, advantages, limitations, and other reasons behind this decision will be discussed and tested in methodology chapter.

1-2-4. Methodology
I tested the validity of the hypothesis through a) reviewing the background of robotics in architecture, b) Investigating the robotic manipulation fundamentals, c) Developing a Robot-Tool-Material system, d) Developing a computational rule-based analytical system to address design process and fabrication based upon RTM (robot-tool-material system) characteristics, e) Fabricating small scale besides an architectural-level model by means of that system, and f) analyzing the procedure. Figure 1 depicts these steps and their relationship to the overall research structure.
1-2-5. Intended Contribution
This thesis aims to make the following contributions:

1- It defines a new approach towards the application of robotics in architecture, based on robot, mounted tool and material system characteristics.
2- It proposes a system that helps designers take the command over design-making in architectural robotic procedures.
3- It proposes a rule-based computational system for robotic hot wire cutting.
4- An architectural-scale installation to test the capabilities of the proposed system.

1-2-6. Thesis Organization
This thesis is organized into seven chapters as described below:

In chapter one, I explained the problem and framed the question. Chapter two is dedicated to reviewing the architectural robotics background in depth. In chapter three the hypothesis will be discussed in detail. Including why it is crucial to apply an integrated approach and the advantages of grammatical approach towards robotics. Chapter four addresses the methods adopted to test the validity of the hypothesis. Chapter five explains the experiments and tests of the platform besides documentation of the architectural scale model. Chapter six covers the discussion and next steps.
Chapter 2 | Background

“Over the past decade, robotic fabrication in architecture has succeeded where early digital architecture failed: in the synthesis of the immaterial logic of computers and the material reality of architecture where the direct reciprocity of digital designs and full-scale architectural production is enabled.”

Fabio Gramazio, Mathias Kohler

Figure 2 - Milestones of industrial robotics, 1950s-1970s

It took around only twenty years to develop the earliest CNC machines into sophisticated five-axis arms that we generally categorize as industrial robots.

13 (Gramazio, Kohler, and Willmann 2014)

14 During world war II, U. S. Air force heavily invested on advanced technologies to boost efficiency and accuracy of aircraft manufacturing technologies. Aftershocks of this wave turned last years of 1940’s into an astonishing era for what we nowadays know as digital fabrication. During that period, John T. Parsons and Frank L. Stulen were awarded a contract to manufacture sophisticated rotary wings for military helicopters by driving a milling machine using punch cards. Parson initially hired IBM and MIT among the sub-
Early robots\textsuperscript{15} first introduced to industrial manufacturing through the efforts of George C. Devol and Joseph Engelberger in the 1950s and early 1960s. They were both sci-fi fans and exceptionally skilled in cutting edge technologies of the era. By 1954, Devol registered his basic ideas about a programmable manipulator as US2988237 patent called “Programmed Article Transfer,” which became the ground for future industrial robotics.\textsuperscript{16} Devol and Engelberger established and grew Unimation Inc. after meeting each other on 1956, to share their enthusiasm for robotics. In the same year, they began the robotics’ market studies by visiting 15 automotive assembly plants and 20 other different manufacturing facilities. They anticipated the demand for such service in the post-war industry to replace human workers in the subhuman working conditions. They were already familiar with the technological prerequisites, largely due to Devol’s background in the WWII era radar and counter radar manufacturing, where he gained comprehensive knowledge about aerospace technology and electronics. Servo-Mechanism, digital computation and finally solid state electronics were three cutting-edge technologies that they needed for the robot. Finally, they were funded by industrial giants including Condec Corporation and Pullman Inc. These three elements (finding the need, mastering the necessary knowledge and having access to

\textsuperscript{15}The word “Robot”, borrowed from sci-fi world, was first coined by Czech writer, K. Čapek for his play ‘Rossum’s Universal Robots’, or simply “R.U.R.”, around 1920. It was derived from the word Robota, which means forced labor in Czech language. (Oxford dictionary n.d.)

\textsuperscript{16}(Nof 1999)
financial resources) paved them the way towards success.

By 1959, they have their first working robot. In a historical photo, the first prototype of Unimate is shown while serving them with a cocktail. Two years later, the project was developed enough to be installed in one of the targeted factories. The first commercially successful robotic application in the industry was a hot die casting machine at a GM plant in Trenton, New Jersey, 1961.\textsuperscript{18} It was powered hydraulically, controlled by a digital control system, paired with a magnetic drum memory and a discrete solid-state control component.\textsuperscript{19} Other companies had imitated this configuration for decades. Unimation rapidly grew its robotic market towards welding and other application after this achievement.

By 1970, hydraulic robots were commonplace in automated paint shops in numerous factories. However, it was in 1973 that ABB\textsuperscript{20} introduced the distinctive IRB-6, the first serially-produced robot with all-electric motors and an Intel’s microcontroller for programming and controlling motions.\textsuperscript{21} With 5-axis, human-like arm, and remarkable orange coating, this robot is the ancestor of the ones we use in architecture today. During 17 years of production, ABB sold over 19000 units of IRB 6, as a symbol of a new era in the labor market. As of now, industrial robots are extensively being used in mass production lines in different sections of industry. However, “most applications of robotics remain similar to what robotics offered six decades ago, namely Programmed Article Transfer.”\textsuperscript{22}

\textsuperscript{17} (Naboni and Paoletti 2015)  
\textsuperscript{18} (Hägele, Nilsson, and Pires 2008)  
\textsuperscript{19} (Malone 2011)  
\textsuperscript{20} This robot was initially marketed under ASEA brand, which was later merged with Brown, Boveri & Cie to form ASEA Brown Boveri or A.B.B. group.  
\textsuperscript{21} (Roy 2014)  
\textsuperscript{22} (Morel 2014)
2-1. Robots in Architecture

While robots were dominating mass production lines one after each other, it is hard to find any evidence of their application in AEC industry until late 1980’s, when construction companies in Japan tried to test their performance in mass construction. Even though their progress was cumbersome and painfully slow, they are among the pioneers of architectural robotics in their period, paving the way for the second wave of robotics in architecture that happened in early 2000’s. This new movement sought for mass-customization and complexity, in contrast with the previous movements.

2-1-1. Season One: Construction Automation Approach (the 1980s and 1990s)

By the end of 80’s, several Japanese construction companies invested on using custom-made robots in construction sites for various functions, including finishing concrete slabs and painting façades. (Figure 4) These experiments were following the concept of on-site mass construction by robots. In Japan, automated construction was of high demand to reduce dependency on construction workers, increasing the productivity, optimizing

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23 Images from (Bock and Langenberg 2014) & (Gramazio, Kohler, and Willmann 2014)
24 Architecture, Engineering and Construction
25 The term Mass-Customization was coined in 1987 by Stanley Davis in his book titled “Future Perfect”. (Davis 1997)
building process and improving site safety. However, their machines were highly specialized, extremely expensive, and suffered from the lack of flexibility. Accordingly, after a while they proved to be inefficient and unable to satisfy their initial goals. Among those companies who were investing in automated robotic construction, including Fujita Corp., Obayashi Corp., Kajima Corp. and others, no one was actively using them by mid-2000's anymore.

Figure 4 - Japanese robots in architecture during the 1980s & 1990s

In 1992, Thomas Bock used a 5-axis robot for on-site brick assembly in Germany. Despite the fact that this project was also exploring the on-site automation, the use of generic industrial robot was a turning point that could help construction companies overcome the hardship of developing customized robots. (Figure 3, left)

However, it took until early 2000, when two major evolutions happened in robotics and architecture to reinvent architectural robotic. First, the significant drop in the costs and expenses of robotic tools. Second, the wind of a major paradigm shift that stormed architecture discourse.

2-1-2. Season two: Industrial robots and the quest of complexity (post-2000s)

At the turn of the millennium, the attitude towards robotics in architecture met the shift in the paradigms of architecture. The tide of computational movement, besides rapid integration of computer controlled machinery in architectural research projects, significantly steered the direction of robotics exploration in architecture.

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26 (Bechthold and King 2013)
27 (Gramazio, Kohler, and Willmann 2014)
28 (Bechthold and King 2013)
29 (Bock and Langenberg 2014)
30 Ibid.
In such new environment, robotic was considered as a new vehicle to push the limits:

... Robotic technologies in combination with computational design techniques liberate this widespread building typology from the limitations of a serial production paradigm.  

Digital design as a constructed relationship between information and complex forms thoroughly changed the way designers used to design objects. Digital design gave designers freedom to shift their task from designing artifacts into creating the production process that generate instances of the design procedure. This approach let them integrate more complex and multifaceted information into the design process. Designers well adopted this paradigm in late 1990's and early 2000's since the required technologies were advanced enough, CAD software packages were in reach, and processing power was abundant and cheap. These factors convinced architectural firms to take the risk and enter the field, spreading the range of digital design from academia to professional practice.

However, the complexity of the design solutions was beyond the borders of conventional construction methods, demanding for matching techniques to this ever increasing level of complexity. Digitally controlled manufacturing systems were the corresponding solution:

The gap between what it is digitally possible to design and what is physically feasible to build narrowed when throughout the early 2000s CNC machines became more commonly available and eventually enabled designers and architects to bring their designs back from the virtual medium into the physical world.

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31 (Budig, Lim, and Petrovic 2014)
32 (Sass and Oxman 2006)
33 (Gramazio and Kohler 2008)
34 (Menges 2012)
35 However, the idea of mass-customization by exploiting the electronically controlled production systems had already been discussed by M. McLuhan as early as 1969: “once electronically controlled production has been perfected, it will be practically just as easy and affordable to produce a million different objects as to create a million copies of the same object.” (Sass and Oxman 2006)
36 (Hack and Lauer 2014)
While the majority of CNC machines were tailored for a definite set of tasks, the generic nature of industrial robots gave them the privilege to be adapted for diverse demands in architecture context. However, it took more than a decade to see them in action while a variety of other types of CNC machines has extensively been used.

In the mid-2000s, Switzerland-based architects and professors Gramazio and Kohler took the lead of an advanced research cluster at ETH, Zurich, which was thoroughly dedicated to architecture and digital fabrication. They were the first multipurpose fabrication lab in architecture which used an industrial robot in 2005, followed by Harvard Robotic Environment in 2007. This new blood hyped a vigorous movement in architectural robotics, mostly known for its focus on broadening the scope of design, often through highly complex experimental aggregations and installations. 2008 Venice Biennale project by Gramazio and Kohler, followed by their flight assembled architecture installation and R-OB fabrication unit project, among many others, were at the forefront of this movement by that time.

Gramazio and Kohler manifesto was shaped around the idea of Digital Materiality and bridging the gap between the immateriality of computationally driven design descriptions and real materiality of architecture. Taking advantage of robots, they sought for integration of construction and programming in the design process. In the second thought, it is derived from the old promise of digital fabrication culture, as it was framed by Sass and Oxman: “…bridge the gap between two currently separated entity of design environment and building information/construction data environment.” Gramazio and Kohler demonstrated this hypothesis in numerous cutting edge experiments, distinguished by their unique complex brick laying.

37 [Castle 2014]
38 [Bechthold and King 2013]
39 [Gramazio and Kohler 2008]
40 [Sass and Oxman 2006]
41 [Helm et al. 2014]
Since then the number of creative design experiments involving industrial robots grew dramatically. This rapid expansion of knowledge in the field encouraged scholars to organize a dedicated event for architectural robotics. Rob|Arch conferences was the response to this need. As a biennale, Rob|Arch was the beating heart of architectural robotics since 2012.

Meanwhile, robots gradually secured their place as an avant-garde research tool in architectural schools and research centers. As of March 2015, fifty-nine institutions (excluding Penn State) all around the world are indexed in the Robots in Architecture web page with at least one industrial robot installed. Some own more, like SCI-Arc, which decorated its sophisticated lab with six.\(^42\) They are located in five continent, where Europe and U.S. hosted the most.

Reviewing projects from different regions implies the existence of regional trends. In the west coast, a tendency towards visual opportunities of robots is tangible. UCLA collaboration with Bot&Dolly Move is one of the frontiers of this region. East coast studies are more focused on fabrication and material opportunities. Great names, spanning from CMU to MIT belong to this region. In Europe, the trend is mostly inclined towards robotic tectonics and less purely performative systems. Achim Menges’s experiments are well known as one of the leaders of architectural robotics in this region. However, due to Gramazio and Kohler’s influential works, some researchers use to call it Zurich-Style.\(^43\)

\(^{42}\) [Association for Robots in Architecture n.d.]
\(^{43}\) [Avis 2014]
2-1-3. Why Does Robotics Matter
Gramazio and Kohler described the importance of robotics in a series of academic publications in the past ten years. They believed in the industrial robots as a tool that architects should choose consciously and master it to create their customized design instruments and accordingly, generate diverse forms of expression. They claimed that by using architectural robotics, design culture will be “evolved both in expression and productive capacity”. They also argued that it will gradually affect the physis of architecture until eventually reframe society’s image of architecture. They extensively credited architectural robotics as a game changer and savior of digital architecture. In their 2014 article “Authoring Robotic Processes”, they expressed this idea:

Over the past decade, robotic fabrication in architecture has succeeded where early digital architecture failed: in the synthesis of the immaterial logic of computers and the material reality of architecture where the direct reciprocity of digital designs and full-scale architectural production is enabled.

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44 (Association for Robots in Architecture n.d.)
45 (Gramazio and Kohler 2008)
46 Ibid.
47 (Gramazio, Kohler, and Willmann 2014)
They described industrial robots as versatile, flexible, generic, cheap machines that are capable of showing a high level of “manual dexterity”. Exploiting these features, they draw a path to eliminate the division between intellectual work and manual production, between design and realization. 48

Architectural robotics can be the missing part of the seamless design-production cycle in architecture, a promise from the dawn of CAD. 49 In a procedural design process, robots’ contribution to materialization is undeniable. With the characteristics that were mentioned earlier, they can apply diversity and complexity to the artifacts beyond almost every other available technology. As Budlig and other stated, “Digital fabrication technology allows architects to conceive designs both digitally and physically” 50, they argued that such opportunity will let designers engage more actively in the construction and materialization. Architectural robotics can amplify such effect. Architectural robotics’ affordances distinguish it not only from conventional fabrication methods but also from mainstream digital fabrication systems in a variety of fields, including but not limited to:

**Flexibility:**
Robots can accept different tools for different purposes in adverse environments and switch between a task and another one in a reasonable time. This flexibility comes from two properties, being generic and ease of programming.

Being Generic: Industrial robots are designed to take the role in different industries. They are not tailored for a specific job. Universal connectors, industrial standards, and modularity make them the perfect host for a wide range of tools. From heavy industrial activity to entertainment, specialists have adapted their tools to be installed and manipulated with these robots. This is fundamentally in contrast to other fabrication tools like laser cutters, 3D

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48 (Gramazio, Kohler, and Willmann 2014) 
49 (Cardoso Llach 2015) However, Cardoso traced this long lasting promise of automated materialization back to the Renaissance. As he stated, the roots can be seen in Alberti’s skilled craftsman and later Coons’s Perfect Slave idea. 
50 (Budig, Lim, and Petrovic 2014)
printers, etc. An industrial robot can handle a camera, a torch, and a 3D printing tool and switch between them in a matter of seconds thanks to the available fast tool changing equipment.

Ease of programming: Major robot makers have developed their native programming languages during the past four decades. Those languages are the primary way to communicate with robots. Their rich libraries help designers to program the robot as the way they want and take command of the mounted tool.

**Accuracy:**
Once well calibrated, they actuate commands at industrial precision, a hundredth of mm.

**Large work span:**
However, they exist in smaller top table models with the working range of .5 meter, gigantic models like KUKA Titan series can cover up to 3.5 m in radius. Except large scale CNC machines, other digital fabrication tools rarely exceed this range.

Accordingly, taking advantage of industrial robots in architecture is inevitable, and it can be a potential vehicle for creative design in the future.

2-1-4. Current Approach towards Architectural Robotics

Reviewing the literature of architectural robotics signifies that researchers have explored the possible affordances of robotics in fabrication, design process and proposed novel approaches towards integrated design-making procedures. However, some researchers believe that current approaches towards robotics are obsessed with the industrial characteristics of robots and neglects their potentials in the design process. Daas states that “…a lion’s share of literature in the field is dedicated to Robots for fabrication.”

Lack of communication between design and making is another criticism that targeted these projects. Such one-way approach also lacks the back and forth design

---

51 (Daas 2014)
process, converting the robot from an active part of the design into an end-effector that only acts passively upon

<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILLING</td>
<td>Accurate, works for wide range of forms, generate fine details. Fast, silent, left overs of material is still usable, almost clean while working, perfect for making costume made components. Fast, in some cases, left overs of materials are still usable.</td>
</tr>
<tr>
<td>CUTTING</td>
<td>Useful when using components which can get together by melting down partially. Create some types of free forms in 3D. Hard to control, mostly used as a kind of welding. Mosty works by adding thin lines of material, takes too long when making complex volumes, hard to calculate the final relaxed form and defomarion after pouring material.</td>
</tr>
<tr>
<td>3D PRINT</td>
<td>For connecting metal objects, in pointing or in lines. Needs one or two other robots to keep the connecting objects in place. For joining wide range of materials. The same limitation for weldings apply here.</td>
</tr>
<tr>
<td>CASTING</td>
<td>Best for making free frame 3D forms. Needs a heavy collaboration among a team of robots, one machines and users. For steam bending of plywood, very hard to calculate final form of every elements. For heavy gripper, heavy frames or holders. For steam bending of plywood, very hard to calculate final form of every elements.</td>
</tr>
<tr>
<td>BENDING</td>
<td>For accurate forming of metal sheets, loud noise and super slow procedure. Good for free form making by resembling human hand form making. Good for folding in different direction and angles based upon die cut lines. Useful when using components which can get together by melting down partially.</td>
</tr>
<tr>
<td>INCENTIAL</td>
<td>Generate forms from available or costume made components, very use for large scale projects, can be combined with welding, gluing and etc. to put them in their exact position. Can be connected to computer vision and AI. Limited to specific type of form and setup.</td>
</tr>
<tr>
<td>PRESSING</td>
<td>For making drawings from available or generated graphic, especially in monochrome. For making graphic patterns. For drawing different graphics. For taking pictures in exact position and exact time. Spatially for stop motion and HDRI and merged picture. For generating super accurate movement in the video. For making image of moving object like glowing lines, making stop motions and.</td>
</tr>
</tbody>
</table>
design commands, limiting the opportunities of architectural robotics.52

Figure 6 illustrates a set of recent projects in this field, organized by their fabrication methods. However, researchers have proposed different taxonomy methods to setup a framework for architectural robotics categorization. 1) Manufacturing methods, 2) design paradigms, and 3) the possibility of performing the same job by human counterparts are among the factors that researchers selected as their criteria. 53 These systems are introduced and discussed further in appendix 2.

2-1-5. Case Studies
In this research, I used a set of criteria to select and organize case studies, by accentuating the importance of the architectural question, robotic offer, and proposed material system. Every project demonstrates different characteristics regarding its approach towards pushing the boundaries of both architecture and robotics disciplines. Researchers may contribute by using robots to address a challenging architectural question that has already been discussed in both academia and practice. A step forward, they can reframe existing questions in a new context, crossing boundaries by developing novel robotic solutions or using an existing robotic method to address a novel architectural possibility. Finally, by exploring the untouched sides of both discipline they can seek for the new affordances, constituting new demands and new means to satisfy them. This falls in the synergy field of architecture and robotics.

52 To elaborate this argument, one can think about a simple 3D printer, which drops melted material on the designated coordination in space. There is almost no communication between the 3D printer and design process, the printer is an end effector that reaches points in space. However, in a two way characteristics of robot, tool and material system can affect design outcomes in real-time or during design process through off-line simulation.
53 (Daas 2014), (Bechthold and King 2013), (Kelly 2012)
Accordingly, every project was studied from two points of view, the architectural one and the corresponding fabrication one, covering both robotics and material system. To evaluate, every side was compared with the existing literature to assess its novelty and contribution. In the review of case studies, this method is adopted to define the impact of every project on the development of discourse. This is not a system of categorization, since it doesn’t suggest a clear measure to distinguish between projects. Hence it will help us to compare them in a borderless range, addressing the gap I mentioned earlier in section 1-1-3.

Case studies presented here are selected from a larger pool of projects that have been explored in depth at the early stages of this research, a brief report of those studies is presented in appendix 3.

Every selected project may consist of a set of sub-projects that combined to form eventually a robust statement. Regarding the fact that they follow the same path, I bundled them as a single project. The criteria for project selection are illustrated in figure 8.
<table>
<thead>
<tr>
<th>Case Study</th>
<th>In-Situ Robotic Fabrication</th>
<th>Processes for an Architecture of Volume</th>
<th>Aggregated Structures</th>
<th>Fibrous Morphologies Integrative</th>
<th>Water-Based Robotic Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Bricklaying</td>
<td>Stereotomy</td>
<td>Aggregated Structures</td>
<td>Woven fiber structure</td>
<td>Sustainable Structure</td>
</tr>
<tr>
<td>#2</td>
<td>Pick and Place</td>
<td>Robot Band Saw</td>
<td>Pouring systems</td>
<td>Robotic Weaving</td>
<td>Robotic 3D printing</td>
</tr>
<tr>
<td></td>
<td>Existing Affordance</td>
<td>EPS/Concrete</td>
<td>Costume components</td>
<td>New Affordance</td>
<td>Carbon fiber</td>
</tr>
<tr>
<td></td>
<td>Brick</td>
<td>Existing Material</td>
<td>New Material</td>
<td>Carbon fiber</td>
<td>Water-based Bio-material</td>
</tr>
</tbody>
</table>

*Figure 8 - Case Studies Summary*
**Case #1: In-Situ Robotic Fabrication**

<table>
<thead>
<tr>
<th>Architectural Question</th>
<th>Robotic Offer</th>
<th>Material System Offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing [Bricklaying]</td>
<td>Existing [Pick and Plane]</td>
<td>Existing [Brick]</td>
</tr>
</tbody>
</table>

During mid-2000’s Fabio Gramazio and Mathias Kohler at ETH conducted a series of studies on self-standing brick structures by robotic arms. Their projects were highly praised especially after their 2008 Venice Biennale installation, Structural Oscillation.

![Figure 9 - ROB, installing a part of Structural Oscillation in Venice Biennale 2008](https://example.com/figure9.jpg)

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54 Image from architizer.com/projects/structural-oscillations/
They adopted a standard industrial pick and place procedure to assemble algorithmically designed brick structures. For the biennale, they brought their robot to the site and assembled the wall compartments outside of the pavilion and then moved installations one by one to the designated spots as a semi-on site fabrication process. They did it by ROB, a mobile platform that convey the robot, its controller, and designated tools. They described it as “... a robotic fabrication concept that enables the flexible production of architectural building elements”.

Despite the illusion of automated fabrication, this project was highly dependent on a group of operators to monitor constantly the material feed and relocate fabricated compartments to their final positions. However, they are barely reflected in the documentation.

---

55 (Bonwetsch, Gramazio, and Kohler 2012)
56 (Bonwetsch, Gramazio, and Kohler 2012)
Later, in Pike Loop installation, ROB and the team deployed in the central mall on Pike str., New York to perform a four-week on-site public installation. This time, the compartments were fixed in their places while the robot had to be shifted precisely into a new position whenever it exceeds its span limit. Although this project was the closest one to the fully automated on-site construction, it still required extensive human effort to calibrate the robot after every shift and feed it with materials constantly.

Figure 11 - Structural Oscillation, top: relocating finished compartment, bot.: final form
Figure 12: ROB in action on the Pike Loop installation\textsuperscript{37}

\textsuperscript{37} (Bonwetsch, Gramazio, and Kohler 2012)
Case #2: Robotic Stereotomy

<table>
<thead>
<tr>
<th>Architectural Question</th>
<th>Robotic Offer</th>
<th>Material System Offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing [Stereotomy]</td>
<td>New [Robotic band saw cut]</td>
<td>Existing [EPS / Concrete]</td>
</tr>
</tbody>
</table>

In this family of independent projects, the old art of stereotomy was revived by developing an RTM system. In the first studies by Clifford and colleagues, EPS foam blocks were treated by a modified hot wire cutting system, a modernization of old-school decorative stereotomy methods. The novelty of their work was hidden on the cutting tool they used, a U-shaped knife that could recreate the effect of a sculptor’s hammer. However, they finally used these models as molds to cast volumetric architectural elements using Glass Fiber Reinforced Gypsum (GFRG). They stated that:

The act of rapidly carving volumetric material mines knowledge from the past in an effort to create novel forms that are not possible in the aggregation of standard building components.59

This method was significantly faster in compare with other volumetric digital fabrication methods like milling or 3D printing. However, the range of possible outcomes is relatively limited.

![Quarter sized rapid prototypes of serial variability](image)

58 Expanded Polystyrene Foam  
59 (Clifford et al. 2014)
In the second project, RDM Vault, at Hyperbody’s robotics workshop in Rotterdam, the EPS foam blocks were cut by a robotic hot wire cutter to form an all pressure vault. Resembling stone vaults, researchers used a custom-made form finding and structural optimization tool, called RhinoVAULT, developed by BLOCK group at ETH. Fifty-three unique components were generated by the algorithmic design procedure considering the fabrication constraints in a construction-aware procedure. The final model was covered with fiberglass and acrylic coating to solidify the structure.

Figure 14 – Left: diagram describing the range between the minimum and the maximum step-over. Right: A sample of carved mold.

---

60 (Clifford et al. 2014)
61 (Mcgee, Feringa, and Søndergaard 2013)
Having the design and optimization methodology in hand, the researchers pushed forward the material system to get closer to the architecture-grade stereotomy, shifting from EPS blocks into stone or concrete. This goal was achieved by mounting a diamond wire cutter on a heavy ABB robotic arm. Using this RTM, researchers could build a self-standing vault using concrete components with an integrated joint system. This system was demonstrated in Rob Arch 2012 in a workshop conducted by Wes McGee, Jelle Feringa, and Lauren Vasey.

Image from: www.rok-office.com/projects/dragon-skin-vault-1017/
Image from: www.rok-office.com/projects/dragon-skin-vault-1017/
Eventually, ten blocks of concrete were cut to build a small section of an overall form, due to the extremely slow fabrication procedure and the messy nature of the workflow.

This chain of projects gains more weight when being studied as a part of a larger project that tries to revive an aged art using high-tech tools while exploiting its potentials.

In 2013, another custom made cutter were used by Jelle Feringa in collaboration with Carrara Robotics and T&D Robotics to cut astonishing forms out of marble, finally connecting the whole research project to its origin.

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64 Images from: www.laurenvasey.com
Figure 18 - Marble cutting with diamond-wire saw, Carrara Robotics.

Images from: https://goo.gl/QSVFVS
Case #3: Aggregated Structures

<table>
<thead>
<tr>
<th>Architectural Question</th>
<th>Robotic Offer</th>
<th>Material System Offer</th>
</tr>
</thead>
</table>

In this project, Dierichs and Menges have developed a logic for aggregated systems, and then a basic component was designed to satisfy the desired characteristics which, in this case, were self-supporting self-efficiency.

Aggregates suggest a perpetual mode of (re)construction, where stability is an intrinsic part of, rather than opposed to, destabilization ... as opposed to assembly systems, granulates as a material compute their overall structure and form through spatiotemporal patterns of behavior. 66

The granular material, as the author calls it, behaves like a solid one once the whole system finds its stable configuration. This unique behavior leads to the possibility of pouring material in the desired pattern if it is being combined with a proper toolpath.

This novel approach was accompanied with a carefully orchestrated pouring mechanism, controlled by a robot

66 (Dierichs and Menges 2012)
67 image from: goo.gl/YZ90IZ
and a custom-made nozzle. Every layer of granular material was poured on the previous ones to guarantee the equilibrium of the system, the overall process resembles an additive procedure, specifically 3D printing, but the fabrication speed significantly surpass the conventional additive systems mostly due to the large size of the components. This project is a successful example of developing a new possibility on the architectural side and combining it with an existing robotic functionality.

Figure 20- Aggregate Structure, delivery tool and study models 68

68 images from: goo.gl/7R4YLD
Case #4: ICD-ITKE Pavilion 2012 & 2014

<table>
<thead>
<tr>
<th>Architectural Question</th>
<th>Robotic Offer</th>
<th>Material System Offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>New</td>
<td>Existing</td>
</tr>
<tr>
<td>[Woven fiber structure]</td>
<td>[Robotic Weaving]</td>
<td>[Carbon fiber]</td>
</tr>
</tbody>
</table>

Achim Menges 69 and his colleagues in two sequential projects studied the possibility of using high-performance composite materials to make complex, light and self-supporting structures. They first developed the material system using carbon fiber yarns and hardener resins and specific frameworks to host it during the fabrication phase.

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69 (Weigle et al. 2014)
70 Images from www.gabreport.com
In the 2012 pavilion, the whole structure was weaved around a computer-controlled rotary scaffold that was equipped with hundreds of small hooks to keep the carbon fiber yarns in their places. The robot was handling the constant yarns feed that had just passed through a resin bath. After completion, the scaffold was removed, and the pavilion was installed in its designated place, as a stand alone structure. After this experiment, they developed a complex array of robots and apparatuses to elaborate a robotic weaving method. From early single robot motion to

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rotary scaffold and finally the choreography of two robots with mounted frames, they increased the level of complexity to reach the zenith.

In the 2013 pavilion, the structure was made of several hexagonal cells. To fabricate the cells, two hexagonal metal frame with adjustable variable geometries were made to act as the rotary scaffold. Having frames attached to two robots, the yarn delivery system was fixed to the ground this time. After the completion, every component was cured to obtain its highest reachable performance and then they were all assembled by hand on site.

72 Image from: vimeo.com/98783849
Figure 25- ICD-ITKE 2013 Pavilion

73. Images from: monograph.io/icd/icd-itke-research-pavillion-2013-14
Case #5: Water Based Robotic Fabrication

<table>
<thead>
<tr>
<th>Architectural Question</th>
<th>Robotic Offer</th>
<th>Material System Offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>New</td>
<td>New</td>
</tr>
<tr>
<td>Sustainable Structure</td>
<td>Robotic 3D printing</td>
<td>Water-based Bio-material</td>
</tr>
</tbody>
</table>

In this project, Neri Oxman and her colleagues started a new field almost from scratch by developing the idea of using variable property bio-material systems and robotic 3D printing. The question was untouched before they frame it, and the robotic fabrication method they suggested is just in its adolescent, demanding for extensive studies to reach its potential power.

They exploited the water based biomaterials to reach a wide range of material behavior, from soft to rigid and transparent to translucent, by changing the level of water in the base material. They managed to print out a dragonfly wing-shaped structure by adjusting the water percentage in the raw material. However, the results were not completely predictable or under control, but the landscape of the field seems promising.
Figure 27- Early studies and tests
Figure 28 - Water-Based Robotic Fabrication\textsuperscript{74}

\textsuperscript{74} Images from: matter.media.mit.edu
2-2. Shape Grammar

The idea that design can be described through a vocabulary of shapes and a set of rules was first brought to attention by George Stiny and James Gips as the Shape Grammar theory. In 1971, they proposed it as a method of shape generation, in accordance with Chomsky’s phrase structure grammar in linguistics. However, instead of alphabetical symbols, they defined an alphabet of shapes to generate n-dimensional shapes rather than one-dimensional strings of symbols.

As Knight stated, “a shape grammar is a set of shape rules that apply in a step-by-step manner to generate a set or language of design.” A shape grammar consists of 1)a finite set of shapes, 2)a finite set of symbols, 3)a finite set of shape rules and 4)the initial shape. Shapes and symbols are the building blocks for the rules and initial shapes, where new shapes are being generated by recursively applying rules on the initial shape.

![Figure 29](image)

*Figure 29- An example of what a shape grammar looks like and how it works. The grammar is based on a Renaissance church in the form of a Greek cross.*

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75 (George Stiny and Gips 1971), (G Stiny and Mitchell 1978)
76 (George Stiny and Gips 1971)
77 (Knight 2000)
78 (George Stiny 1980)
79 (Knight and Stiny 2002)
At the beginning, Stiny and Gips used it to illustrate shape grammars for the original languages of paintings. However, later it was developed by the original authors and other fellow researchers into parametric and color shape grammars, “generative fabrication” grammars for manufacturing and several others. It has already been used in architecture, landscape design, product design, and art.

In architecture, Stiny used shape grammar to analyze and codify different designs procedures in various scales and disciplines, from Chinese ice-ray patterns to ground plans of Palladio’s villas. Later, other researchers covered Frank Lloyd Wright’s prairie houses, Alvaro Siza’s houses at Malagueira, etc.

Figure 30- Koning and Eizenberg’s studies on Frank Lloyd Wright prairie house shape grammar

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80 (Knight and Stiny 2002)  
81 (Knight 1993)  
82 (Cardoso Llach and Sass 2008)  
83 (Noel 2013)  
84 (G Stiny 1977)  
85 (G Stiny and Mitchell 1978)  
86 (Duarte 2005)  
87 (Koning and Eizenberg 1981)
2-2-1. Why to use grammatical approach?
However shape grammar has been adopted as a generative tool in numerous research studies, for the first two decades it was used chiefly as an analytical tool to describe design styles. (images 30-31) This approach secured shape grammar position as an established paradigm in design theory and CAD.89

A well-crafted analytical grammar can concisely describe the simplicities and regulation behind a design system that may seem complex or random at the first glance. 90 Accordingly, using such approach gave me the opportunity to formulate and codify the robot’s design space in relationship with the designed tool and material system. I used this opportunity to make it more tangible for the user to understand and dominate the design space.

Finally, the defined geometrical description for the robotic motion and the accompanying design space had the potential to be developed into a grammatical system, were

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88 [Duarte 2005]
89 Knight listed a series of influential researches in the field as: shape grammars for the architecture of Giuseppe Terragni, Frank Lloyd Wright, Glenn Murcutt, Christopher Wren, and Irving Gill, for the vernacular styles of Japanese tearooms, bungalows of Buffalo, Queen Anne houses, and Taiwanese traditional houses, and for the landscape architecture of Mughul gardens. (Knight 1999)
90 (Knight 1999)
among the other reasons to use the grammatical approach for this research. These geometrical properties will be discussed thoroughly in section 4-1-1.
Chapter 3 | Hypothesis

Louis Kahn once told a story about a dialogue: 91
‘You say to a brick, ‘What do you want, brick?’ And brick says to you, ‘I like an arch.’” 92
Brick agonizes to correspond through its natural characteristics. It directs the design procedure to
preserve an equilibrium by suggesting and evaluating.

If we start such a dialogue with a robot and ask it
‘What do you want, robot?’, what will the robot say to us?
How does the robot communicate with the design system? How does it suggest solutions or evaluate the
proposals? I say, it generates and evaluates, by looking inward to find its artificial nature.

As it was briefly discussed in section 2-2-4, the majority of
studies in the architectural robotics lean towards exploiting
the fabrication capabilities of robots, abandoning their
potential role as an active design agent. Such approach
suppresses the latent capacities of robotics in the
architectural context. Considering this gap, this research
aims to assess the effectiveness of a well-articulated

91 (Voyatzis 2013)
92 The conversation continues as “And you say to brick, ‘Look, I want one, too, but arches
are expensive and I can use a concrete lintel.’ And then you say: ‘What do you think of
that, brick?’ Brick says: ‘I like an arch.’”
medium between design process and robotics to unleash such dormant capabilities by bringing up this question:

How can an analytical rule-based design method help changing robots’ role from an end-effector to an active medium of the design?

To answer this question, I hypothesise that:

While software toolboxes that were introduced in section 1-1-2 are playing a pivotal role by enhancing the architectural robotics workflow, they are not sufficient to explore this new realm. An ideal medium should embed all the constraints that affect a specific RTM from early stages of design to materialization.

Integrating the physical and kinematic behavior of RTM, into the design description is the core concept of this medium. The result would be a computational model that encapsulates both design logic and robotic fabrication procedure which can help designers simultaneously engage with creative form finding and producing robot’s control data to materialize them, seeking an equilibrium between design and making. This approach can prevent from the dominant obsession of digital design practices with computation and on the other side alleviates the risk of the excessive privilege of fabrication.

I expect that such an approach will establish a dialogue between the RTM and design procedure to convert robot’s role from an end-effector to an integrated active part of the design procedure.

\[93\text{The irony is strong here. Robots are by definition active tools, but from this specific point of view they passively execute commands that come from the controller.}\]

\[94\text{The assembly of robot, mounted tool and the material system. In this research it specifically refers to the combination of an ABB 2400 industrial robot, the custom-made hot wire cutter and blocks of EPS foam.}\]

\[95\text{(Budig, Lim, and Petrovic 2014)}\]

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I propose a rule-based analytical system that let designers describe robotic characteristics and combine it with the design process to establish an active dialogue between the robotic system and design process. This medium that uses a modified version of shape grammar, called Motion Grammar formulizes behavior, characteristics and limitations of a designated combination of the robot, tool, and material system. Combined with a set of other computational tools, this grammatical system can codify design and making procedures to shape a framework to understand and control robot’s design space.

In the next chapters, I will describe the methods to test the functionality of this medium hypothesis. But first, it is necessary to discuss briefly shape grammar and clarify the necessity of grammatical approach to address this question.
Chapter 4 | Methods

I tested the validity of the hypothesis through a) reviewing the background of robotics in architecture, b) investigating the robotic manipulation fundamentals, c) developing a Robot-Tool-Material system, d) developing a computational rule-based analytical system to address design process and fabrication based upon RTM (robot-tool-material system) characteristics, e) fabricating small scale besides an architectural-level model by means of that system, and f) analyzing the procedure. While items a was discussed in the earlier chapters, in this chapter I will cover items b, c, d and the remaining ones will be the subject of discussion in chapter 5.

Embedding the capabilities and shortcomings of every RTM into a design system, will impose a “Domain of Affordances” \(^\text{96}\) which results in a limited, but yet unexplored, “Fabrication Range”. Apparently, developing a matching design procedure will define a corresponding “Design World” that only a portion of that can be navigated using the defined medium. This space is a relatively small region of all possible design solutions, which represent the synergy of architectural design and robotic fabrication. Borders of this navigable space are bounded by both disciplines, but not limited to the former borders anymore, as it was discussed.

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\(^{96}\) The term is borrowed from Bill Mitchell’s The Logic of Architecture (Mitchell 1990)
in section 1-1-3. Some researchers believe that expanding these boundaries can also be recognized as a creative act of design by itself.97

![Fabrication range/design space and navigation means relationship](image)

Architectural Robotics covers a variety of methods and corresponding material systems. Exploring even a portion of this space is beyond the scope of this research. Thus, the study is limited to a single type of tool with its prevalent material system to reduce the level of uncertainty and to keep the research structure confined. However, one could imagine this approach is being applicable to navigate through other RTMs and machines’ design world.

97 (Budig, Lim, and Petrovic 2014)
4-1. Design-Making Machine

Researchers have already tried to establish a dialogue between design process, material properties, and robotic fabrication, following the long lasting quest of integrating material/structural knowledge into the design process. Picon suggests a unified design and fabrication process based upon “... a series of conversations between men, (designers and workers), and machines, (computers and robots)”. 98 Lloret et al. proposed a design-making-simulation cycle to embed the material-based observation to the architectural robotic procedure. 99 Schwartz et al. used the same feedback loop to catalog material behavior in the fabrication procedure. 100 In all cases, a lion share of efforts focused on the material study and computer simulation to encapsulate material properties in the design process and predict its behavior during and after fabrication. This attitude marginalized the robotic behavior, degrading its role to an end-effector.

98 (Picon 2014)
99 (Lloret et al. 2015)
100 (Schwartz et al. 2014)
As a step forward, the suggested medium is by design emphasizes the dialogue between the RTM and design procedure. Integrating the RTM properties with the rule-based system makes it possible to suggest constantly solutions from the defined design space and evaluates the generated instances according to its fabrication range. In such scenario, the RTM plays a pivotal role in the process, crossing the boundaries of a passive end-effector for an active design agent, by establishing a constant back and forth dialogue between the design generator and RTM properties. A descriptive subsystem handles such critical task. Figure 35 schematically demonstrate this framework.\textsuperscript{102}

Figure 35- The research method for the development of the robotic slipforming process \textsuperscript{101}

Stiny in his influential paper “Design Machine” described its schema of design as a combination of four parts: receptor, effector, the language of design and a theory which

\textsuperscript{101} (Lloret et al. 2015)
\textsuperscript{102} I should assert that this communication is not necessarily a real-time interaction between the physical effector and other two components, but it is taking place during the offline simulation, before sending the control data to the robot.
\textsuperscript{103} This figure is basically a derivation of the diagram 31, however the three components are shown as separated entities, they are tightly integrated through the constant dialogue.
comprise to make a design machine. He emphasized the equal importance of each component and their intimate relationship with them.\textsuperscript{104} In accordance with such system, I propose a similar structure to define this design-making machine that consists of a) Descriptive System, b) Generator, and c) Effector.

The descriptive system (DS) consists of a parametric definition that encapsulates the RTM properties, design criteria, and the designated grammar. DS is the main core library that enables the system to describe geometrically complex forms, based on a limited set of rules and initial shapes. Integration was sought through embedding robotic affordances into this part. The generator is designed to breed objects according to the descriptive system and convert them into the robot executable codes. Visual programming environment of Grasshopper and its add-on called HAL, are the backbone of this part. The effector is the hardware compartment, including the robot, mounted tool and the material. Since the properties of the effector are embedded in the descriptive system and generator, I argue that in this context, the effector is a crucial design tool rather than merely fabrication tool. Combined, descriptive system, generator, and effector define a design-making machine, which can generate and fabricate a relatively large range of objects in its corresponding design space.\textsuperscript{105}

\textsuperscript{104} (G Stiny and March 1981)

\textsuperscript{105} However, as an inevitable next step, a language of design and related theory should be developed to address the correspondence between objects designs and design contexts.
4-1-1. Effector (RTM)

After reviewing several fabrication methods, including milling, pick and place, 3D printing, and hot wire cutting\textsuperscript{106}, the latter one was selected as the method of choice for this research. Compared with CNC milling as one of the dominant fabrication methods, hot wire cutting consume significantly less energy, takes considerably less time, and produces less projectile debris that reduce the safety concern.

The RTM comprise an ABB IRB 2400-16 robotic arm and a custom-designed hot-wire cutter (HWC). The material substrate was blocks of high-density EPS foam. The robot has six degrees of freedom (DOF), three of which enable a working area of 1.55 diameter with 0.1 mm position accuracy, while the three others precisely orient the end effector. Together, position and orientation define the pose of the robot’s end effector.\textsuperscript{107}

**Hot-wire cutting**

The mounted tool is a two feet wide aluminum frame, holding a tensioned Rene’ 41 wire. The wire can be heated by electric current up to 200-300 c° to cut EPS foam steadily

\textsuperscript{106} For a comprehensive study of mounted tools and fabrication methods, please refer to the appendix 2.

\textsuperscript{107} (Corke 2011)
and smoothly. Making it possible to fabricate either the final objects or partial components that can be assembled into a complex compound object. The process is extremely efficient time-wise. Commonly, hot wire cutting is being used to fabricate large objects like boat hulls because of its fast and efficient operation. Because of fragile nature of foam, besides the delicate details in the manufactured objects, in most cases they need to be sprayed or coated with layers of glass resin to protect them from environmental exposure.\textsuperscript{108} To summarize, advantages of this method over the other ones can be listed as:

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule-based by design</td>
<td>Wire always cut the material block in the form of a ruled surface.\textsuperscript{109} This fundamental characteristics make this method an ideal one for rule-based design systems since robot’s motion in space can be described based on the spatial coordination of two points, the hot wire’s start and end.</td>
</tr>
<tr>
<td>Simplicity</td>
<td>Its basic compartments are the frame, wire, and power supply, making it easy to build and maintenance system.</td>
</tr>
<tr>
<td>Ease of control</td>
<td>On one simple parameter, input voltage, is necessary for this tool. Accordingly no I/O control system is required for this method.</td>
</tr>
<tr>
<td>Safety in work</td>
<td>This method makes no excessive heat (compared with arc welding of metal extrusion), flame or ballistic debris. However, generated fumes might be toxic if not being ventilated properly.</td>
</tr>
<tr>
<td>Fast fabrication</td>
<td>On EPS 200 and at 200\textdegree C, it can cut material at the speed of 1.5 m/min. For more accuracy, speed can be reduced to 0.3 to 0.6 m/min by making an equilibrium between speed and temperature.</td>
</tr>
</tbody>
</table>

\textsuperscript{108} (Naboni and Paoletti 2015)  
\textsuperscript{109} (Spikker 2014)
**Cleanness**  It does not make small floating debris, dust or moist, reducing the need for special dressing pack or filters to protect users and tools.

Finally, working with EPS is pretty convenient, due to its light weight, and endurance against environmental factors.

However, this system has its disadvantages including but not limited to:

Challenging tool maneuvers management, which requires extra endeavor to anticipate collisions, very limited material library, (only EPS and some other foam types) and producing toxic fumes.

![Figure 39- Schematic configuration of SALA Robotic Fabrication Lab](image)

The custom-designed robotic hot wire cutter (RHWC) consists of a power supply unit, robotic arm and the cutter assembly. The cutter assembly is a wire tensioned in an aluminum frame. It is being heated by controlled current of electricity.
Wire

In industrial HWC, Cobalt based alloy from 0.30 mm to 0.50 mm diameter are being used. This wire provides proper mechanical resistance. A more sophisticated alloy is a custom Tungsten based alloy with excellent mechanical resistance and durability. René 41 alloy is among the most popular wire type for commercial foam cutting purposes. I chose René 41 because of its optimum mechanical properties and affordable price and availability. Foam can be cut by wire sizes from 40 gauge (.003" dia.) all the way up to 11 gauge (.091" dia.). The most common size is 26 gauge. 16 to 11 gauge are used for foam cutters to cut shapes such as molding because they are stiff enough to hold a shape rather than being straight. The bigger the diameter, the more current is required to heat it to the same temperature. Also, the larger the diameter wire, the longer it will take to reach the equilibrium temperature. Using the wire to cut foam, the normal desired temperature is 300 °C.

Due to metal expansion, a mechanism to keep tension in the wire is needed. A springy frame that stretches the wire between its legs is among the most effective methods to address this issue. However, in this case, to keep the assembly in constant accurate shape, a smaller spring mechanism applied to the wire anchor pins.
Transformer
According to the type of alloy, the wire size, its length and necessary temperature certain amperage and voltage should be connected to the wire. These properties of the current should be kept constant and steady. Therefore, a transformer is being used to guarantee these conditions. For René 41 in a span of 2 feet, a 50VA transformer with 24-volt output is needed, preferably with a dimmer. For longer cutters, it might be needed to have a more powerful transformer.

Frame
The frame was made of aluminum profiles, which reduces the weight while maintaining the sturdiness. Since the size of the cutters are relatively big and their center of gravity if far from the robot wrist, it must be kept light to match robot loading charts and reduce inertia. The frame weights around 7 lbs. and spans 2 feet. However, the safety margins limit its cutting width to 20 inches.

Mounting adapting plate
This plate will connect the frame to the wrist of the robot or simply connects to the tool side of ATI tool changer.

Generator
The Generator is configured in two modules, a) Design Compiler (or in specific cases Design Generator), b) RAPID code generator. ¹¹⁰ This component is thoroughly

¹¹⁰ However, this RAPID code generator can also be seen as a compiler which compiles coordination from Rhino/Grasshopper platform to RAPID.
developed in Grasshopper, a visual programming environment built on Rhinoceros modeling software, which is by now one the most popular parametric modeling platforms among architects. In this thesis, parametric modeling is used to maintain full control over the elements of design and create variations by manipulating input parameters. The generator has two basic modules, the design compiler/generator, and the rapid code generator.

**Design Compiler/Generator**

The idea of motion grammar was implemented in the grasshopper environment to compile pre-modeled geometries or generated new forms into the elements of motion grammar vocabulary. This procedure is discussed in depth in the next section.

**RAPID code generator**

To simulate robotic motion and generate the RAPID code for the robot’s operation, I used HAL, an add-on for controlling industrial robots from KUKA, ABB and UR, developed by Thibault Schwartz. 111 To express the importance of HAL contribution into this research, it is crucial to review the workflow that happens in the background.

As researchers have pointed out, it takes a significant effort to understand the relationship between the Cartesian system of conventional CAD and CNC systems, and the complex behavior of end effectors. 112 Comparing a sample of Cartesian coordination vs. its equivalent in RAPID code depict the difference clearly.

<table>
<thead>
<tr>
<th>System</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>P10 = {600, -100, 800}</td>
</tr>
<tr>
<td>RAPID</td>
<td>p10 := [{600, -100, 800}, [1, 0, 0, 0], [0, 0, 0, 0], [9E9, 9E9, 9E9, 9E9, 9E9, 9E9]];</td>
</tr>
</tbody>
</table>

111 (Schwartz 2014)
112 (Johannes Braumann and Brell-Cokcan 2012)
RAPID data codifies the robot’s end effector’s correct pose, including position, orientation, as well as each designated axis’ angles and values. In many design scenarios, designers can think about the pose of the end effector. In such cases, Kinematics, which deals with the relationship between robot motors/joints and the end-effector motions is not useful, as we should go through an inverted procedure to find the value for every axis to reproduce the desired pose. Thus, these numbers are processed in an inverse kinematic solver to generate the rotating angle for each of the robot’s axes.

As other authors have noted, this environment provides the opportunity to understand visually the relationship between changes in the generators’ parameters, the robot’s motion and produced forms in an interactive environment. For this research, the generated RAPID scripts were later being

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113 (Avis 2014)
114 (Hägele, Nilsson, and Pires 2008)
115 (Johannes Braumann and Brell-Cokcan 2012)
tested in the RobotStudio environment to check for execution errors, and finally uploaded to the robot to be executed.

![Image](image_url)

*Figure 44- Rhino | Grasshopper | HAL environment*

To simplify all these procedures and help designers getting more involved with creative design rather than technical issues, a semi-automated procedure was developed. Throughout the generator development, several functionalities were added to the model core, making it possible to generate ruled surfaces and rationalized complex skins using the basic characteristics of ruled surfaces.

4-1-3. Descriptive system

The Descriptive system represents and replicates the behavior of RTM system. The tool description, robot’s configuration, fabrication restrictions, and material characteristics are all embedded in this part and later modeled and embedded in the generator. The main idea behind the descriptive system is shaped around the concept of visual computation and specifically the proposed motion grammar, which will be discussed in more detail hereafter.
4.2. Motion Grammar

I developed a structure, founded on the basics of shape grammar theory, but tailored to fit the context of architectural robotics. A Motion Grammar, as I call it, seeks to address the 3-D harmonic movements of robot, tool, and material substrate choreographically, suggesting motion as a generative vehicle of exploration in both designing and making.

Before focusing on the technical aspects, it will be both informative and refreshing to review briefly the concept of motion. Sir. Isaac Newton was among the firsts who studied the relationship between geometry and motion:

> Lines are described, and thereby generated not by the apposition of parts, but by the continued motion of points. Superficies’s by the motion of lines, solids by the motion of superficies.\(^{116}\)

Klee also illustrated the same logic in his Pedagogical Sketchbook as is shown in figure 44.

Motion can be described as a change in the state of position and orientation that happens through time.\(^{117}\) Although the starting pose and ending pose of a given body might be the same, movement is the process of the change that happens in between.\(^{118}\) Comparatively, in an abstract process of combination, the movement of an RTA in space can transform objects. This movement can be visualized as the displacement of a series of points in space, which in turn defines lines.\(^{119}\) Recently, researchers have tried to incorporate motion into grammar formulation, although mostly to define kinematic behavior\(^{120}\) or bodily transformations\(^{121}\) as insight into the design of architectural structures.

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\(^{116}\) (Newton n.d.)
\(^{117}\) (von Laban 1956)
\(^{118}\) (Zhao and Badler 2001)
\(^{119}\) (Klee et al. 1953)
\(^{120}\) (El-Zanfaly 2011)
\(^{121}\) (Ferreira, de Mello, and Duarte 2011)
Figure 45- Klee's illustrations, from point to plane

122 (Klee et al. 1953)
Robotic control is hard to grasp for inexperienced users especially for architects who do not have a background in kinematics, but the motion in space is a tangible phenomenon. Synthesizing this idea, I sought to formalize a vocabulary of motions able to generate complex forms. In this thesis, I used motion grammar as a way to address machine and material-specific aspects of the system that uses a robotic arm to cut precisely and carve 3-D blocks of solid material. Thus, the grammar’s vocabulary members are not shapes nor objects, but movements. Its derivations are not artifacts as much as choreographed assemblages of robot, tool, and material, with a tangible result.

4-3. **Motion Grammar Structure**

Knight, in her 1994 paper “Shape grammar and color grammar in design” named the basic foundations of a shape grammar,¹²³ accordingly, I defined the proposed

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¹²³ She listed them as a vocabulary of shapes, spatial relations between shapes in the vocabulary, additive shape rules based on the spatial relations and rule labeling. (Knight 1994)
motion grammar by 1) geometric vocabulary, 2) combination rules and 3) labeling system.

4.3.1. Geometric vocabulary
The Hot Wire cutting design range is defined by Ruled Surface (RS) geometry. RSs are formed by the movement of a straight line over a curve in space. They have been used by architects to create complex forms, including Antonio Gaudi’s Sagrada Familia Cathedral.124 By definition, an RS needs a generator line and two directrices to define the pose of the generator and limits of the surface.

![Diagram of a basic motion rule](image)

*Figure 47: Example of a basic motion rule $A \rightarrow t(A)$*

In hot wire cutting, the wire plays the role of the generator, which moves through directrices to cut EPS material. Any changes in the properties of the directrices will affect the motions and consequently the final form. Accordingly, I developed a design space, based upon these possible variations to navigate through the probable vocabulary of robot’s motion in space.

In Rhinoceros modeling environment, a curve may refer to any curve that can be represented by NURBS definition that is a mathematical representation of 3D geometries that can accurately describe any shape from 2D lines to complex 3D forms.125 In this thesis, Line or Polyline refers to a NURBS curve of degree 1 or simply a straight line, while Curve will refer to NURBS of higher degrees. By definition, the generator is always a line, while directrices can be lines, polylines or curves.

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124 (Stavric and Kafan 2012)
125 (“Rhinoceros - NURBS” n.d.)
The grammar defines the possible range of changes in the properties of directrices (morphemes) to generate basic motions (lexicon) and categorize the methods to combine these motions (rules) to generate more complex motions.

**Morphemes**
Two basic parameters can affect the form of directrices, first degree of NURBS and second their relation in space. By changing the degree, they can shift from a line (or polyline) to a smooth curve. They can be in a same plane, parallel, intersecting or skew ones. By changing the degree of curve and position of their controller points, one can generate these basic elements of grammar. (Figure 47)

Figure 48 - Effects of directrices’ degree on the motion

**Lexicon**
Based on these characteristics, a range of basic motions can be defined, comprising the grammar’s vocabulary (Figure 48)
Figure 49- Vocabulary of motions (Lexicon)

Figure 50- Generated motions from directrices of different degrees and related forms

4-3-2. Combination Rules | Labeling System
In this motion grammar, a rule such as \( A \rightarrow t(A) \) defines a movement in which \( (A) \) is the state of the RTA in a specified pose and time, and \( t(A) \) represents a new state by applying a transformation to the original state. \( A \) and \( t(A) \) might be the same pose, but generated motion is the process between these two states.
Motions can operate on each other to generate more complex motions (and more complex material effects). I categorized these rules in two basic groups:

**Sequential**
Sequential rules join two vocabulary members into a new motion. Members can be joined either by the generator or by the directrix. Sharing the generator will result in a continuous motion, meanwhile, sharing a directrix requires the robot to finish the first motion, find its initial pose for the second motion and then perform it to complete the procedure.

Therefore, we can annotate this procedure as:

\[ m_1 = A \rightarrow t_1(A) \text{ and } m_2 = t_1(A) \rightarrow t_2(t_1(A)) \]  
\[ M = m_1 + m_2 \]  
(1)  
(2)

**Composite**
Composite procedures are two or more motions that cut each other to generate new virtual directrices and trim
previous generators. This composition can generate extremely complex motions. While in sequential procedures the length of the generator is constant, in composites it is variable.

\[ m_1 = A \rightarrow t_1(A) \text{ and } m_2 = B \rightarrow t_2(B), \quad M = A \rightarrow t_i(m_1, m_2) \quad (3) \]

\[ t_i(m_1, m_2) = [\text{curve}_1, (m_1, m_2)_{\text{int}}, A [0,1]] + [m_1, m_2]_{\text{int}}, \text{curve}_4, B [1,1] \quad (4) \]

Figure 53 - Composite combination

Basic grammar rules are described in the figures 53 to 56.
Figure 54 - Basic grammar rules
Figure 55 - Grammar rules
Figure 56- Developing from lexicon to motion

Figure 57- Procedure of making a complex motion with labels
Chapter 5 | Tests and Results

After defining the methods, it is time to put them in action and test the functionalities. These tests are aimed to evaluate the functionality of RTM, proposed grammar and finally the performance of the system in making an architectural scale model.

To put the idea of integrated design-making in practice, the motion grammar was converted into a computational model to help generating design solutions besides exporting necessary codes to control robotic fabrication workflow. Effector, generator, and descriptive system were developed in parallel one step at a time while constantly being tested in practice to avoid unwanted abstraction. Accordingly, in every phase of the procedure, the system was functional and capable of making design solutions and fabricate them.

5-1. Test workflow

In every test, the model was defined in Grasshopper environment. Then HAL was used for early off-line simulation, debugging and generating RAPID codes. Generated codes were simulated in Robot Studio to assure the safety of robot and users. Running the code on the robot without feeding material was the final round of simulation.
To test the system performance, a series of experiments has been conducted targeting different modules of the system. Finally to test the integrity of the whole system, an architectural scale installation was designed and fabricated.

Figure 58 demonstrates sequential phases of system development. Since the first phase has already been addressed in previous chapters, phase 2-5 will be discussed here.
5-2. **Effector performance tests:**

Tool calibration, wire temperature and material properties significantly affect the performance of the system in different ways including a) fabrication precision and level of details, b) thickness of cut, c) final texture of the cut surface, and d) fabrication duration. Thus, the early experiments were chiefly focused on finding an equilibrium between material density, wire temperature, and robot motion speed. For the 1.5 kg/m³ architecture-grade EPS foam, the best results were obtained at 10 mm/s speed and 250 °C and 5 mm/s at 300 °C.

**Table 2 - Speed/Temp configurations**

<table>
<thead>
<tr>
<th>Speed</th>
<th>Temp.</th>
<th>Detail</th>
<th>Thickness</th>
<th>Texture</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Fine</td>
<td>Constant</td>
<td>Fine</td>
<td>Slow</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>Poor</td>
<td>Fine</td>
<td>Fine</td>
<td>Fast</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Poor</td>
<td>Thick</td>
<td>Rough</td>
<td>Slow</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
<td>Fast</td>
</tr>
</tbody>
</table>

The temperature was adjustable manually using a dimmer nub on the custom made power supply unit. The speed was also easily adjustable both by defining speed value in RAPID code or upon execution using teaching pendant.

The best results were achieved in the Low-Low scenario. Despite the slow fabrication process, fine details and texture on the cut surfaces besides the high level of control on the cut procedure render this combination the ideal solution.

In High-Low temp scenario, the wire cannot cut material with the speed of the robot. Thus it jumps over details and corners and significantly increase the risk of wire break. This will result in unpredictable curvy corners and faint details.
and total failure in the case of wire break. This combination must be avoided despite its fine texture and fast pace of fabrication.

In Low-High combination, extremely thick cuts will eliminate details and results in a rough texture. Among the all four combinations, this one is the worst in the most cases.

Tuning the system on High-High will make it impossible to keep the consistency of cut thickness, especially when it comes to rotational motions or changes in the engaged length of the wire. It may result in the same Low-High scenario when it cuts a thin layer of material or High Low when it cuts a 20” of material in one move. Regarding these facts, this combination is among the hardest to deal with.

In all scenarios, due to the relatively wide cut thickness, it is crucial to offset out every model relatively. This becomes more troublesome in the parts in which wire travels back and force in the same edge. In figure 62 the gap between components is visible where such margin is not applied.

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**Figure 60 - Hot wire cutting settings comparison chart**

**Figure 61 - Hot wire cutting settings comparison chart, separated**
Another important factor in designing details is to consider the highest level of accuracy in the system, which is fundamentally limited by the wire gauge. Accordingly, with the wire gauge that I used, any cut or detail with less than 2mm is practically impossible to fabricate. Moreover, the density of the material directly affects the thinnest possible cuts, by both its load-bearing limits and gaps among the polystyrene bubbles.
Figure 63 – Cuts with different configurations, Top: High-Low, Left: Low-Low without considering the cut thickness in details, Right: Low-Low setting and considering the cut thickness in the toolpath.

Figure 64 - Different details to cover cut flaws

Figure 65 - Left: Thin cuts show the texture. Right: Low-Low setting for fine cuts.
Fixing the material block in its designated location is a challenging procedure that may increase the overall fabrication duration considerably and significantly cause inconsistencies. To locate EPS foam block in its exact position, a combination of active and passive methods were adopted. As a passive method, a fixed framework with a grid of fixing holes was installed to locate EPS blocks.
with the precision of 1/8". However, the required level of accuracy in details, especially for joints demands high precision in alignment. To obtain such level, the system was being fed with slightly larger blocks that provide it with a margin space. Accordingly, a series of motions were embedded in every fabrication procedure to carve the exact block of material out of the larger stock. Since the new block is cut based upon the robot coordination system, they are aligned accurately. Combining these two methods besides designing the fabrication procedure well in advance significantly improve the efficiency, by reducing the required fabrication time and wasted material management.

Figure 68- Active calibration by framing desired block out of available material stock (Vertical lines on the edges are defining the vertical edges, horizontal edges will be applied at the end of procedure to save material grip to the frame)
5-3, Motion Grammar test

After testing the functionality of the RTM system, studies were focused on the evaluation of motion grammar performance in action. Therefore, a series of studies were designed to test the system at different levels.

5-3-1. Lexicon of Motion Grammar

To test the system, I started with basic vocabulary of motion grammar as stand-alone objects. To do so, a series of basic motion from grammar lexicon were generated and cut. The basic difference between these motion was created by manipulating the directrices degrees from 1 to 3.

This experiment was conducted before adopting calibration method, nor passive, nor active. Accordingly, a part of the third motion is missed due to the disorientation of material block. (Figure 68, Right) Such fabrication flaws signified the importance of using a precisely calibrated
method, which was installed later to fix EPS blocks in their designated location. Moreover, the importance of finding the optimal distance between target planes revealed itself in generating smooth motions. Large gaps between target planes in the motion resulted in coarse texture and visible mark lines of the wire (Figure 68, Left) while tighter gaps led to a smooth finish on the other two models.

5-3-2. Generative Aggregation
The next two test were designed to evaluate the performance of the system in larger arrays. In the first experiment, the final form was shaped by repetition of a single component, while in the second one a surface with a complex pattern was tiled into vertical ribs as a method of rationalization.
These studies were targeted to evaluate the system performance in applying combination rules over basic lexicons. For this particular test, a random motion was generated and by the use of mirror and rotate rules a grid of four complementary motions were created. In this test, the active calibration method was used. Thus, the four components match each other with minor gaps in
between. Gaps between target planes were significantly reduced to prevent from a coarse texture.

![Image of block of material and excavated motion, Right: Aggregated motion, using mirror and rotating rules]

This experiments proved that adopting a proper fabrication workflow will reduce material waste and required time, while improving precision. For the first two experiments, the presence of the user was inevitable throughout the experiment to keep an eye on the system and control the material feed and robotic motion. However, in this procedure it was only necessary to put the material in correct position once the previous one was done. It is possible to claim that the level of automation in the fabrication procedure was improved.
In this test, the form was generated using Perlin noise and attractors in Grasshopper environment. Then a tiling method developed to convert the wavy surface into eight ribs that could later be fabricated by motion grammar logic. So, in this procedure a layer of rationalization was added to the system core.
Matching waves between two adjacent tile required the highest level of accuracy. Thus both passive and active calibration methods were used to guaranty clean, precise edge cuts. This system reduced the overall fabrication time to less than 30 minutes. Significantly improved since early experiment. Since the whole ribs were cut from one single block of material, the user did not need no constantly interfere with the automated procedure. Moreover, this significantly improved the performance and material efficiency. However, I managed to pick every fabricated rib before the robot goes for the next one, to prevent any unpredicted problem. It was unnecessary since the procedure run flawlessly. Ribs later assembled side by side as it is shown in figure 71.

Figure 73 - Cutting wave ribs from one block of material. Grid table is used to fix EPS block in its place while robot cut boundaries of the material to increase level of accuracy
In this level, a generative random method that was developed in processing environment was used to generate motion randomly. This test was designed to test
the reliability of processing interface and the overall automated workflow.

Despite the user-friendly environment of processing, developing generative system in this platform requires much more effort in compare with grasshopper. The 3D geometry library of processing is significantly narrow and suffers from the lack of crucial functionalities. However, the possibility of developing stand-alone software packages and even developing apps for mobile devices is the power points of processing. To test, a version of processing sketch was developed to generate the motion in the format of two sets of points moving on the edges of a cube, sending them through OSC to grasshopper listener. Grasshopper then converts them into directrices and continues the routine workflow to generate the RAPID code. From this part, the procedure was the same as previous ones. Since the motion generator was using Perlin noise to control point distribution in space, the generated forms are extremely abstract but still in the design space and fabrication range of the system.

![Figure 75- Processing environment and motion generator communicating with grasshopper in real-time](image)
Figure 76- The motion generator installed on an android tablet
5-4. Architectural Scale Test

As the final, a stand-alone 6 feet height object was designed to be fabricated using this system. To generate the form, a group of 3-dimensional arrays of points in space was used as the initial motion generator. Points, moving randomly in a defined range, shaped several coarse curves in predefined elevations. The motion of a line in space to span the gap between those curves defined the boundaries of the form.
Figure 78: Four steps of form finding, demonstrated by points in space and corresponding directrices for robotic motion.
Form finding:
In the beginning, a series of points propagated evenly on a fix distance from a series of points in space at a defined vertical distances, forming a group of circles in space. (Figure 78 Top) In the second step, for every group of points, the fix distance was changed, so corresponding circles were scaled in their containing plane, using random values. (Figure 78, second from top) In the next step, for every point, the distance to the center axe was set randomly, forming a free-form curve in the containing plane. (Figure 78, third from top) Finally, points were moved in z-axis to expand 2D curves into 3D ones in space. (Figure 74, bottom) Using these generated curves in pairs as directrices, a series of motions were generated based on the developed grammar.

Fabrication Method one:
In the first fabrication approach, the exact motion of line between curves was replicated by the RTM to materialize the motion in blocks of EPS. Accordingly, every two curves coupled together and formed one component of the final form. In this method, smaller gaps between curves will result in the smoother form. Regarding this format, generated geometries are all belonged to the vocabulary of motion grammar, and it is possible to fabricate them using robotic hot wire cutting.

However, the fluctuations between the peak of curves add to the complexity of material efficiency management. Moreover, since the shared border between every two components were unique and variable, finding an optimum solution to prevent assembling-time errors was cumbersome and challenging.
In figure 78, the red dots demonstrate the motion of a point, first in a 2D surface and then in a 3D space (top two left). From the combination of two sets of such points (middle), two containing curves were generated. These two curves will play the role of directrices of a motion, which can later be a part of a more complex sequential combination to form the final shape as it is demonstrated in figure 80.
In this method, the difficulties facing fabrication process was highly problematic, since the objects are irregular and non-planar on all sides, making it extremely hard to optimize the final motion. It is not possible to simply mimic the motion of points in space with the RTM, since the waste of material and collision of the cutter with both the robot and the fixing structure was very high.

Moreover, from every block of material, it is only possible to extract one single component, which render this approach
inefficient for large scale production. To overcome these problems, another approach was developed with a layer of rationalization.

Fabrication Method two:
In the second approach, a layer of rationalization was applied to facilitate fabrication process, reduce fabrication time obstacles and waste materials. To do so, the final form was divided by horizontal planes, resulting in a series of, so-called, donuts. Every donut was a rolled surface cut with two flat plains. Every donut was reproduced using motion grammar logic, paving the way to fabricate them using robotic hot wire cutting.

Using this method, it was possible to stack an array of components in one single block of material and fabricate them in one run, which significantly reduced material waste and logistic issues during fabrication.

Figure 82- Method two
Therefore, I adopted the later method to fabricate the final model, due to its efficient material management, reduced level of fabrication time difficulties, and ease of assembly.

Figure 83- Component from the final installation

Figure 84- 1/10 study model for the second method
Figure 85- The Final Installation
Figure 87: Final installation close-ups
Chapter 6 | Conclusion/Next Steps

In the foundation of a machine-specific motion grammar for robotic hot wire cutting system was proposed. The grammar and prototypes in this research are mainly a proof of concept and the foundation for more complex studies. Next steps in this route will focus on defining a detailed rule-set of both sequential and composite rules. The sequential or composite character of the rule-set will enable both top-down and bottom-up design processes. This framework will amplify the potential of our RTA as a vehicle for design exploration, constituting a truly generative framework for stereotomic processes.

6-1. Conclusion

There are several ways to simplify the robotic workflow for non-expert users including architects. My approach was to make a software bundle to control and address a specific combination of robot-tool-material and perform the background procedures.

I have focused on one specific RTM, accordingly the range of items\textsuperscript{126} that the bundle should handle was narrowed down to those related to this RTM combination. I should assert that this collection of items is a relatively small subset

\textsuperscript{126}This collection of items covers technical issues including robot performance related errors, generating RAPID code, handling material properties and adjusting variables related to the tool besides the design process. There is no doubt that this list could be much more comprehensive if the constraints of this research would allow me.
of a considerably larger range. Accordingly, any subtle modification in the RTM will urge significant efforts to apply necessary changes. There is an opportunity to continue this line of research to find a modular system, to configure different robot types, tool setup and material systems, with less effort. However, this approach is prone to make an even larger gap between modules and eliminates the dialogue.

Using an integrated design-making approach provide users a certain level of control over robotic procedure, but on the other hand, limiting the system into one specific RTM and a small library of geometries and its related shortcomings. It is crucial to remember that this research is only a pilot study to test the possibility of making a larger universe of design-making machines following the same logic.

While working on this project, I realized that designing the fabrication workflow is among the most challenging parts of the process, where every motion of robot, logistics and tool handling\(^{127}\) shows it’s significant effects on the overall procedure. Robots are rooted in industrial/military manufacturing, where they are assigned to precisely defined tasks, carefully optimized by industrial engineers. They are designed and tuned to perform so. However, architecture is the realm of uncertainties. Designers invest heavily in design process, but poorly manage manufacturing process and logistics. This is the Achille’s Heel of robotics in architecture. We have to endorse the critical role of a group of users behind almost every robotic project, which covers the manufacturing design flaws and keeps the system up and running. A tailored manufacturing process will significantly reduce the level of human-machine interferences, guarantees the logistics, secures material feed and significantly reduces the risk of damage and fail efforts. In this project, with every experiment the manufacturing process was improved. Not only by integrating extra equipment, but also by evolving the

\(^{127}\) Including, but not limited to temperature of the wire in this case, speed of milling tool in a robotic milling system or etc.
tectonics and workflows. Further exploration in this field is of great importance.

The motion grammar has already demonstrated its potential in analyzing and codifying robotic behavior according to the boundaries of RTM’s fabrication range, but it is still an infant, requiring much more studies and development to end up with a mature grammatical structure. Reaching such level was beyond the context of this research.

The application of rationalization methods is an inevitable part of the motion grammar approach. In this research, I adopted a handful number of those methods to rebuild complex geometries into rule surface ones and reproduce them in motion grammar vocabulary. Developing those methods are of equal importance as the grammar itself, when it comes to fabricating available geometries.
6-2. Next Step

I have already mentioned a diverse collection of potential next steps. Meanwhile I want to point out the most important ones from my point of view:

A major motivation behind this research was to develop a new approach towards robotic fabrication by proposing a new way to describe and interpret robotic characteristics in relation to form finding procedures in a machine and material-specific framework. Although this motion grammar is specific to hot wire cutting and architectural-grade EPS foam, the method of studying robotic fabrication as a series of choreographed (sequential or composite) motions, and formulating a vocabulary and a set of grammar rules, can be applied to other combinations of RTM systems. Thus some of potential next steps can be listed as:

- Applying grammar to other Robot-Tool-Material systems
- Developing a comprehensive generative framework to address special requirements of these new RTMs
- Organizing the framework in one software package, covering design, debugging, technical issues and code generation.

Moreover, as an inevitable next step, I want to express the importance of the material system. In such an integrated design-making process, design process and the fabrication methods are digitally controlled and armed with the computational power. However, the material system is still suffers from the lack of control in its internal process which can potentially affect the final form and characteristics of the system, either by manipulating its microstructure or engineering its physical properties variation in a predictable and logical way. The potentials of embedding design process in the material system is a promising landscape in architectural robotics. Developing corresponding variable materials that can partially bear a role in the smartness of the system is of high importance and could be a potential next step. I believe that Neri Oxman’s Water based robotic fabrication project has already demonstrated the opportunities in this field.
Integrating real-time interaction between the RTM and the generator is another potential field of study for further development. Where the dialogue between the components of the system breaks the borders of off-line simulation and establishes an on-line, real-time feedback loop between design and making. Right now, due to technical limitations of ABB S4CPlus controller family, the off-line simulation was inevitable.

Motion grammar has the potential to be developed to merge into rapid prototyping methods for robots, where a user can manipulate a manageable amount of data to control the robot and fabricated model. Combining a real-time communication with such approach would result in a real-time robotic prototyping.

6-3. Contribution

1- An approach towards the application of robotics in architecture, based on robot, mounted tool and material system characteristics.
2- A system that help designers to take command over design-making in architectural robotic procedures. [The System]
3- A generative grammar to address the robotic hot wire cutting
   • Can address the robotic motion
   • Describes the geometries of rolled surfaces
   • Can be modified to address other tools and material systems
Appendix A: Architectural Robotics Categorization

Dominant Paradigms

Multi-criteria Categorization

Fabrication Methods

**Dominant Paradigms**

Above mentioned factors are mostly quantitative and thus can be measured. In their workshop paper at Rob|Arch 2012, titled “Design Robotics”, King and Bechthold categorized the use of industrial robots in architecture based upon their paradigms in three distinguishable categories: \(^{128}\)

1- **Pragmatic approach:**

   To solve practical construction problems using engineering methods without affecting design scope. It mostly covers the Japanese 1980’s mass-construction.

2- **Creative and artistic design experimentation:**

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\(^{128}\) (Bechthold and King 2013)
To leave the constraints of the construction out of the investigation. The usually striking end results are often inspirational but are difficult to connect to the reality of architectural production.

3- Design Robotics:

To link design innovation to the reality of industrial production. By shifting focus away from industrial mass production, and towards design experimentation.

Nathan and Bechthold proposed this approach in contrast to the second one to accentuate the importance of building system and material system, rather than the robotic process opportunity. They tried to put more weight on the building-material sub-systems, including production, distribution, economics, etc. As they claim:

*Design Robotics thus represents a hybrid research method that combines bottom-up, technology-driven design inquiry with traditional, problem-centered approaches.*

Their categorization can clearly set borders between the early efforts of 80’s-90’s and later explorations in the mid-2000’s. However, the border between the second and third categories are not always sharp and clear. Meanwhile they do not provide enough clear measures to dispatch projects between these two. Thus, some projects may fall partially on any of them.

Multi-criteria categorization

Mahesh Daas proposed an array of frameworks to set a taxonomy of architectural robotics. His taxonomy is based upon four frameworks while every framework has its sub-categories.

<table>
<thead>
<tr>
<th>#</th>
<th>FRAMEWORK TITLE</th>
<th>SUB-CATEGORIES</th>
<th>SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

129 Ibid.
130 (Daas 2014)
Role of Robotics in the Architectural Design Process

<table>
<thead>
<tr>
<th>ROLE OF ROBOTICS IN THE ARCHITECTURAL DESIGN PROCESS</th>
<th>Fabrication</th>
<th>Operation</th>
<th>Robots as Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 ROBOT-HUMAN-ARCHITECTURE INTERACTIONS</td>
<td>Architecture</td>
<td>People</td>
<td>Robots</td>
</tr>
<tr>
<td>3 VITRUVIAN TRIAD OF ROBOTICS IN ARCHITECTURE</td>
<td>Utilitas</td>
<td>Firmitas</td>
<td>Venustas</td>
</tr>
<tr>
<td>4 ROBOTS CONSIDERED BY FORM</td>
<td>Biomorphich</td>
<td>Mechanomorphich</td>
<td>Polymorphich</td>
</tr>
<tr>
<td></td>
<td>Amorphich</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 - Daas' taxonomy of architectural robotics 131

Fabrication Methods

Manufacturing method is another key feature in every architectural robotic experiment. Being generic, robots can be equipped with almost every digital fabrication tool, spanning from water jet cutters to incremental deforming hammers. Size and payload is the only limitation. Capable of holding more than 1000 lbs, heavy industrial robots with relatively large reach span can manipulate a huge chainsaw to cut limestone or concrete with no difficulty.

131 Ibid.
## Table 4: Digital Fabrication Methods

<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>SUB-CATEGORY</th>
<th>MATERIAL</th>
<th>NEEDED TOOL</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBTRACTIVE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milling</td>
<td>Subtractive</td>
<td>Foam, Wood, Metal</td>
<td>Milling motor, Milling Tool, Milling grip, tool changer (optional)</td>
<td>Accurate, works for wide range of forms, generate fine details</td>
<td>Slow, need of tool change, needs lubrication and cooling, produce dust</td>
</tr>
<tr>
<td>Cutting</td>
<td>Saw Wire Cut</td>
<td>Stone, wood</td>
<td>Power supply, Corded saw, saw frame, lubricant pump</td>
<td>Fast, stent, leftovers of materials still usable, almost clean while working</td>
<td>Only works with special forms, may make toxic fumes, produce dust</td>
</tr>
<tr>
<td><strong>ADITIVE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D Print</td>
<td>ABF, Plastic</td>
<td>Nuzzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasting</td>
<td>Pouring Components</td>
<td>Clay, Resin</td>
<td>Pouring guide, Nuzzle</td>
<td>Fast, silent, leftovers of material still usable, almost clean while working</td>
<td>Hard to control, mostly used as a kind of welding</td>
</tr>
<tr>
<td>Casting</td>
<td>Real Time Casting</td>
<td>Metal, Clay</td>
<td>Nuzzle, Dier, Injector, Injector</td>
<td>Create some types of free forms in 3D</td>
<td>Mostly works by adding thin lines of material, takes too long when making complex volumes, hard to calculate the final relaxed form and deformation after pouring material</td>
</tr>
<tr>
<td><strong>JOINING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welding</td>
<td>Metal</td>
<td>Welding Torch or Welding Arc</td>
<td></td>
<td>For connecting metal objects, in point or lines</td>
<td>Needs one or two other robots to keep the connecting objects in place</td>
</tr>
<tr>
<td>Gluing</td>
<td>Plastic, Wood</td>
<td>Gluing Nuzzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FORMING PROCESS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>Metal Bending</td>
<td>Metal bars, CNC Bending tool, or heavy bending frame and strong robotic arm, Welding Torch or Arc</td>
<td>Best for making wire frame 3D forms</td>
<td>Needs a heavy collaboration among a team of robots, cnc machines, and users</td>
<td></td>
</tr>
<tr>
<td>Punching</td>
<td>Wood Bending</td>
<td>Plywood, Nuzzle</td>
<td>Welding torch, heavy frames or cutters</td>
<td>For steam bending of plywood</td>
<td>Very hard to calculate final form of every element</td>
</tr>
<tr>
<td>Incremental</td>
<td>Metal</td>
<td>Incremental Forming milling tool, electric hammer machine</td>
<td>For accurate forming of metal sheets</td>
<td>Loud noise and super slow procedure</td>
<td></td>
</tr>
<tr>
<td>Forming</td>
<td>Metals, Ceramic</td>
<td>Pressing surfaces, pressing niddle</td>
<td>Good for free form making by resembling human hand form making, good for folding in different direction and angles based upon die cut lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressing and</td>
<td>Metal, Clay</td>
<td>Pressing surfaces, pressing niddle</td>
<td>Good for free form making by resembling human hand form making, good for folding in different direction and angles based upon die cut lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die Cutting</td>
<td>Metal sheets, Paper</td>
<td>Die Cast, Die blades</td>
<td>Good for free form making by resembling human hand form making, good for folding in different direction and angles based upon die cut lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melting</td>
<td>Metal, Plastic, Paper</td>
<td>Die Cast, Die blades</td>
<td>Good for free form making by resembling human hand form making, good for folding in different direction and angles based upon die cut lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASSEMBLING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembling</td>
<td>Brick, component- based objects, metal, ...</td>
<td>Gripper (Mechanical, Pneumatic, Vacuum, ...</td>
<td>Generate forms from available or costume made component, very use for large scale projects, can be combined with welding, gluing etc. to put them in their exact position</td>
<td>Limited to specific type of form and setup</td>
<td></td>
</tr>
<tr>
<td><strong>DRAWING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawing</td>
<td>Air Pump spray</td>
<td>Nuzzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Air Pump spray</td>
<td>Nuzzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Ink and Spray</td>
<td>Nuzzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Dropping Ink</td>
<td>Brush, Ink Dropper, Ink batch</td>
<td></td>
<td>For making drawings from available or generated graphic, especially in monochrome</td>
<td>Not very accurate, need protection for the robot itself</td>
</tr>
<tr>
<td>Imagery</td>
<td>Ink and Spray</td>
<td>Brush, Ink batch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Still Image</td>
<td>Camera (DSLR), Camera remote control module</td>
<td>For making graphic patterns</td>
<td>Some what out of control</td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td></td>
<td>Camera (DSLR), Camera remote control module</td>
<td>For making graphic patterns</td>
<td>Needs changing the brush and cleaning</td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Video</td>
<td>Camera (DSLR), Camera remote control module</td>
<td>For generating super accurate movement in the video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagery</td>
<td>Long Exposure and</td>
<td>Camera (DSLR), Gripper, Camera remote control module</td>
<td>For making an image of moving object like glowing ones, making stop motions and ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visualization</td>
<td>Moving Subject</td>
<td>Camera (DSLR), Gripper, Camera remote control module</td>
<td>For making an image of moving object like glowing ones, making stop motions and ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weaving</td>
<td>Rope, Textile, Fabric, Carbon Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
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